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STORM WATER MANAGEMENT MODEL, VERSION 4:

USER'S MANUAL

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The Storm Water Management Model (SWMM) described in this manual must be used at the user's own risk. Neither the U.S. Environmental Protection Agency, the State of Florida, the University of Florida or the program authors can assume responsibility for model output, interpretation or usage.

FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Assessment Branch develops state-of-the-art mathematical models for use in water quality evaluation and management.

Mathematical models are an important tool for use in analysis of quantity and quality problems resulting from urban storm water runoff and combined sewer overflows. This report is an updated user's manual and documentation for one of the first of such models, the EPA Storm Water Management Model (SWMM). Detailed instructions on the use of the model are given and its use is illustrated with case studies.

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PREFACE

This version of SWMM is an update and improvement of the 1981 release of Version 3. There are several extensions and improvements to the model, mostly in the area of additional flexibility (e.g., natural channel cross sections in Extran), features (e.g., subsurface flow routing in runoff), and conveniences (e.g., improved input and output). A list of major changes implemented in Version 4 is given in Section 1 of this manual, and Table 1-1 presents a summary of all SWMM characteristics. Effort has been taken to adapt the model for microcomputer as well as main-frame use; the same Fortran-77 code will run on either type of hardware. Unfortunately, this dual personality of the model means that SWMM does not take full advantage of either medium. For example, line-printer plots are still used in lieu of bit-mapped graphics readily available on micros. However, detailed information is provided about the file structures used for hydrographs and pollutographs so that users can employ their own software for graphics, etc. Development of pre- and post-processors is also encouraged.

This manual is basically an edited version of the 1981 Version 3 manual. The most significant changes deal with file management (Section 2), unformatted data input (all sections), new options for reading continuous precipitation, temperature, evaporation and wind speed records (Sections 4, 10 and 11), and a new subsurface quantity routing routine for the Runoff Block (Section 4 and Appendix X). References on some topics, e.g., snowmelt, storage/treatment, were current at the time of writing which may have been as much as 10 years ago. The user should obtain familiarity with current information and alter his/her modeling practices as necessary.

An attempt has been made to provide adequate information in this manual for most users so that they can conceptualize a stormwater problem and simulate it using SWMM. As a result, some of the text is rather lengthy, approaching a hydrology textbook in style. Unfortunately, it will still be the user's responsibility to seek out the proper references for additional information on modeling, especially when dealing with water quality. The SWMM bibliography referenced in Section 1 is a valuable source of literature citations dealing with all aspects of SWMM usage.

Due to the dynamic nature of the model improvements, no detailed examples have been included within this manual itself. However, several examples are provided on the distribution tape (for main-frame) or disks (for micro). These are complete with input and output files and will greatly enhance the learning process. Regarding learning about the model, the user should start with simple examples for which the answers are well known. For example, a good first case study for SWMM is to use just the Runoff Block to simulate the runoff from steady rainfall onto an impervious surface (e.g., corresponding to

Figure 4-14). Inclusion of a single pipe can follow, with more detailed networks that use the Transport or Extran Blocks later.

The authors hope that the user is not "put off" by the length of this volume and the size of the SWMM program. Aside from the fact that it requires a large computer core (about 500 K bytes), the program may often be easily and usefully run with a minimum of input, say a dozen lines of data. For small systems in which time step requirements are not severe, the model is very economical as well, and is within the reach of most users, especially as it may be run on a microcomputer. It is by no means the only engineering tool of its kind available, but it has benefited greatly from its longevity and feedback from model users. The authors hope such feedback will continue, and earnestly solicit suggestions for improvements. Although no major support for model changes is likely to be forthcoming, the EPA Storm Water and Water Quality Model Users Group (formerly the SWMM Users Group) remains a convenient forum. Announcements of corrections, changes and new options will be made through that group, managed by Mr. Thomas O. Barnwell, EPA, Athens, Georgia 30613.

ABSTRACT

The EPA Storm Water Management Model (SWMM) is a comprehensive mathematical model for simulation of urban runoff quantity and quality in storm and combined sewer systems. All aspects of the urban hydrologic and quality cycles are simulated, including surface and subsurface runoff, transport through the drainage network, storage and treatment. This volume represents Version 4 of SWMM as it is an update of three earlier User's Manuals issued in 1971, 1975 and 1981. It should be coupled with Addendum I in order to run the Extran Block (detailed hydraulic flow routing) developed by Camp, Dresser and McKee.

Detailed descriptions are provided herein for all blocks: Runoff, Transport, Storage/Treatment, Combine, Statistics, Rain, Temp and Graph (part of the Executive Block). The latter five blocks are "service" blocks; the first three are the principal computational blocks. In addition, extensive documentation of new procedures is provided in the text and in several appendices. Versions of the model for main-frame, minicomputers and IBM-compatible microcomputers are supported.

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The Fortran-77 code for Version 4 of SWMM is based on a microcomputer version prepared by Mr. Richard M. Baker and Mr. Karl J. Brazauskas of Metcalf and Eddy, Inc., another one of the original three developers. Much of the user's manual text for Version 4 has been adapted from a computerized edition of the Version 3 manuals prepared by Dr. William James of the University of Guelph. We are grateful to Dr. James and to Dr. Stephen Nix of Syracuse University for their helpful comments regarding Version 4. Assistance in printing of the manuals was provided by KBN Applied Sciences and Engineering, Inc. of Gainesville.

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SECTION 1

INTRODUCTION

URBAN RUNOFF ANALYSIS

Urban runoff quantity and quality constitute problems of both a historical and current nature. Cities have long assumed the responsibility of control of stormwater flooding and treatment of point sources (e.g., municipal sewage) of wastewater. Within the past two decades, the severe pollution potential of urban non-point sources, principally combined sewer overflows and stormwater discharges, has been recognized, both through field observation and federal legislation. The advent of modern, high speed computers has led to the development of new, complex, sophisticated tools for analysis of both quantity and non-point pollution problems. The EPA Storm Water Management Model, SWMM, developed in 1969-71, was one of the first of such models, it has been continually maintained and updated, and is perhaps the best known and most widely used of the available urban runoff quantity/quality models.

Many of the changes that have occurred to SWMM during the past 15 years have been poorly documented and were not readily visible to users. This volume includes documentation (of both the theory and programming details) of major changes to the model since its original development. This documentation is located primarily in the appendices whereas the text consists primarily of the User's Manual. Theory that underlies unchanged parts of the model may still be reviewed in the original documentation (Metcalf and Eddy et al., 1971a, 1971b, 1971c, 1971d) plus intermediate reports (Huber et al., 1975; Heaney et al., 1975). This volume supersedes Version 3 documentation (Huber et al., 1981b) and includes essentially all material from that manual.

URBAN RUNOFF MODELS

Objectives

Models are generally used for studies of quantity and quality problems associated with urban runoff in which four broad objectives may be identified: screening, planning, design and operation. Each objective typically produces models with somewhat different characteristics, and the different models overlap to some degree.

Screening Models

Screening models are preliminary, "first-cut" ("Level I"), desktop procedures that require no computer. They are intended to provide a first estimate of the magnitude of urban runoff quantity and quality problems, prior to

an investment of time and resources into more complex computer based models. Only after the screening model indicates its necessity should one of the latter models be used. Examples of screening models include SWMM Level I procedures (Heaney et al., 1976; Heaney and Nix, 1977) and others: Howard (1976), Hydroscience (1976, 1979), Chan and Bras (1979).

Planning Models

Planning models are used for an overall assessment of the urban runoff problem as well as estimates of the effectiveness and costs of abatement procedures. They may also be used for "first-cut" analyses of the rainfall-runoff process and illustrate trade-offs among various control options. They are typified by relatively large time steps (hours) and long simulation times (months and years), i.e., continuous simulation. Data requirements are kept to a minimum and their mathematical complexity is low.

Various continuous simulation models are reviewed in Appendix I. SWMM has had this capability since 1976, following the earliest work of the Stanford Watershed Model (Crawford and Linsley, 1966) and the latter widely-used Corps of Engineers STORM model (Roesner et al., 1974; HEC, 1977a).

A planning model may also be run to identify hydrologic events that may be of special interest for design or other purposes. These storm events may then be analyzed in detail using a more sophisticated design model (Huber et al., 1986). SWMM can be used in both the planning and design mode. Planning or long-term models may also be used to generate initial conditions (i.e., antecedent conditions) for input to design models. They may occasionally be coupled to continuous receiving water models as well; for example, SWMM and STORM may be used as input to Medina's (1979) Level III Receiving Water Model.

Design Models

Design models are oriented toward the detailed simulation of a single storm event. They provide a complete description of flow and pollutant routing from the point of rainfall through the entire urban runoff system and often into the receiving waters as well. Such models may be used for predictions of flows and concentrations anywhere in the rainfall/runoff system and can illustrate the detailed and exact manner in which abatement procedures or design options affect them. As such, these models are a highly useful tool for determining least-cost abatement procedures for both quantity and quality problems in urban areas. Design models are generally used for simulation of a single storm event and are typified by short time steps (minutes) and short simulation times (hours). Data requirements may be moderate to very extensive depending upon the particular model employed.

In its original form (Metcalf and Eddy et al., 1971a, 1971b, 1971c, 1971d), SWMM was strictly a design model. However, as described above, it may now be used in both a planning and design mode. In addition, it has acquired additional design potential through inclusion of the Extended Transport Model, Extran, developed by Camp, Dresser and McKee (formerly Water Resources Engineers). Extran is probably the most sophisticated program available in the public domain for detailed hydraulic analysis of sewer systems (Shubinski and

Roesner, 1973; Roesner et al., 1981; Roesner et al., 1987).

Operational Models

Operational models are used to produce actual control decisions during a storm event. Rainfall is entered from telemetered stations and the model is used to predict system responses a short time into the future. Various control options may then be employed, e.g., in-system storage, diversions, regulator settings.

These models are frequently developed from sophisticated design models and applied to a particular system; Schilling (1985) provides a review. Examples are operational models designed for Minneapolis-St. Paul (Bowers et al., 1968) and Seattle (Leiser, 1974).

Other Models

SWMM is by no stretch of the imagination the only urban runoff model available, or necessarily the preferred one under many circumstances. Many other urban runoff models have been described in the literature and are too numerous to list here. However, good comparative reviews are available, e.g., Brandstetter (1977), Chu and Bowers (1977), Huber and Heaney (1980, 1982), Kibler (1982), Kohlhaas (1982), EPA(1983a), Whipple et al. (1983) and Hall (1984). EPA's water quality models are reviewed by Barnwell (1984). A general review of methods available for urban quality modeling and six operational urban quality models is provided by Huber (1985, 1986). Many more models are available for purely hydrologic and hydraulic analysis.

DEVELOPMENT OF THE STORM WATER MANAGEMENT MODEL

Under the sponsorship of the Environmental Protection Agency, a consortium of contractors -- Metcalf and Eddy, Incorporated, the University of Florida, and Water Resources Engineers, Incorporated -- developed in 1969-71 the Storm Water Management Model, SWMM, capable of representing urban stormwater runoff and combined sewer overflow phenomena. Both quantity and quality problems and control options may be investigated with the model, with associated cost estimates available for storage and/or treatment controls. Effectiveness can be evaluated by inspection of hydrographs, pollutographs, pollutant loads, and modeled changes in receiving water quality.

The original project report is divided into four volumes. Volume I, the "Final Report" (Metcalf and Eddy et al., 1971a), contains the background, justifications, judgments, and assumptions used in the model development. It further includes descriptions of unsuccessful modeling techniques that were attempted and recommendations for forms of user teams to implement systems analysis techniques most effectively. Although many modifications and improvements have since been added to the SWMM, the material in Volume I still accurately describes much of the theory behind updated versions. Documentation of some of the procedures included in the 1975 Version II (Huber et al., 1975) release of SWMM is also provided by Heaney et al. (1975).

Volume II, "Verification and Testing," (Metcalf and Eddy et al., 1971b),

describes the methods and results of the application of the original model to four urban catchments.

Volume III, the "User's Manual" (Metcalf and Eddy et al., 1971c) contains program descriptions, flow charts, instructions on data preparation and program usage, and test examples. This was updated in 1975 by the Version II User's Manual (Huber et al., 1971) and in 1981 by the Version 3 User's Manuals (Huber et al., 1981; Roesner et al., 1981). This present report supersedes all of these previous documents.

Volume IV, "Program Listing" (Metcalf and Eddy et al., 1971d), lists the entire original program and Job Control Language (JCL) as used in the demonstration runs. Since many routines in the updated version are similar or identical to the original, it is still a useful reference, but on the whole should be disregarded since the present coding is in most cases, completely different.

All three original contractors have continued to modify and improve the SWMM, as have numerous other users since its release. Through EPA research grants, the University of Florida has conducted extensive research on urban runoff and SWMM development, and has evolved into an unofficial "clearinghouse" for SWMM improvements. There has clearly been a large benefit from the fact that SWMM is in the public domain and non-proprietary since the present version reflects the input and critical assessments of over ten years of user experience. Of course, lingering "bugs" are the responsibility of the present report's authors alone.

An extensive bilbiography of SWMM usage is available (Huber et al., 1985) and is highly recommended for new users. Case studies mentioned in the bibiography are especially useful.

As described earlier, this report is both a SWMM Version 4 User's Manual and also documentation of new procedures. In order to accomodate both mainframe and microcomputer versions of the Fortran code, input formats have been revised from previous versions, including Version 3. The main difference is that all input is now unformatted, eliminating the field restrictions of all previous versions. Hence, although basic data requirements remain the same, some data groups will need to be revised for input into Version 4. (Since card input is no longer routinely used for input to any computers, references to "card group" will now be "data group" or "data line.") Hence, it must be assumed by the user that <u>all</u> input must be prepared anew for this SWMM version. Further details on new aspects of Version 4 are given later in this section.

OVERALL SWMM DESCRIPTION

Overview

SWMM simulates real storm events on the basis of rainfall (hyetograph) and other meteorological inputs and system (catchment, conveyance, storage/treatment) characterization to predict outcomes in the form of quantity and quality values. Since study objectives may be directed toward both com-

plete temporal and spatial detail as well as to gross effects (such as total pounds of pollutant discharged in a given storm), it is essential to have both time series output, i.e., hydrographs and "pollutographs" (concentrations versus time) and daily, monthly, annual and total simulation summaries (for continuous simulation) available for review.

An overview of the model structure is shown in Figure 1-1. In simplest terms the program is constructed in the form of "blocks" as follows:

1. The input sources:

   The Runoff Block generates surface and subsurface runoff based on arbitrary rainfall (and/or snowmelt) hyetographs, antecedent conditions, land use, and topography. Dry-weather flow and infiltration into the sewer system may be optionally generated using the Transport Block.

2. The central cores:

   The Runoff, Transport and Extended Transport (Extran) Blocks route flows and pollutants through the sewer or drainage system. (Pollutant routing is not available in the Extran Block.) Very sophisticated hydraulic routing may be performed with Extran.

3. The correctional devices:

   The Storage/Treatment Block characterizes the effects of control devices upon flow and quality. Elementary cost computations are also made.

4. The effect (receiving waters):

   SWMM does not include a receiving water model. The Receiving Water Block (Receiv) is no longer included within the SWMM framework. However, a linkage is provided for the EPA WASP and DYNHYD models (Ambrose et al., 1986).

Quality constituents for simulation may be arbitrarily chosen for any of the blocks, although the different blocks have different constraints on the number and type of constituents that may be modeled. The Extran Block is the only block that does not simulate water quality.

As indicated in Figure 1-1, the Transport, Extran and Storage/Treatment Blocks may all use input and provide output to any block, including themselves. The Runoff Block uses input from no other computational block but may recieve input from new Rain and Temp Blocks for meteorological input.

Service Blocks

Executive Block --

In addition to the four computational blocks mentioned above, six service

can link with EPA models like linehyd.

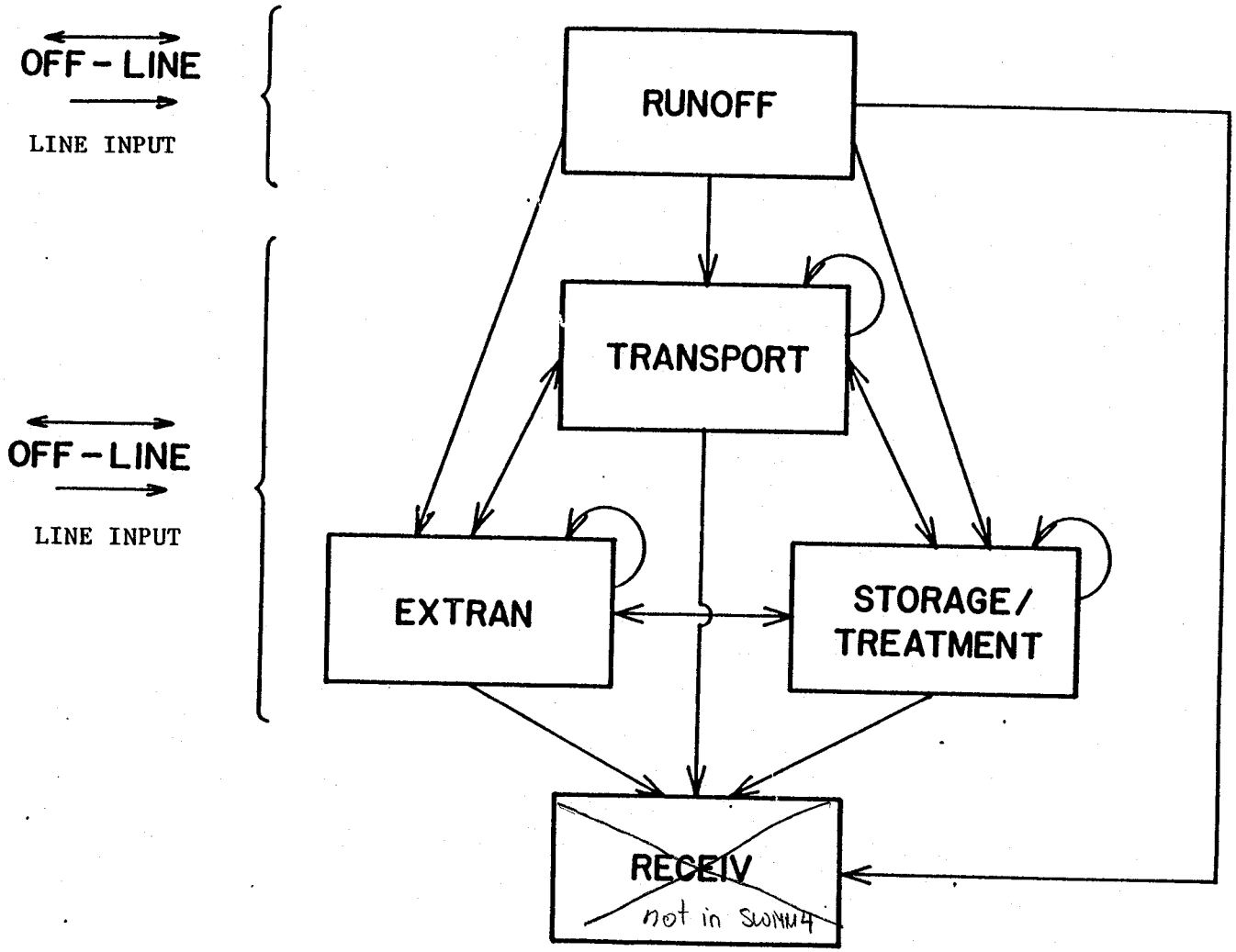


Figure 1-1. Overview of SWMM Model Structure, Indicating Linkages Among the Computational Blocks. Receiving water Simulation is by external programs, not Receive Block. "Line input" refers to data input from terminal, etc.

blocks are utilized. The Executive Block assigns logical unit numbers to off-line files (disk/tape/drum) and determines the block or sequence of blocks to be executed. All access to the computational and service blocks and transfers between them must pass through the MAIN program of the Executive Block. Transfers are accomplished on off-line devices (disk/tape/drum) that may be saved for multiple trials or permanent record using control parameters described in Section 2. Dependency on machine-dependent job control language should be minimized.

Graph Block --

Line-printer plots of hydrographs, pollutographs and other time series output may be obtained using the Graph Block, which is documented along the Executive Block in Section 2. Measured as well as predicted time series may be plotted. Alternatively, the user may access the time series file (known in this manual as the "interface file") for plots by other graphics software.

Combine Block --

This block allows the manipulation of multiple interface files in order to aggregate results of multiple previous runs for input into subsequent blocks. In this manner large, complex drainage systems may be partitioned for simulation in smaller segments.

Rain Block --

Continuous simulation relies upon precipitation input using long-term data available on magnetic tapes from the National Weather Service (NWS) National Climatic Data Center in the United States or Atmospheric Environment Service in Canada. The Rain Block processes NWS tapes for input into the Runoff Block. A synoptic statistical analysis may also be performed on rainfall data, similarly to the EPA SYNOP program (Hydroscience 1976, 1979).

Temp Block --

In a similar manner, the Temp Block processes NWS long-term temperature data for input into the Runoff Block for snowmelt calculations.

Statistics Block --

Output from continuous simulation can be enormous if results for every time step are printed. Even the monthly and annual summaries contain more information than may easily be assimilated. The Statistics Block has the capability to review the time step output from a continuous (or single event) simulation, separate output into discrete storm events, rank the events according to almost any desired criterion (e.g., peak or average runoff rate, pollutant load, etc.), assign empirical frequencies and return periods to runoff and pollutant parameters, tabulate and graph the results, and calculate statistical moments. Output from this block can thus be used to identify key events for further study and for many other screening and analytical purposes.

Total Simulation

The capability exists to run up to 25 blocks sequentially in a given run, although from a practical and sometimes necessary viewpoint (due to computer memory limitations) typical runs usually involve only one or two computational blocks together with the Executive Block. This approach may be used to avoid overlay and, moreover, allow for examination of intermediate results before continuing the computations.

This manual provides for each block a description of program operation, documentation of most algorithms used within the block (or reference to earlier documentation), and instructions on data preparation with input requirements. However, the user's manual and documentation for the Extended Transport (Extran) Block has been prepared by Camp, Dresser and McKee (Roesner et al., 1987) as an addendum to this report and is available as a separate document. Thus, Section 5 of this report merely introduces Extran.

Detailed SWMM Summary

A concise description of most features of SWMM is given in Table 1-1, adapted from similar tables prepared by Huber and Heaney (1980, 1982). An indication of almost all modeling techniques is included in the table.

USAGE REQUIREMENTS

Computer Facilities

SWMM may be run on both main-frame and IBM-PC compatible microcomputers. Development and testing of Version 4 has been performed using RM/Fortran on a Zenith Z-248, AT-compatible microcomputer, followed by main-frame testing using VS-Fortran on an IBM 3033 at the University of Florida. Fortran-77 standards are followed. Version 4 was developed from a base version of the Version 3 code developed for EPA by Metcalf and Eddy, Inc. (Baker and Brazauskas, 1986) for the microcomputer. Further refinements were based on an alternative microcomuter version of SWMM (James and Robinson, 1984).

VS Fortran requires at least 2500 K words of storage using virtual memory (no overlay). Mainframe and minicomputer users should not have to bother with any overlay structure. Those who still have system memory limitations can simply employ an overlay structure with each SWMM block in a single overlay. The largest combination will be the Executive Block and Runoff Block together (less than 600 K). Microcomputer users must have at least 512 K bytes of memory and an 8087 or 80287 math coprocessor and will benefit from a hard disk, although the latter is not a rigid requirement. Main-frame users will have to compile and link the Fortran code. Microcomputer users will have the option of using executable code or recompiling and linking the source code.

Distribution of both the main-frame and microcomputer versions of the program is through:

Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
College Station Road
Athens, Georgia 30613

Input Data Requirements

As will be seen from a review of following sections, the data requirements for the SWMM may be extensive. Collection of the data from various municipal and other offices within a city is possible to accomplish within a few days. However, reduction of the data for input to the model is time consuming and may take up to three man-weeks for a large area (e.g., greater than 2000 acres). On an optimistic note, however, most of the data reduction is straight forward (e.g., tabulation of slopes, lengths, diameters, etc., of the sewer system).

SWMM is flexible enough to allow different modeling approaches to the same area, and a specific, individual modeling decision upstream in the catchment will have little effect on the predicted results at the outfall. Furthermore, a lumped approach may often be used for preliminary modeling in which catchment propterties are aggregated and only minimal data are needed. The user should realize that only portions of the overall model (e.g., one block) need be run at any one time.

Verification and Calibration

Calibration is the adjustment of model parameters using one set of data. Verification is the testing of this parameter selection by using an independent data set. Although the simulation of many of the urban runoff processes found in SWMM is physically based, the concept fails in practice because the input data and the numerical methods are not accurate enough for many real applications. Furthermore, many computational procedures within the model are based upon limited data themselves and highly empirical, especially surface quality predictions. As a result it is essential that local verification/calibration data be available at specific application sites to lend credibility to the predictions of any urban runoff model.

Calibration and verification data are usually in the form of measured flows and concentrations at outfalls or combined sewer overflow locations. However, it is important to note that detailed short-time-increment pollutographs during a storm are seldom needed for analysis of recieving water quality (see discussion in Section 4). Hence, total storm event loads or event mean concentrations are usually sufficient for quality calibration and verification. (Note that quality concentrations without accompanying flows are of little value.) SWMM has sufficient parameters that may be "adjusted," particularly in the Runoff Block, such that calibrating the model against measured data is usually readily accomplished.

Quantity (hydrograph) predictions are often "within the ball park" on the first try, given decent rainfall, area and imperviousness data. However, initial quality estimates may be off by orders of magnitude (Huber, 1985). Hence, quality predictions are not credible without adequate site-specific

data for calibration and verification. At best, relative effects of pollution abatement alternatives may be studied if such data are not available.

METRIFICATION

Use of metric units for input and output of data and results is an option in all blocks as an alternative to U.S. customary units. In the Runoff and Transport Blocks, metric units are used strictly for I/O; all internal quantity calculations are still performed in units of feet and seconds. (Feet-second units also apply to program generated error messages printed during the simulation.) However, the Storage/Treatment and Extran Blocks use metric units for internal calculations also, when used. Most quality calculations use conventional concentration units (e.g., mg/l) and loads may be given in both pounds and kilograms, depending on the particular subroutine, although pounds will not be used if metric I/O is specified.

No attempt has been made to conform to SI standards or even customary metric units for some parameters. For instance, because of output format complications, metric pipe diameters are requested and printed in meters instead of the more usual millimeters. However, all units are clearly stated for both input and output. It should be a simple task to convert to other metric alternatives.

CHANGES FOR VERSION 4

Not all users will require Version 4 since in most respects the computations are identical to Version 3. Significant modifications are listed below.

1. Input/output has been enhanced. All input is free-format with line (data group) identifiers. The line identifiers are now a requirement since the program uses them as the only means of separating one data group from another. Program-generated error messages make it easier to locate problems causes by improper entry of data. Input strings of up to 230 characters are allowed in SWMM 4. Strict column sequencing of input data is still possible as long as at least one space separates the fields.

Comment lines are allowed in this version of SWMM. A comment line begins with an asterisk in the first column. A template for full screen editing is included as an example for each block of SWMM. The templates include brief comments about each input field.

2. Errors have been corrected for all blocks as best they are known.

3. Extran is available in a metric format and uses data group identifiers. Additional features include: a "hot start" capability (restart from end of previous run); natural channel cross sections, with cross-sections input as in HEC-2; minor improvements to surcharge and flow routing routines; and automatic adjustment of small pipe lengths.

4. SWMM output may be linked to the DYNHYD4 (water quantity) and WASP4 (water quality) programs for receiving water quality simulation (Ambrose et al., 1986). Runoff, Transport, Storage/Treatment, and Extran interface files

can be read by both DYNHYD4 and WASP4. DYNHYD reads only the flows from the interface file. WASP4 reads water quality loading rates from Runoff, Transport, and Storage/Treatment. A model of an estuary therefore can include Runoff to generate surface pollutant loadings, Transport or Extran for detailed simulation of surface routing network, DYNHYD4 for simulating a link-node estuary model, and WASP4 for simulating the water quality of the estuary under the stress of the Runoff or Transport pollutant loadings.

5. The microcomputer version permits greater manipulation of interface files and other scratch and I/O files. The Combine Block may be used to convert any interface file to formatted (ASCII/text) files capable of being read by programs such as Lotus 1-2-3 or other software. All interface files can be permanently saved and retrieved. Users can input their own interface files.

6. A subsurface routing package (quantity only) has been added to the Runoff Block. A separate accounting is made for the unsaturated and saturated zones, and the water table elevation can fluctuate. Baseflow to Runoff channel/pipes may be generated from the saturated zone.

7. The Runoff Block (through access to the Rain Block) will read the new National Weather Service format for precipitation tapes. In general, continuous simulation is easier, with several options for input of precipitation data and other time series. User-defined input time series may also be used. Continuous simulation is capable of using up to 10 rain gages.

Instead of processing continuous meteorological data in the Runoff Block, two new blocks have been added: Rain and Temp. These include the capabilities of the former Subroutine CTRAIN in Runoff with additional statistical analysis similar to the SYNOP program of Hydroscience (1976, 1979). It is also possible to process rainfall data with the SWMM Statistics Block.

8. Numerical methods have been improved in the Runoff Block. A variation of the extrapolation method (Press et al., 1986) is used to couple the nonlinear reservoir equations, evaporation, infiltration, and groundwater flow. Subroutine Gutter no longer has convergence problems. There is no distinction any more between single event and continuous simulation, eliminating parameter ICRAIN. Runoff uses a wet, dry and intermediate (wet/dry) time step defined by the user.

9. This version of SWMM tries to use more Fortran primitives. There is one subroutine to read interface files, one subroutine to write interface files, one clock subroutine, one file opening routine etc. for all blocks. The common functions of all blocks are exactly the same.

10. This version can be made more modular than the EPA Version 3 for the microcomputer. It is possible to run files containing only the blocks of interest, saving the interface file for use by the next block. This permits file compression for ease of distribution and much faster execution times.

11. The Graph Block is no longer limited to 200 data points. An unlimited number of points for both measured and predicted graphs can be plotted. Graph plots loadographs (mass/time versus time) and pollutographs (concentra-

tion versus time).

12. The user has more control over printout in this version of SWMM. Most printout can be bypassed at the user's discretion. Error messages are summarized at the end of a run instead of being printed every time step.

13. Microcomputer users will see the current time or time step printed on the screen during the simulation as well as other program messages.

WHEN SHOULD SWMM BE USED?

SWMM is a large, relatively sophisticated hydrologic, hydraulic and water quality simulation program. It is not appropriate for all applications or for all personnel. For instance, hydrologic routing (e.g., prediction of runoff from rainfall) may be performed simply using standard techniques (e.g., units hydrographs, linear reservoirs) described in hydrology texts and suitable for programmable hand-held calculators (e.g., Croley, 1977) or microcomputers (e.g., Golding, 1981). In addition, many other, smaller Fortran programs are available for urban hydrologic simulation that may be entirely suitable for a given problem and much easier to implement on a given computer system. Notable among the hundreds of such program are the Corps of Engineers, Hydrologic Engineering Center program STORM (Roesner et al., 1974, HEC, 1977a) for continuous simulation and the Illinois State Water Survey program ILLUDAS (Terstreip and Stall, 1974) for single-event simulation and pipe sizing. Both have good documentation and user support and have been extensively tested and utilized by engineers other than the model developers. HSPF (Johanson et al., 1980) is another alternative for catchments that are primarily nonurban or that require more sophisticated simulation of pollutant interaction.

SWMM is certainly formidable both in terms of its size and capabilities. Who, then, should use SWMM and for what purposes? Some criteria for usage are given below:

1. The engineer must be knowledgeable of the modeling techniques (e.g., non-linear reservoirs, kinematic waves, St. Venant equations, buildup-washoff equations). An appreciation for how physical processes may be simulated in a Fortran program is a necessity. As a corollary, the engineer is assumed to be familiar with the problem to be solved and with customary techniques for handling it. A clear problem definition is a prerequisite to any solution methodology.

2. By virtue of the problem size (e.g., sewer system with hundreds of pipes) or complexity (e.g., hydraulic controls, backwater) a simpler technique or model will not work. It may be borne in mind, however, that if calibration/verification data are available, SWMM may also be used as a very simple "black box" model with minimal input data, at the expense of computer overhead to manage the program size and off-line files.

3. Quality is to be simulated. Although there are other models that also simulate quality, SWMM is perhaps the most flexible of any. Of course, SWMM is often applied just to quantity problems.

A large body of literature on theory and case studies is available for SWMM. Since the model was originally introduced in 1971, a wealth of such information is available, including citation in hydrology texts (e.g., Viessman et al., 1977; Wanielista, 1978; Kibler, 1982). A bibliography of SWMM-related literature is available (Huber et al., 1985)

While any number of examples could be presented for when SWMM should not be used, attention is drawn to just one: the user is already familiar with an adequate alternative technique or model. It is far more important for the engineer/user to understand the methodology being utilized than it is for a model such as SWMM to be employed on the premise of a more sophisticated technique. In the final analysis, the engineer/analyst is responsible for the decisions made using any technique of analysis; the technique or model is only a tool that must be clearly understood by those using it.

MODELING CAVEATS

The preceding section may be summarized by a few caveats for modeling in general and use of SWMM in particular.

1. Have a known project and modeling objective at the outset of work. Do not let the model capabilities or lack of them dictate the objective.

2. Use experienced personnel. A knowledge of engineering fundamentals is essential to proper model use and interpretation.

3. Use the simplest model suitable for the job. Although SWMM can be run in a very simple (e.g., minimal data) manner, there may be alternative models that require less initial effort to install. Sometimes a conclusion will be apparent simply from a review of data and prior studies, with no modeling necessary.

4. Start simple when learning. Obtain model familiarity by simulating very simple configurations for which the result is known, e.g., runoff from a steady rainfall onto an impervious surface.

5. Models are poor substitutes for data collection. Do not use the model to generate "real" data.

6. Examine the results critically. Is continuity preserved? Are predictions physically realistic? If not, review parameter estimates and model assumptions. Perhaps the model cannot simulate a particular physical process of interest.

7. Use one set of data for calibration and an independent set for verification of parameter choices.

8. Absolute magnitudes of quality predictions by SWMM or any other model are not to be trusted without calibration and verification data. At best, relative comparisons can be made between runs with differing conditions. Urban runoff quality processes involve too many unknown physical, chemical and biological factors to be simulated accurately.

Table 1-1. Summary of EPA Storm Water Management Model (SWMM) Characteristics

Applicable Land Drainage Area
(1) Urban. (2) General nonurban.
Time Properties
(1) Single-event or continuous simulation; both modes have an unlimited number of time steps. (2) Precipitation: input at arbitrary time intervals for single-event simulation (typically 1-15 min) and continuous simulation (typically 1-hr); for snowmelt daily max-min temperatures required for continuous, temperatures at arbitrary intervals for single-event. (3) Output at time step intervals (or multiples); daily, monthly, annual, and total summaries for continuous simulation. (4) Time step arbitrary for single-event (typically 5 minutes) and continuous (typically one hour); variable time step available in Runoff Block; time step for Extended Transport Block (Extran) routing depends on stability criteria, may be as small as a few seconds.
Space Properties
(1) Small to large multiple catchments. (2) Surface: lumped simulation of surface flow with allowance for up to 200 subcatchments and 10 input hyetographs, up to 200 channel/pipes may be simulated by nonlinear reservoir routing. (3) Channel/pipes: one-dimensional network, up to 200 conduit/nonconduit elements for Transport Block, up to 200 conduits in Extran Block, up to 30 in-line storage units in Transport Block. Values easily changed using Fortran Parameter statement. (4) Catchment area may be disaggregated and modeled sequentially for simulation of areas too large for existing SWMM dimensions. (5) Storage/treatment simulated separately, receiving input form upstream routing. (6) Output from surface, channel/pipe, or storage/treatment simulation may serve as new input for further simulation by same or different blocks.
Physical Processes
(1) Flow derived from precipitation and/or snowmelt; snow accumulation and melt simulated using temperature-index methods developed by National Weather Service; snow redistribution (e.g., plowing, removal) may be simulated. (2) Overland flow by nonlinear reservoir using Manning's equation and lumped continuity, depression storage, integrated Horton or Green-Ampt infiltration (with optional subsurface routing), recovery of depression storage via evaporation between storms during continuous simulation, also exponential recovery of infiltration capacity. (3) Subsurface routing only of flows through unsaturated and saturated zones simulated using lumped storages; subsurface outflow by power equation; simulation of ET and water table fluctuation. (4) Channel/pipes: (a) nonlinear reservoir formulation for channel/pipes in Runoff Block, includes translation and attenuation effects, (b) modified kinematic wave formulation in original Transport Block assumes cascade of conduits,

cannot simulate backwater over more than one conduit length, surcharging handled by storing water at surcharged junction pending available flow capacity; (c) Extended Transport Block solves complete St. Venant equations including effects of backwater, flow reversal, surcharging, looped connections, pressure flow, (d) infiltration and dry-weather flow may enter conduit of either transport simulation. (5) Storage routing using modified Puls method assuming horizontal water surface, outlets include pumps, weirs, orifices. (6) Surface quality on basis of linear or non-linear buildup of dust/dirt or other constituents during dry-weather and associated pollutant fractions, power-exponential washoff with decay parameter a power function of low rate only (rating curve); erosion by Universal Soil Loss Equation. (7) Dry-weather flow quantity and quality on basis of diurnal and daily variation, population density and other demographic parameters, buildup of suspended solids in conduits by dry weather deposition using Shield's criterion. (8) Quality routing by advection and mixing in conduits and by plug flow or complete mixing in storage units, scour and deposition of suspended solids in conduits (original Transport Block) using Shield's criterion. (9) Storage/treatment device simulated as series-parallel network of units, each with optional storage routing. (10) Treatment simulation: (a) use of arbitrary user-supplied removal equations (e.g., removal as exponential function of residence time); (b) use of sedimentation theory coupled with particle size-specific gravity distribution for constituents.

Chemical Processes

(1) Ten arbitrary conservative constituents in Runoff Block, rainfall quality included, choice of concentration units is arbitrary; erosion "sediment" is optional. (2) Four constituents may be routed through the original transport module (with optional first order decay), three through the storage/treatment module and none through Extran (quantity only).

Biological Processes

(1) Coliform simulation may be included. (2) Biological treatment may be simulated.

Economic Analysis

Amortized capital plus operation and maintenance costs for control units are determined.

Mathematical Properties

(1) Physically-based model. (2) Surface quantity: iterative solution of coupled continuity and Manning equations, Green-Ampt or integrated form of Horton infiltration (infiltration rate proportional to cumulative infiltration, not time). (3) Surface channel/pipe routing: non-linear reservoir assuming water surface parallel to invert. (4) Channel/pipes: (a) original Transport: implicit finite difference solution to modified kinematic wave equation; (b) Extran

transport: explicit finite difference solution of complete St. Venant equations, stability may require short time step. (5) Storage/detention: modified Puls method requires table look-up for calculation of outflow. (6) Surface quality, quality routing and treatment: algebraic equations, no iterations required once flows and conduit volumes are known.

Computational Status

(1) Coded in Fortran-77, approximately 25,000 statements long. (2) Has been run on IBM, UNIVAC, CDC, Amdahl, VAX, Prime, Harris, Boroughs and other main-frame and minicomputers; main-frame version must be compiled. (3) Microcomputer version for IBM-PC compatibles uses same Fortran code; requires 512 K bytes plus math co-processor; hard disk desirable; executable and source code available. (4) May be run in modular form (surface runoff, original or Extran transport, storage/treatment, plus executive and service routines, i.e., plotting, file combining, statistics, data input. (5) Largest block requires about 125,000 words or 500K bytes of storage. (6) Available on a magnetic tape or floppy disks. (7) Requires up to eight off-line storage files.

Input Data Requirements

(1) Historical or synthetic precipitation record; uses National Weather Service precipitation tapes for continuous simulation. (2) Monthly or daily evaporation rates. (3) For snowmelt: daily max-min (continuous) or time-step (single event) temperatures, monthly wind speeds, melt coefficients and base melt temperatures, snow distribution fractions and areal depletion curves (continuous only), other melt parameters. (4) Surface quantity: area, imperviousness, slope, width, depression storage and Manning's roughness for pervious and impervious areas; Horton or Green-Ampt infiltration parameters. (5) Subsurface quantity: porosity, field capacity, wilting point, hydraulic conductivity, initial water table elevation, ET parameters; coefficients for groundwater outflow as function of stage and tail water elevation. (6) Channel/pipe quantity: linkages, shape, slope, length, Manning's roughness; Extran transport also requires invert and ground elevation, storage volumes at manholes and other structures; geometric and hydraulic parameters for weirs, pumps, orifices, storages, etc.; infiltration rate into conduits. (7) Storage/sedimentation quantity: stage-area-volume-outflow relationship, hydraulic characteristics of outflows. (8) Surface quality (note: several parameters are optional, depending upon methods used): land use; total curb length; catchbasin volume and initial pollutant concentrations; street sweeping interval, efficiency and availability factor; dry days prior to initial precipitation; dust/dirt and/or pollutant fraction parameters for each land use, or pollutant rating curve coefficients; initial pollutant surface loadings; exponential and power wash-off coefficients; concentrations in precipitation; erosion parameters for Universal Soil Loss Equation, if simulated. (9) Dry-weather flow constant or on basis of diurnal and daily quantity/quality variations, population density, other demographic parameters. (10) Optional particle size distribution, Shields parameter and decay coefficients for channel/pipe quality routing and scour/deposition routine. (11) Storage/treatment: parameters defining pollutant removal equations; parameters for individual treatment options, e.g.,

particle size distribution, maximum flow rates, size of unit, outflow characteristics; optional dry-weather flow data when using continuous simulation. (12) Storage/treatment costs: parameters for capital and operation and maintenance costs as function of flows, volumes and operating time. (13) Data requirements for individual blocks much less than for run of whole model; large reduction in data requirements possible by aggregating (lumping) of subcatchments and channel/pipes, especially useful for continuous simulation. (14) Metric units optional for all I/O.

Ease of Application

(1) Nonproprietary model available from EPA, Athens, GA or University of Florida, Department of Environmental Engineering Sciences, Gainesville. (2) Updated user's manual and thorough documentation of most routines published as EPA reports; no one report covers all model aspects. (3) Test cases documented in several EPA and other reports. (4) Short course proceedings also useful for model applications. (5) U.S. and Canadian users groups with newsletters and semi-annual meetings permit publication of changes. (6) Due to its age (originally published in 1971), availability, and documentation, examples of SWMM usage are widely available in the literature; bibliography available. (7) Frequent model update/corrections/improvements are often difficult to learn about; new model released approximately on a bi-annual basis. (8) Size of model most frequent deterrent to use, however, see item 13 above under Input Data Requirements (9) Initial model setup often moderately difficult due to size. (10) Model supported by EPA Center for Water Quality Modeling, Athens, GA.

Output and Output Format

(1) Input data summary including precipitation. (2) Hydrographs and pollutographs (concentrations and loads versus time) at any point in system on time step or longer basis; no stages or velocities printed. (3) Extran transport also outputs elevation of hydraulic grade line. (4) Surcharge volumes and required flow capacity; original transport model will resize conduits to pass required flow (optional). (5) Stage, discharge and soil moisture content for subsurface routing in Runoff Block. (6) Removal quantities in storage/treatment units, generated sludge quantities. (7) Summaries of volumes and pollutant loads for simulation period, continuity check, initial and final pounds of solids in conduit elements. (8) Daily (optional), monthly, annual and total summaries for continuous simulation, plus ranking of 50 highest time-step precipitation runoff and pollutant values. (9) Line printer plots of hyetographs, hydrographs, and pollutographs. (10) Costs of simulated storage/treatment options. (11) Statistical analysis of continuous (or single event) output for event separation, frequency analysis, moments and identification of critical events.

Linkages to Other Models

(1) Linkage provided to EPA WASP and DYNHYD receiving water quality models.

(2) Individual blocks and the total SWMM model have been linked to the HEC STORM model, the QUAL-II model, simplified receiving water models, and others. (3) Individual blocks (e.g., Runoff Block) have been altered by various groups.

Personnel Requirements

(1) Civil/environmental engineer familiar with urban hydrological processes for data reduction and model analysis. (2) Computer programmer for model setup and establishment of off-line files on main-frames.

Costs

(1) Model and documentation available at little or no charge from EPA Center for Exposure Assessment Modeling, Athens, GA, 30613; also available for nominal charge from Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, 32611. (2) Data assembly and preparation may require multiple man-weeks for a large catchment or urban area. (3) Example main-frame computer execution costs given in user's manual, on the order of $20 for a surface runoff and transport run for a single storm event with about 50 subcatchments and channel/pipes; use of Extran transport can be more costly (> $100 per run) due to short time step; continuous simulation (hourly time step) of one subcatchment with snowmelt for two years costs about $20. (4) Microcomputer execution times depend on machine, execution times on AT-compatible approximately 50 times longer than for main-frame. (5) Extensive calibration may be required to duplicate measured quality results, quantity calibration relatively simple. (5) National Weather Service precipitation tapes for continuous simulation cost about $200 for at least a 25-year hourly record for all stations in one state.

Model Accuracy

(1) Quantity simulation may be made quite accurate with relatively little calibration. (2) Quality simulation requires more extensive calibration using measured pollutant concentrations; quality results will almost certainly be very inaccurate without local measurements. (3) Extran transport accurately simulates backwater, flow reversal, surcharging, pressure flow; original transport routines may be used at less cost if these conditions not present. (4) Sensitivity to input parameters depends upon schematization, however, surface quality predictions are most sensitive to pollutant loading rates.

SECTION 2

EXECUTIVE BLOCK, GRAPH ROUTINES AND SYSTEM REQUREMENTS

BLOCK DESCRIPTION

Functions

The Executive Block performs six main functions:

1) assignment of logical units and files,
2) control of the sequencing of computational blocks,
3) graphing of data files by the line printer,
4) control of the simulation time clock for all blocks,
5) input error checking, and
6) control and summarization of input and computational errors.

These six functions are summarized under the subheadings Program Operation (1,2), SWMM Graphics (3), SWMM Time (4), Input Errors (5), and No-Fault Error Summary (6). This block is the operating "shell" of SWMM; no hydrologic computations as such are performed in the Executive Block. The relationship of the Executive Block to other blocks is shown in Figure 2-1.

Before diving into the world of program functionality the following discussion of data entry should be read and understood.

How to Enter Data in SWMM

The following significant changes have been made to SWMM input files relative to previous versions:

1) free format input,
2) line identifiers are required in all blocks,
3) comment lines are allowed in the input,
4) SWMM reads up to 230 columns of input, and
5) OPEN FILE statements are controlled by the user with the @ function.

This documentation recognizes that almost all input to SWMM will be prepared at a terminal using an editor to create an input data file. Hence, use of the word "card" to indicate an 80-column line of input has been superseded by "line" or "data group" within this manual. Of course, a few users may still prepare input on punched cards, in which case each line of input will be on one card.

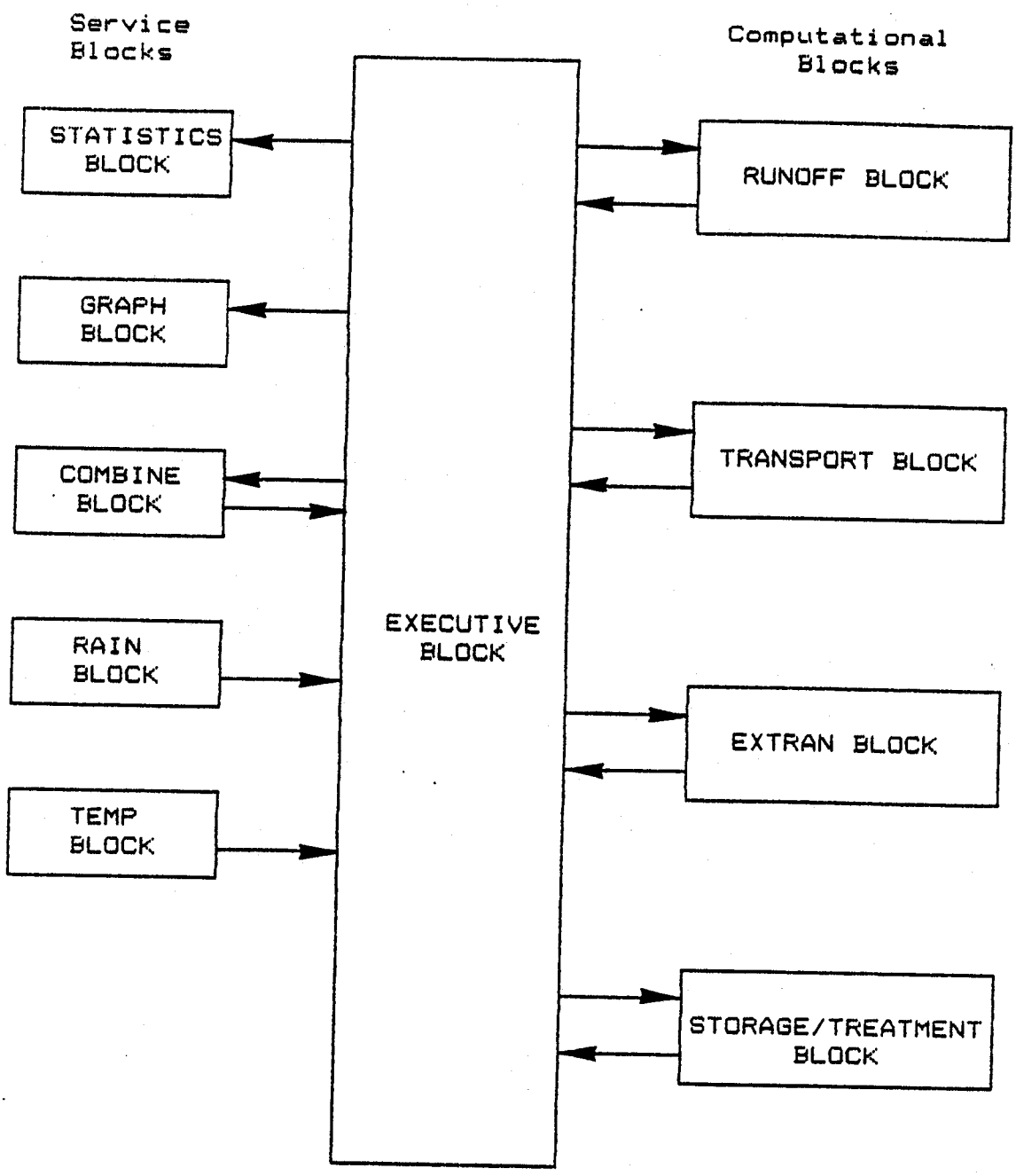


Figure 2-1. Relationship Among SWMM Blocks. Executive Block manipulates interface file and other off-line files. All blocks may receive off-line input (e.g., tapes, disks) and user line input (e.g., terminal, cards, etc.)

In a major departure from the restrictions of fixed format 80 column input this version of SWMM has been written to accept up to 230 columns of free format input. Free format input means that data do not have to be entered in fixed columns. The only restrictions are: (1) decimal points may not be used when an integer number is expected, (2) at least one space must separate each data field, (3) character data must be enclosed by single quotes, and (4) a number or character must be entered for all data fields. All SWMM blocks have free format input.

An additional SWMM requirement is the line identifiers entered in columns one and two of each data line. See Table 2-1 for example line identifiers. Do not put quote marks around the line identifiers. These identifiers are necessary for the following reasons:

1) they control the sequence of read statements,
2) they are used in the error checking of data files, and
3) they help in understanding the input.

There are three special symbols (always entered in column 1) that signal block and file control to the program. These symbols are:

$ --> Signals the calling of a SWMM Block, e.g. $RUNOFF, $RAIN.

@ --> Enables the user to permanently save an interface or scratch file (see Table 2-1 for an example, and Table 2-9 for the input format).

* --> Comment line. Enter an asterisk to place comments in SWMM input files. No closing asterisk is necessary.

These special control characters are read by subroutine STRIP, which is called by the MAIN program of SWMM. STRIP edits the input file, which has a logical unit number of 55, and creates a temporary file sans comment and @ lines that is saved on logical unit number 5. Numbers 5 (input), 6 (output) and 55 are thus restricted numbers in this version of SWMM. Interface and scratch files should not use 5, 6 or 55 as logical unit numbers.

Comment and @ function lines are never read by the simulation blocks of SWMM. Input lines beginning with * or @ can be placed anywhere in the input file, since they are acted upon only in subroutine STRIP. Listed below is an example of a set of comment and @ function lines. The example will work on both microcomputers and main-frames. (Do not be concerned that the example file name follows MS-DOS conventions.)

```
*      JIN(1)  JOUT(1)      The next line lists the logical unit numbers for
*                           an example SWMM run.
SW  1    9       8
*
*    Permanently save interface file 8 under the name 'INT.OUT'
@    8  'INT.OUT'
*
*    The @ function also allows the use of an existing file
*        Use 'INT.IN' as interface file 9
@    9  'INT.IN'
```

The form of the @ function is simply @, in column 1, followed by the logical unit number of the scratch or interface file, and lastly the filename in single quotation marks. The @ line uses free format input. Just make sure there is a space between the unit number and the filename.

Subroutine STRIP opens the file with STATUS = 'UNKNOWN'. This has the following effects on filename FILE depending on the preexisting conditions:

1. FILE does not exist - creates (opens) a file named FILE. If FILE is read by a subsequent SWMM block, the proper format must be used (e.g., an interface file must be read according to the format of the interface file). Otherwise, an error message is generated and the program stops.

2. FILE exists - opens FILE. If subsequently FILE has information written on it the old information on FILE is lost.

It is hoped that the above changes will make SWMM an easier model to use and facilitate the construction of input preprocessors.

Program Operation

The Executive Block assigns logical units and files, and controls the computational block(s) to be executed. These functions depend on reading in a at least four data lines which must be supplied according to the needs of a given computer run. These data lines are: (1) the interface file numbers, (2) the the scratch file numbers, (3) the names of the various blocks called in the simulation run, and (4) $ENDPROGAM.

The Executive Block assigns logical unit numbers to the interface and scratch files by reading the SW and MM data groups, respectively. The first line (denoted by SW in the first two columns) may contain up to 50 integer numbers, corresponding to 25 input and 25 output units. The maximum number of files open at any one time is eight (two interface files and six scratch files). These file limits should not exceed the realistic capability of most computer systems. Usually only two to six units will be needed for any single simulation. The output file is saved (during the run) for use by a subsequent

astrisks means comment

Table 2-1. Example SWMM Input with Control Symbols.

```
*        SPECIAL CONTROL SYMBOLS NOW CONTROL THE SWMM INPUT FILE
*        THE SPECIAL SYMBOLS ARE '*', '@', AND '$'.
*            * ---> COMMENT LINE
*            @ ---> SAVE A FILE PERMANENTLY OR USE A SAVED FILE
*            $ ---> CALL A SWMM BLOCK
*   THE FIRST LINE CONTAINS THE NUMBER OF BLOCKS TO BE RUN AND
*       THE JIN AND JOUT INTERFACE FILE UNIT NUMBERS.
*       (NOTE THAT A SECOND BLOCK IS NOT RUN IN THIS EXAMPLE.)
* NBLOCK JIN(1) JOUT(1) JIN(2) JOUT(2)
SW  2     0      10      10      0
*   THE SECOND LINE CONTAINS UP TO 6 SCRATCH FILE UNIT NUMBERS.
MM 6 11 12 13 14 15 16
*   FILE 10 (OR ANY UNIT NUMBER) COULD BE PERMANENTLY SAVED.
@  10  'SAVE10.OUT'
*   CALL THE RUNOFF BLOCK USING $RUNOFF
$RUNOFF
*   THERE ARE TWO A1 OR TITLE CARDS IN EVERY BLOCK.
*      ALL CHARACTER DATA MUST BE ENLOSED IN SINGLE QUOTES.
A1 'RUNOFF EXAMPLE 2, SIMPLE CONFIGURATION'
A1 'SINGLE CATCHMENT PLUS SINGLE PIPE, CONST. RAIN'
*   COMMENT LINES CAN BE USED TO IDENTIFY INPUT VARIABLES.
* METRIC ISNOW NRGAG INFILM KWALTY IVAP NHR NMN NDAY MONTH IYRSTR
B1  0      0     1      0     0      0   0   0   3    1     88
B2 0 0 2
* 5-MIN TIME STEP, 2-HR SIMULATION
B3 300. 300. 300. 2 2.0
B4 0 0
D1 0
* KTYPE KINC KPRINT KTHIS KTIME KPREP NHISTO THISTO TZRAIN
E1  2    1     0      0     0     0     3     60.0    0.0
* STEP-FUNCTION HYETOGRAPH
*  TIME-REIN(1)  RAIN-REIN(2)
E3    0.0           1.0
E3   60.0           0.0
E3  120.0           0.0
* 2-FT DIAMETER CIRCULAR PIPE
* NAMEG NGTO NPG GWIDTH GLEN  G3    GS1 GS2  G6  DFULL GDEPTH
G1 101 102    2    2.0  300.0 0.005 0.0 0.0 0.014 0.0    0.0
* 2-AC IMPERVIOUS CATCHMENT
* JK NAMEW NGTO WW1  WW2  WW3  WW4   WW5  WW6  WW7  WW8 WW9 WW10 WW11
H1 1 201  101  200.0 2.0 100.0 0.01 0.020 0.20 0.03 0.3 3.0 0.3 0.001
* PRINT CONTROL PARAMETERS
M1 2 1
* DEFAULT STARTING AND STOPPING PRINT TIME IS DURATION OF SIMULATION.
M2 1 0 0
* PRINT HYDROGRAPHS FOR PIPE 101 AND INLET 102.
M3 101 102
*   END THE SWMM SIMULATION BY USING $ENDPROGRAM.
*     (ANOTHER BLOCK COULD FOLLOW INSTEAD.)
$ENDPROGRAM
```

computational block and is subsequently deleted, unless the file is saved permanently by using the '@' function. The output files can be examined directly during the run by using the graphing and statistical capability of the Executive Block.

The file assignments in the second data group (denoted as MM) are for scratch files, i.e., files that are generated and used during execution of the program, and erased at the end of the run. Again, there is provision for up to six such files, but only one or two are typically needed. The unit numbers of the interface and scratch files are stored in the labeled common COMMON/TAPES/ for use by all blocks.

Scratch files are opened when a block is called and closed when control returns to the executive block. This was done to ensure that the Runoff Block does not erase valuable user data. The Runoff Block uses NSCRAT files for precipitation, evaporation, temperature, and wind speed input. Thus, the @ lines should be clustered within the data of a block. Multiple @ functions should be used when a scratch file has a different meaning from block to block. For example, NSCRAT(1) may be the rainfall input file in Runoff and be a true scratch file in Transport. An @ line should be used anywhere before the $TRANSPORT to open the file for Runoff. The file will be closed when Runoff finishes execution. A new file called FORT#, where # is the unit number assigned to NSCRAT(1) will then be opened when the Transport Block is called.

SWMM Line Printer Graphics

The graphing subroutines enable hydrographs and pollutographs to be plotted on the line printer for selected locations for output data files (e.g., predicted results); measured data that are input by the user may be plotted as well. The predicted and measured results may be plotted on one graph for comparison. Operation of the graph routines is described later. The subroutines include GRAPH, called from the main executive program only, in which control information, titles, and measured data (if any) are read.

Subroutine HYSTAT is called from GRAPH for computation of hydrograph volumes, durations, peak flows, and times of peaks. This is done for both predicted and measured hydrographs. Statistical comparisons between measured and predicted flows and pollutants are printed either under the graph or a separate summary page is written. Similarly, total loads, durations, peak concentration, and time of peaks for both predicted and measured pollutographs can be printed.

Subroutine CURVE is called from GRAPH to coordinate the actual plotting. It is also called directly from the Runoff and Extran blocks. The control information, titles, etc. are supplied from those blocks, bypassing Subroutine GRAPH. Subroutine CURVE performs the following operations:

1) Determines maximum and minimum values of arrays to be plotted, calculates the range of values, and selects appropriate scale intervals using subroutine SCALE.

2) Computes vertical axis labels based upon the calculated scales.

3) Computes horizontal axis labels based upon the calcuated scales.

4) Joins individual parts of the curve using Subroutine PINE.

5) Outputs the final plot using Subroutine PPLOT.

Subroutine SCALE calculates ranges and scaling factors. Subroutine PINE joins two coordinate locations with appropriate characters in the output image array A of PPLOT. Subroutine PPLOT initializes the plotting array, stores individual locations, and outputs the final array A for the printer plot.

SWMM Time

The simulation clock for all blocks is controlled by the Executive Block. Previous versions of SWMM had different "clocks" in each block which often caused problems in reading interface files. The multiplicity of clocks also complicated the process of model verification. This version of SWMM uses variable time steps in runoff modeling that necessitated a restructuring of the clock time in the Runoff, Transport, Graph and Statistics Blocks in any event.

For these reasons a single "SWMM Clock" based on integer numbers was created. The basic units of time in SWMM are the second of the day and the Julian date. Julian dates are five digit numbers incorporating the year and the day of the year. The Julian dates for 1987 range from 87001 to 87365. As an example, March 20, 1987 at 10:30:00 would be the 37800th second of day 87079.

It is not necessary to have a time step smaller than one second in any block, including Extran. The two numbers necessary to define any moment during the simulation are the Julian date and the second of the day. There are 86,400 seconds in a Julian day. Thus, the largest integer number in SWMM can easily be handled by any INTEGER*4 variable in FORTRAN.

The interface and scratch files use only the Julian date and the second of day to define the flow and concentration time. Subroutine DATED in the Executive Block uses the date/second combination to return the year, month, day, hour, minute, and second. This subroutine is used extensively by the print and graph routines in SWMM. Subroutine STIME updates the Julian date and second counter at each time step based on the current time step increment DELTA.

Input Errors

Upon encountering an input error each input subroutine of SWMM calls Subroutine IERROR. IERROR prints the data group identifier of the problem line, prints the first 80 characters of the line, and stops program operation. This subroutine should eliminate mysterious operating system error messages

and provide the user with a least some assistance in correcting input mistakes.

Possible input errors include: (1) decimal points in integer fields, (2) double decimals, (3) missing input fields, (4) improper character data, and (5) the wrong input order. The user should consult the data input tables for the proper input order and format.

No-Fault Error Summary

Another type of error in SWMM consists of error/warning messages about non-convergence, surcharging, etc. Subroutine IERROR also prints summary error/warning tables when a SWMM Block is finished executing. The error/warning message is printed once during the program execution and then the total number of errors/warnings are printed at the end of program execution. The first message is to inform the user of potential problems with his/her model in case a catastrophic event such as repeated division by zero occurs and the model run aborts.

Run-time errors may also be generated by the compiled Fortran program and appear on the screen when run on a microcomputer. These may be defined by reference to the Ryan-McFarland or IBM Professional Fortan users manuals. Please notify the SWMM program authors of repeated errors or bugs.

Default/Ratio Data Lines

Within the Runoff and Transport Blocks, default/ratio lines may be used to create default values and ratios for selected variables (denoted by asterisks in selected data groups). These lines are indicated by a -1 (new ratio) or -2 (new default) for the requested location ID number. Altered ratios or defaults are input for any nonzero parameter value.

The user triggers the use of the default value when 0.0 is used in the input field of a data group. Since default values included in a model can lead to lack of initiative on the part of the modeler in collection of data, the user must thus explicity and knowingly enter all but a very few default values. The parameter ratios may be used for sensitivity analysis and global model adjustment. For instance, a ratio of 1.1 would indicate that the value of the input parameter used in the program will be 10 % higher than the value given on the input data line. A parameter value is always multiplied by the current ratio.

The new default value or ratio is only valid for the subsequent lines of the current data group. When a new data group is read the default values become 0.0 and the ratios become 1.0. Multiple default/ratio lines can be used within a data group.

INTERFACING BETWEEN BLOCKS

Data may be transferred or interfaced from one block to another through the use of the file assignments on data group SW. The interface file header consists of:

1) descriptive titles,
2) the simulation starting date and time,
3) the name of the block generating the interface file,
4) the total catchment or service area,
5) the number of hydrograph locations (inlets, outfalls, elements, etc.),
6) the number of pollutants found on the interface file,
7) the location identifiers for transferred flow and pollutant data,
8) the user-supplied pollutant and unit names,
9) the type of pollutant concentration units, and
10) flow conversion factor (conversion to internal SWMM units of cfs).

Following the file header are the flow and pollutant data for each time step for each of the specified locations. The detailed organization of the interfacing file is shown in Table 2-2, and example FORTRAN statements that will write such a file are shown in Table 2-3. These tables may be used as guidelines for users who may wish to write or read an interfacing file with a program of their own. Further information on required pollutant identifiers, etc. may be found later in the Runoff Block input data descriptions.

The title and the values for the starting date and time from the first computational block are not altered by any subsequent block encountered by the Executive Block. All other data may (depending on the block) may be altered by subsequent blocks. The individual computational blocks also have limitations on what data they will accept from an upstream block and pass to a downstream block. These limitations are summarized in Table 2-4. Detailed discussions are presented in the manuals for each block.

Block limitations can be adjusted upwards or downwards by the user by modifying the PARAMETER statement found in the include file TAPES.INC. Follow the instructions of Table 2-5.

Table 2-2. Detailed Organization of SWMM Interface File

	Variable Name	Description[a]
FROM FIRST COMPUTATIONAL BLOCK	TITLE(1)	First line of title from first block, maximum of 80 characters.
	TITLE(2)	Second line of title from first block, maximum of 80 characters.
	IDATEZ	Starting date; 5-digit number, 2-digit year plus Julian date within year, e.g. February 20, 1987 is 87051.
	TZERO	Starting time of day in seconds, e.g., 5:30 p.m. is 63000. This date and time should also be the first time step values found on the interface file.
FROM CURRENT INTERFACING BLOCK	TITLE(3)	First line of title from immediately prior block, maximum of 80 characters.
	TITLE(4)	Second line of title from immediately prior block, maximum of 80 characters.
	SOURCE	Name of immediately prior block, maximum of 20 characters.
	LOCATS	Number of locations (inlets, manholes,outfalls,etc.) on interface file.
	NPOLL	Number of pollutants on interface file.
	TRIBA	Tributary or service area, acres.
	(NLOC(K), K=1, LOCATS)	Location numbers for which flow/pollutant data are found on interface file.
	(PNAME(J),J=1,NPOLL)	NPOLL pollutant names, maximum of 8 characters for each.
	(PUNIT(J),J=1,NPOLL)	NPOLL pollutant units, e.g., mg/l, MPN/l, JTU, umho, etc., max. of 8 characters for each.
	(NDIM(J),J=1,NPOLL)	Parameter to indicate type of pollutant concentration units. =0, mg/l =1, "other quantity" per liter e.g. for bacteria, units could be MPN/l. =2, other concentration units, e.g., JTU, umho, ^{o}C, pH.

Table 2-2. Concluded.

	Variable Name	Description[a]
	QCONV	Conversion factor to obtain units of flow of cfs, (multiply values on interface file by QCONV to get cfs).
FLOW AND POLLUTANT DATA FOR EACH LOCATION. REPEAT FOR EACH TIME STEP.	JULDAY	Starting date; 5-digit number, 2-digit year plus Julian date within year, e.g. February 20, 1987 is 87051.
	TIMDAY	Time of day in seconds at the beginning of the time step, e.g.,12:45 p.m. is 45900.
	DELTA	Step size in seconds for the next time step[c].
	(Q(K),(POLL(J,K),J=1,NPOLL),K=1,LOCATS)	Flow and pollutant loads for LOCATS locations at this time step. Q(K) must be the instantaneous flow at this time (i.e.,at end of time step) in units of volume/time. POLL(J,K) is the flow rate times the concentration (instantaneous value at end of time step) for Jth pollutant at Kth location, e.g.,units of cfs·mg/l or m^3/sec·JTU[b].

[a]Unformatted file. Use an integer or real value as indicated by the variable names. Integer variables begin with letters I through N.

[b]If units other than cfs are used for flow, this will be accounted for by multiplication by parameter QCONV.

[c]I.e., the next date/time encountered should be the current date/time plus DELTA.

Table 2-3. FORTRAN Statements Required to Generate an Interface File

FILE HEADER	WRITE(NOUT)	TITLE(1),TITLE(2)
	WRITE(NOUT)	IDATEZ,TZERO
	WRITE(NOUT)	TITLE(3),TITLE(4)
	WRITE(NOUT)	SOURCE,LOCATS,NPOLL,TRIBA
	WRITE(NOUT)	(NLOC(K),K=1,LOCATS)
	IF(NPOLL.GT.0)WRITE(NOUT)	((PNAME(L,J),L=1,2),J=1,NPOLL)
	IF(NPOLL.GT.0)WRITE(NOUT)	((PUNIT(L,J),L=1,2),J=1,NPOLL)
	IF(NPOLL.GT.0)WRITE(NOUT)	(NDIM(J),J=1,NPOLL)
	WRITE(NOUT)	QCONV
	NOUT is the interface file or logical unit number for output, e.g., NOUT = JOUT(1) for first computational block.	

FLOW AND POLLUTANT DATA FOR EACH LOCATION: REPEAT FOR EACH TIME STEP	IF (NPOLL.GT.0) THEN
	WRITE(NOUT) JULDAY,TIMDAY,DELTA,(Q(K),
	(POLL(J,K),J=1,NPOLL),K=1,LOCATS)
	ELSE
	WRITE(NOUT) JULDAY,TIMDAY,DELTA,
	(Q(K),K=1,LOCATS)
	ENDIF	

Note: The interface file should be unformatted. The time step read/write statements must include IF statements to test for the appearance of pollutants.

Table 2-4. Interface Limitations for Each Computational Block[a]

Block	Input	Output[b]
Runoff	--	200 elements (inlets), 10 pollutants
Transport	200 elements (inlets), 4 pollutants	200 elements (non-conduits), 4 pollutants
Extended Transport	200 elements (inlets), no pollutants (ignored if on the file)	200 junctions
Storage/ Treatment	10 elements (inlets or non-conduits), 3 pollutants	10 elements[c], 3 pollutants

[a]These limitations are based on the "vanilla" SWMM sent to the user. As explained in Table 2-5 these limitations can easily be changed by the user by modifying the PARAMETER statement accompanying the file 'TAPES.INC'.

[b]The number of pollutants found on the output file from any block is the lesser of the number in the input file or that specified in the data for each block.

[c]Although the Storage/Treatment Block will read and write data for as many as 10 elements, the data for only one element pass through the storage/treatment plant; the rest are unchanged from the input file.

Table 2-5. SWMM Parameter Statement Modification
This is file TAPES.INC in SWMM Fortran source code.

```
C
C     NW  = NUMBER OF SUBCATCHMENTS IN RUNOFF BLOCK
C     NGW = NUMBER OF RUNOFF SUBCATCHMENTS WITH GROUNDWATER COMPARTMENTS
C     NG  = NUMBER OF CHANNEL/PIPES  IN RUNOFF BLOCK
C     NET = NUMBER OF ELEMENTS IN TRANSPORT BLOCK
C     NC  = NUMBER OF CONDUITS IN EXTRAN BLOCK
C     NJ  = NUMBER OF JUNCTIONS IN EXTRAN BLOCK
C     NEA = NUMBER OF EVENTS ANALYZED IN STATISTICS BLOCK
C
C     INSTRUCTIONS - INCREASE DIMENSIONS OF SUBCATCHMENTS ETC.
C                    BY MODIFYING THE PARAMETER STATEMENT
C                    AND RECOMPILING YOUR PROGRAM
C
      PARAMETER (NW=200,NG=200,NET=200,NC=200,NJ=200,NGW=100,NEA=4000)
C
      COMMON /TAPES/ INCNT,IOUTCT,JIN(25),JOUT(25),
     *               NSCRAT(7),N5,N6,CC,JKP(57),CMET(11,2)
      CHARACTER*2 CC
```

COMPUTER SYSTEM REQUIREMENTS

FORTRAN

This version of SWMM was programmed in FORTRAN 77, specifically using the RM/FORTRAN compiler on the PC and VS/FORTRAN on an IBM 3033 main-frame. The problems of the past with FORTRAN compatibility on main-frames should be alleviated in this version of SWMM.

The likely sources of any potential incompatibility are Subroutines CHKFILE and INTCHR. CHKFILE opens and closes interface and scratch files. INTCHR converts character data to integer data in the Rain Block. This is based on the ASCII character set and intrinsic functions in RM/FORTRAN and VS/FORTRAN. However, this will only affect people who are using pre-1980 National Weather Service (NWS) precipitation tapes.

The NWS sells fixed format and variable block/length precipitation tapes. This version of SWMM is written to read both fixed format and variable block/length tapes. However, the IBM mainframe at the University of Florida cannot read variable block/length records. Hence, the variable block/length code is obviously unverified. User beware. It is recommended that the user purchase fixed format (record length of 43, blocksize of 6300), ASCII tapes from the NWS.

Sample execution times on an 8 Mhz IBM Compatible AT (Zenith Z-248) are shown in Table 2-6. Clock time refers to human waiting time. This table tries to show the gamut of possible SWMM runs. Multiply or divide for faster or slower machines.

Table 2-6. Example SWMM Execution Times on an 8 Mhz IBM Compatible AT.

Block/ Schematization	Number of 5 Minute Time Steps	Clock Time
Runoff		
1 Subcat/No Quality	120 steps	30 seconds
10 Subcat/No Quality	1200 steps	60 seconds
1 Subcat/5 Pollutants	120 steps	45 seconds
Runoff + Transport		
29 Subcat, 34 Channel/ pipes, 50 Elements	24 steps	180 seconds

System Memory

Main-frame users of SWMM should have no need for any overlay structure or any concern for memory limitations. The entire SWMM program compiled under VS FORTRAN is approximately 2500 kb on an IBM main-frame. Virtual memory allows program sizes in the gigabyte range. This statement also applies to minicomputers and Macintoshs.

Program Verification, i.e. Bugs

The current state of art in program verification is pretty dismal. It is impossible to prove an algorithm "totally correct" (Harel ,1987). A totally correct algorithm provides the correct answer for all legal forms of input. A partially correct algorithm provides the correct answer for some forms of legal input. As is often said, testing and debugging cannot be used to demonstrate the absence of errors in software, only their presence.

The total program "correctness" of SWMM was increased by the following methods:

1) Increasing the number of subroutines in SWMM. Smaller subroutines are easier to debug, test, and verify.

2) Testing subroutines for failure. Input data sets are constructed to force failure by straining the limits of the program. For example, test channel/pipe convergence in the Runoff Block using pipes of 1 cm diameter and 1 cm length at time steps of years. Then if the program works correctly for extreme input, it should work for "normal" input.

3) Eliminating duplicate coding in SWMM. Test, debug, and verify one subroutine to perform a task in all blocks. Examples are the clock subroutines, statistics subroutines, integration subroutine, interpolation subroutine, etc.

In spite of these ecumenical attempts at debugging, the program authors suspect that some errors will be found by users and earnestly solicit user feedback for model improvements.

INSTRUCTIONS FOR EXECUTIVE BLOCK DATA PREPARATION

Logical Units

Logical units or file numbers are simply the numbers assigned to various input/output devices (files) for use in the program. On most mainframes, logical numbers for the card reader, line printer and card punch are:

I/O Device	Logical Unit
Card Reader	5
Line Printer	6
Card Punch	7

"Card reader" is used figuratively as the device for reading user input data files. SWMM is programmed under the assumption that the card reader and line printer are so defined (no cards are punched by SWMM). However, in an attempt to allow versatility, all READ and WRITE statements use parameters N5 and N6 for the logical unit numbers of the card reader and line printer respectively. These are defined only once,

```
N5  = 5
N6  = 6
```

near the beginning of the Executive Block MAIN program and passed to all other blocks through the labeled COMMON/TAPES/. Thus, if other logical numbers are required for input and output, the only programming changes required should be at the above location.

Other files are typically assigned logical units between 1 and 99 (but not 5, 6, 7 or 55). Unit 55 is a special scratch file used by subroutine STRIP (see earlier discussion on SWMM input).

Interface and Scratch Files

The SWMM interface and scratch files are "scratch files," that is, files that are used during program execution, and erased (lost) at the end of the simulation. As discussed previously, the user can permanently save any interface or scratch file by using the @ function (see Table 2-1 for example and Table 2-9 for input format).

Ordinarily, scratch files will be used for parameters JIN, JOUT, and NSCRAT of the Executive Block. JIN and JOUT are used only to transfer data between blocks, with the exceptions being a JIN data set needed for rainfall input in the Rain and Runoff Blocks, and temperature input in the Temp Block. The NSCRAT files are used for miscellaneous tasks within each block, most typically to store output for later printing. Current requirements are shown

in Table 2-7. The Runoff Block potentially requires the largest number of scratch files.

Table 2-7. Scratch Data Sets Required by SWMM

1. Runoff Block		
NSCRAT(1)	-	Always required.
NSCRAT(2)	-	Always required.
NSCRAT(3)	-	Required for continuous SWMM with snowmelt, may contain temperature, evaporation, and wind speed data.
NSCRAT(5)	-	Required for groundwater simulation.
NSCRAT(6)	-	Required for groundwater simulation.
2. Transport Block		
NSCRAT(1)	-	Always required.
NSCRAT(2)	-	Always required.
3. Storage/Treatment Block		
None required.		
4. Receiving Water Block (not implemented, see Section 8)		
5. Extended Transport Block (EXTRAN)		
NSCRAT(1)	-	Always required.
NSCRAT(2)	-	Always required.
NSCRAT(3)	-	Required for "hot start" capability.
6. Combine Block		
NSCRAT(1)	-	Required if using combine or collate.
7. Statistics Block		
NSCRAT(1)	-	Always required.
8. Rainfall Block.		
NSCRAT(1)	-	Required only if the storm event data are saved on an output file.
9. Temperature Block.		
NSCRAT(1)	-	Required only if the data are saved on an output file.

The following example of the interface and scratch data sets may help explain the logic of the SW and MM data lines. Assume Runoff, Transport, and Storage/Treatment are to be run in order. The unit numbers assigned to the various data sets are arbitrary:

Line Identifier	Number of Blocks	RUNOFF JIN(1)	RUNOFF JOUT(1)	TRANSPORT JIN(2)	TRANSPORT JOUT(2)	STORAGE JIN(3)	STORAGE JOUT(3)
SW	3	0	9	9	10	10	0

Here, JIN(K+1) = I refers to an input file and JOUT(K) = I refers to the same output file from a preceding block. Thus, the output of the Runoff Block, JOUT(1) = 9, is the input of the Transport Block, JIN(2) = 9. For example, a typical read statement in a FORTRAN program may be READ(I,80). The I is replaced by the symbolic unit number of the file, 9 in this case. (Since the numbers 5, 6, 7, and 55 have standard meanings, they are not used.) The sequential execution shown above is not required in general. For instance, a sequence of several Runoff Block runs could be performed, each with different input and output unit files (hence, different unit numbers). However, for this example, the meaning of the unit numbers is as follows:

JIN(1) = file number for input into the first block to be run (Runoff Block). JIN(1) = 0 means there is no file input.

JOUT(1) = file number for output from the first block to be run (Runoff Block). JOUT(1)=9 means there is an output file.

JIN(2) = file number for input to the second block to be run Transport Block). (This is often the same as the output number from the preceding block.) JIN(2) = 9 means there is an input file (from the Runoff Block).

JOUT(2) = file number for output from the second block to be run (Transport Block). JOUT(2) = 10 means there is output to be saved.

JIN(3) = file number for input to the third block to be run (Storage/Treatment Block). JIN(1) = 10 means there is input from the Transport Block.

JOUT(3) = file number for output from the third block to be run (Storage/Treatment Block). JOUT(3) = 0 means there is no output to be saved.

These files have either the default FORTRAN filenames or a user defined filename (from executing the @ function). The default names are usually FORTn, where n is the logical unit number. Thus, logical unit number 8 has the default filename of FORT8.

Block Selection

The instructions for data preparation are divided into two parts corresponding to control of the SWMM Block selection and graphing capability. Table 2-9 at the end of these instructions gives the procedure for data preparation.

The Executive Block controls the computational block(s) to be executed by reading the name of that block, for example: $RUNOFF. The program compares this word with a dictionary of such words (first eight characters). If a match is found, as it would be in this case, control is passed to the appropriate part of the Executive Block to read that data. Here, for example, a call would be made to the Runoff Block. After execution of the Runoff Block, control is returned to the Executive Block.

The Executive Block again reads a sentinel ($) line, which might indicate that another block to be executed. For example, if the Transport Block is to be executed, the control word $TRANSPORT would be given, etc. If results are to be graphed, the control word $GRAPH would be on the next input line. If the run is to be terminated $ENDPROGRAM is entered. A summary of the control words and corresponding action is given in Table 2-8.

The use of control words on sentinel lines allows considerable flexibility in the utilization of the Storm Water Management Model. The most common type of run involves the execution of one of the computational blocks along with the graphing of results on the line printer. Thus, for the Runoff Block, such a run would be made by appropriate use of the words $RUNOFF, $GRAPH, and $ENDPROGRAM. If the Runoff, Transport and Storage/Treatment Blocks were to be run with graphical output at the end of the the latter two blocks, the sequence would be: $RUNOFF, $TRANSPORT, $GRAPH, $STORAGE, $GRAPH, $ENDPROGRAM.

GRAPH ROUTINE

Capabilities

When called from the Executive Block, the graph routines will plot predicted and/or measured hydrographs, pollutographs, and loadographs for specified inlets or elements. A hydrograph is a plot of flow rate versus time, a pollutograph is a plot of concentration versus time, and a loadograph is a plot of pollutant load rate (e.g., mass/time) versus time. All three will simply be called "graphs" in the following discussion. Predicted graphs can be generated by the Runoff, Transport, Extran, and Storage/Treatment blocks. Their output (interface) files can be input to the graph routines. Measured graphs (i.e., data input by the user) may also be plotted whether or not predicted graphs are produced. Thus, the graph routines may be treated as standalone programs and used independently of the other SWMM blocks. When predicted and measured graphs are available for the same location, they will be overprinted on one plot for comparison purposes. This greatly facilitates calibration work.

Table 2-8. Summary of Control Words and Corresponding Action[a]

Control Word	Action to be taken
@	Either: (1) Open an interface or scratch file with a user defined filename and save the file permanently; or, (2) open an existing file for use as an input file.
*	Comment line. No action.
$RUNOFF	Execute Runoff Block
$TRANSPORT	Execute Transport Block
$EXTRAN	Execute Extended Transport (EXTRAN) Block
$STORAGE	Execute Storage/Treatment Block
$COMBINE	Execute Combine Block
$STATS	Execute Statistics Block
$GRAPH	Produce graphs on line printer
$RAIN	Execute Rainfall Block
$TEMP	Execute Temperature Block
$ENDPROGRAM	Terminate run at this point
Any other word	Terminate run[b]

[a]Program compares first four characters only.
[b]Only one additional line will be examined for a possible match prior to terminating the run.

A few simple statistics are also computed for each hydrograph and printed below each plot: volume, peak, time of peak, and duration. As an option, the user can request a printout only of the statistics. Similar statistics are printed below the plot of each pollutograph and loadograph: mean concentration or loading rate, peak concentration or loading rate, time of peak, and duration. When both measured and predicted graphs are plotted on the same plot, the above statistics and differences (absolute and percent) are also given for the overlapping time period (recognizing that the period of measurements may not correspond exactly to the period of predictions).

The final plot is produced by printing the array "A", dimensioned 51 (vertical) by 101 (horizontal). The vertical and horizontal scales are determined on the basis of the range of the input data. The left-most plotting location (at the left vertical axis) corresponds to the graph value at the start of the simulation (TZERO). The user has two options in the plotting of data: (1) all data are plotted, or (2) the program selects only 100 points to be plotted. If the number of points to be plotted exceeds 100 then multiple graphs are generated in option 1 until all points are plotted. In option 2 the program will plot up to 100 points selected evenly from the entire range of the time scale. Thus, option 2 will compress the time scale (if more than 100 time steps are available for plotting).

The particular graph routines used in SWMM "fill in" between separated points, horizontally or vertically, to form a continuous line. Thus, it is sometimes difficult to determine exactly the points that were input for plotting, except that they are usually the end points of line segments.

Input Parameters and Options

The predicted graphs from up to four locations may be plotted on a single sheet. Typically, however, only the predicted and/or measured graphs from a single location are plotted on a sheet. It is not possible to overlay the predicted and measured graphs for multiple locations on a single sheet. If measured and predicted graphs are both supplied for the same location, they will be overprinted on one plot for comparison.

Up to 20 predicted and measured locations may be plotted during one call to GRAPH. (If more locations need to be plotted, GRAPH can be called again.) The predicted and measured locations need not be the same. For example, the subroutine may be used to plot only predicted or only measured graphs.

The routine will always plot hydrographs (when supplied) but will plot pollutographs/loadographs only if NQP > 0 (data group A1). Up to five pollutants may be plotted (data group B1), assuming the pollutant(s) is(are) available on either the interface file or on the E3 lines. Any number of pollutants (maximum of 10) may be input to GRAPH. The parameter IPOL selects the IPOLth pollutant on the interface file.

The time scales for input of the measured graphs need not be the same as for the predicted graphs, nor does the time spacing of measured graphs have to be constant. The plot will run from the minimum to the maximum times of the predicted or measured graphs. Several options are available for input of the times associated with graph ordinates (data group E1).

Input of the horizontal axis label is not required, and it always reads "Time of Day in Hours." The times are actually elapsed time, beginning at the start of the simulation (TZERO). Conversion to hour of day does not include a reset at midnight. Thus, if a simulation period begins at 10 p.m. and last 4 hours, the graph abscissa will run from 22 to 26 hours.

Vertical axis labels are either "Flow in cfs," "Flow in m^3/s," "Pounds per Day", "Kilograms per Day", or the concentration units of the pollutant

being plotted. All pollutographs are plotted in concentration units, and loadographs are plotted in pounds or kilograms per day. The same units are required for both predicted and measured hydrograph/pollutograph/loadograph inputs.

The input format of all measured data may be supplied by the user (data group E2). This facilitates the use of data already prepared under an arbitrary format. In addition, the number of data values per line may be varied (LCARD on data group E1).

Measured data may be read as line input (MEAS=1) or may be previously stored on file number MFILE and read from that file (MEAS=2 on data group A1). Retrieval from file MFILE may avoid reading voluminous data more than once.

Table 2-9. Executive and Graph Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

★ a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

★ b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1  1  2  3  4  5  6
    7  8  9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	I/O File Assignments	
SW	Group identifier	None
NBLOCK	Number of blocks to be run (max of 25)	1
JIN(1)	Input file for the first block	0
JOUT(1)	Output file for the first block	0
.	.	
.	.	
.	.	
JIN(NBLOCK)	Input file for the last block	0
JOUT(NBLOCK)	Output file for the last block	0
	Scratch File Assignments	
MM	Group identifier	None
NITCH	Number of scratch files to be opened (max of 6)	0
NSCRAT(1)	First scratch file assignment	0
.	.	
.	.	
.	.	
NSCRAT(NITCH)	Last scratch file assignment	0
	Control Data Indicating Files To Be Permanently Saved (Optional)	
	REPEAT THE @ LINE FOR EACH SAVED FILE	
@	Group identifier	None
FILENUM	Logical unit number of the JIN, JOUT, or NSCRAT file to be permanently saved (or already saved file to be used) by the SWMM program.	None
FILENAM	Name of permanently saved file. Enclose in single quotes, e.g. 'SAVE.OUT'	None

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Control Data Indicating Blocks To Be Called	
	REPEAT THE $CNAME LINE FOR EACH BLOCK TO BE CALLED	
$	Group identifier	None
CNAME	Name of block to be called. (No space between $ and CNAME.)	None
$CNAME	- $RUNOFF for Runoff Block, - $TRANSPORT for Transport Block, - $EXTRAN for Extended Transport Block, - $STORAGE for Storage Block, - $COMBINE for Combine Block, - $STATS for Statistics Block, - $GRAPH for Graph Block, - $RAIN for Rainfall Block, - $TEMP for Temperature Block, and - $ENDPROGRAM for ending the SWMM run.	
	Data group $CNAME is the last Executive Block line unless the graph routines are called. From the first $CNAME line, control is passed to the appropriate block. When execution of that block is complete, control returns to the $CNAME line that follows the input data for the block just executed.	

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Input Data for Graph Block	
	Read data groups A1-E3 only if GRAPH has been called using $GRAPH in Executive Block. Do not read SW and MM lines again.	
	General Graph Information	
A1	Group identifier	None
NTAPE	File (logical unit) where predicted graph information is stored. Will usually equal JOUT value of previous block. If zero, only measured data will be plotted.	0
NPLOT	Number of locations (e.g. inlets) for which predicted hydrographs and pollutographs are to be plotted. Maximum of 20 locations.	0
MEAS	Input and plot measured data. - 0, No measured data to be plotted. - 1, Read (and plot) line-input data. - 2, Read (and plot) data stored as line images on file MFILE	0

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	THE FOLLOWING TWO PARAMETERS ARE NOT REQUIRED IF MEAS = 0	
MFILE	File (logical unit) where measured data are stored. Not required if MEAS $\leq$ 1. (If zero, defaults to input file reader).	N5
MPLOT	Number of locations (e.g., inlets, manholes) for which measured data are to be input and plotted (MEAS = 1, 2). Maximum = 20.	0
NQP	Number of pollutants plotted (max of 5).	0
METRIC	Metric units used for input/output = 0, U.S. customary units. = 1, Metric units used, indicated in brackets [] in the remainder of the table.	0
	Pollutant Selection Data	
	IF NQP = 0 (A1), SKIP TO GROUP C1 OTHERWISE, REPEAT GROUP B1 NQP TIMES.	
B1	Group identifier	None
IPOL	Pollutant identifier from sequence on interface file. e.g., if IPOL(1) = 3, first pollutant plotted will be third on interface file. User must know sequence, as determined from input to preceding block (e.g. group J3 of Runoff Block). If IPOL =0, pollutant is not found on interfacing file and is special input only.	0
***	If IPOL not = 0, omit all the following parameters since they will be obtained from the interface file. For discussion of these parameters, see group J3 of the Runoff Block and its discussion. ***	
NLOAD	Type of pollutant plot = 0, plot concentration vs. time, = 1, plot load (e.g., mass/time) vs. time.	0
PNAME	Pollutant name. Format A8.	'None'
PUNIT	Pollutant units. Format A8.	'None'

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
NDIM	Type of units = 0, mg/l = 1, 'other' per liter, e.g., MPN/l = 2, other concentration units, e.g. JTU, pH.	0
	IF NPLOT = 0, (A1) SKIP TO GROUP C2.	
	Locations (e.g. inlets, manholes) for plotting of predicted output. Supply NPLOT values.	
C1	Group identifier	None
IPLOT(1)	First location to be plotted	0
.	.	
.	.	
IPLOT(NPLOT)	Last location to be plotted	0
	IF MPLOT = 0, (A1) SKIP TO GROUP D1.	
	Locations (e.g. inlets, manholes) for input and/or plotting of measured data. Supply MPLOT values.	
C2	Group identifier	None
KPLOT(1)	First location to be input and plotted.	0
.	.	
.	.	
.	.	
KPLOT(MPLOT)	Last location to be input and plotted.	0
	Plot Title	
D1	Group identifier	None
TITL	Title to be printed at bottom of each plot.	'Title'

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	IF MPLOT = 0, (A1) SKIP REMAINING GROUPS. OTHERWISE READ MPLOT GROUPS OF DATA GROUP(S) E1 (AND POSSIBLY E2 AND E3) A TOTAL OF NQP + 1 TIMES.	
	First, for measured hydrograph, there are MPLOT data groups, E1, E2, and E3:	
E1	Group identifier	None
MDATA	Measured data for this graph and location corresponding to sequence for Group C2. =0, No measured data to be entered for this location. =1, Input measured data according to remaining parameters and format of Group E1.	0
	THE FOLLOWING PARAMETERS ARE NOT REQUIRED IF MDATA = 0 (E1).	
LCARD	Number of graph ordinates per Group (MTIME > 0) or pairs of time-graph ordinates per Group (MTIME = 0). Maximum = 16.	0
MTIME	Option for time of graph ordinates. = 0, Enter a time with each ordinate. Cease input of time-ordinate pairs when entered time is > TQUIT. > 0, The time for each ordinate will be computed starting at TMZERO and using time increment DTMHR. Read a total of MTIME ordinates.	0

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
MUNIT	Units of time if MTIME = 0. Not required if MTIME > 0. =0, Time is in minutes. =1, Time is in hours.minutes (i.e. decimal point between hours and minutes). =2, Time is in decimal hours (and may have values > 24).	0
TMZERO	Initial time (decimal hours) of measured data if MTIME > 0. Value of TMZERO is added to times entered if MTIME = 0. May be used to provide a time offset for measured data, avoiding revision of their times.	0.0
TQUIT	A time greater than TQUIT ends entry of time -ordinate pairs if MTIME = 0. Not required if MTIME > 0.	0.0
DTMHR	Time increment (hours) if times of graph ordinates are calculated (MTIME > 0). Not required if MTIME = 0.	0.0
	DATA GROUPS E2 AND E3 ARE NOT REQUIRED IF MDATA = 0 (E1) FOR THIS GRAPH AND LOCATION.	
E2	Group identifier	None
FIRMAT	Format by which measured data of group E3 will be read. Include beginning and final parentheses. If blank, the default format will be used. If FIRMAT is 'FREE' then free format input will be used.	(2X,F8.0,7F10.0)

Table 2-9 (continued). Executive and Graph Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** Note: If MEAS $\leq$ 1 (Group A1) this Group will be read from the card reader (unit N5). Otherwise, the formatted read will be from unit number MFILE (Group A1). ***	
E3	Group identifier	None
TIMX (optional) and YVAL	Time (if MTIME = 0) and graph ordinate, LCARD pairs (if MTIME = 0) per Group, according to format of Group E2. Entries are stopped when a time is > TQUIT (this time is not included as a data entry). If MTIME > 0, only YVAL will be read, a total of MTIME values, LCARD values per line according to format of Group E2. Units of hydrograph ordinate must be cfs [m^3/sec if METRIC = 1], and pollutograph ordinates must be concentrations corresponding to NDIM of Group B1.	0.0

Repeat groups E1, E2, and E3 for remaining MPLOT-1 locations for measured hydrograph inputs. Then, input MPLOT groups of Groups E1, E2, and E3 for first pollutograph, second pollutograph, etc., up to NQP pollutographs. Note data for the MPLOT locations must appear in the order in which the locations were entered on Group C2. There will be a total of MPLOT * (NQP+1) entries of group(s) E1 (and possibly E2 and E3).

END OF GRAPH BLOCK INPUT DATA

Control returns to the $CNAME line of the Executive Block.

SECTION 3

COMBINE BLOCK

BLOCK DESCRIPTION

The Combine Block adds the capability of modeling larger areas by combining the output of SWMM model runs from either the same or disparate blocks. The output of any other model can also be combined or collated with SWMM files by the Combine Block if the model output is in SWMM interface format -- see Section 2. This block has five possible objectives.

The first objective is to collate two different interface files into a single interface file that contains the hydrographs/pollutographs for all nodal locations (and sums flows and loads at common locations). For instance, if two separate output interface files, one Transport and one Storage/Treatment, are to be input into the same downstream block, the Combine Block would be used to collate the two output data sets into one input interface file. (Keep in mind that a SWMM computational block can accept only one interface file as input.)

The second objective is to combine hydrographs and pollutographs at different locations and on different interface files into a single hydrograph/pollutograph time series (i.e., at just one location) on a single interface file. For example, suppose the Transport Block is used on two different drainage networks, giving two separate output interface files. Both files contain hydrographs/pollutographs that go to the same treatment facility at the same inlet node; the Combine Block combines the two different Transport output interface files into one interface file at a single node which then can be input into the Storage/Treatment Block.

The third objective is to select and/or renumber nodes from a single file or while collating or combining. For example, if the same number has been used for two different nodes while modeling a large city, one (or both) of these two nodes could be assigned different numbers in order to combine the output files. Alternatively, suppose only a subset of all of the nodes on a file is needed for a subsequent block. The desired nodes can be extracted (and optionally renumbered).

The fourth objective is to aid the user's memory. Eventually, the source of a permanent interface file will be forgotten. Combine will read the file header information and print basic information about the original simulation run. Combine will also let the user know if a file is not a SWMM interface file.

The fifth objective is to convert an unformatted interface file into a formatted ASCII or text file capable of being read by external programs. Such a file can be input to a spreadsheet program or read by a Basic program, for example, for further analysis.

The Combine Block can be used in a number of different ways and gives SWMM the capability of simulating the largest and most diverse cities. For example, Figure 3-1 shows how the Combine Block was used on a combination of SWMM runs for Lancaster, Pennsylvania.

DATA PREPARATION

Collate

Two different output interface files from Runoff, Transport, Storage/Treatment, Extran, or any combination thereof (including two runs of the same block) may be collated. One file is indicated by JIN(K) and the other by NSCRAT(K). The resulting collated interface file (indicated by JOUT(K)) could then be used as input into any block (Transport, Extran, Storage/Treatment or a receiving water model), except Runoff. For example (Figure 3-2), an output file from Transport area 'A' with manhole number 5, 6, 12 was collated with an output file from Transport area 'B' with manhole numbers 1, 3, 6, 19. Manhole number 6 is common between both output data sets, therefore the hydrographs and pollutographs from both manholes are added together (load rates, quantity/time, are added for pollutants). The new output file produced from the Combine Block has manhole numbers 1, 3, 5, 6, 12, 19. This new data set could then be used as input to any other block, including Transport itself.

Combine

The combine section combines two different files (indicated by JIN(K) and NSCRAT(1)) and output locations into a single file with one output location. For example (Figure 3-3), an output file from Transport area 'X' with manhole number 16 and an output data set from Transport area 'Y' with manhole number 23 are to be used as input into a receiving water model at junction number 14. The Combine Block would be used to combine the two output data sets into one data set with one location, assigned the new number 14. This number would correspond to the junction number of the receiving water model.

Extracting and Renumbering

Data groups C1, C2 and C3 may be used to extract only selected nodes for collating or combining, or to select and/or renumber nodes from a single file. The latter option is invoked by setting parameter ICOMB = 2 on data group A1. Then the desired locations will be extracted from the file indicated by JIN(K), optionally renumbered, and placed on file JOUT(K).

While combining or collating two files, the extraction/renumbering option is indicated by parameters NUMX and NUMR on data group C1. If NUMX = 0, then all nodes are extracted from both files, and data group C2 is not required. Otherwise, if NUMX > 0, then NUMX nodes will be extracted; these NUMX locations are indicated on data group C2. The locations on data group C2 apply to

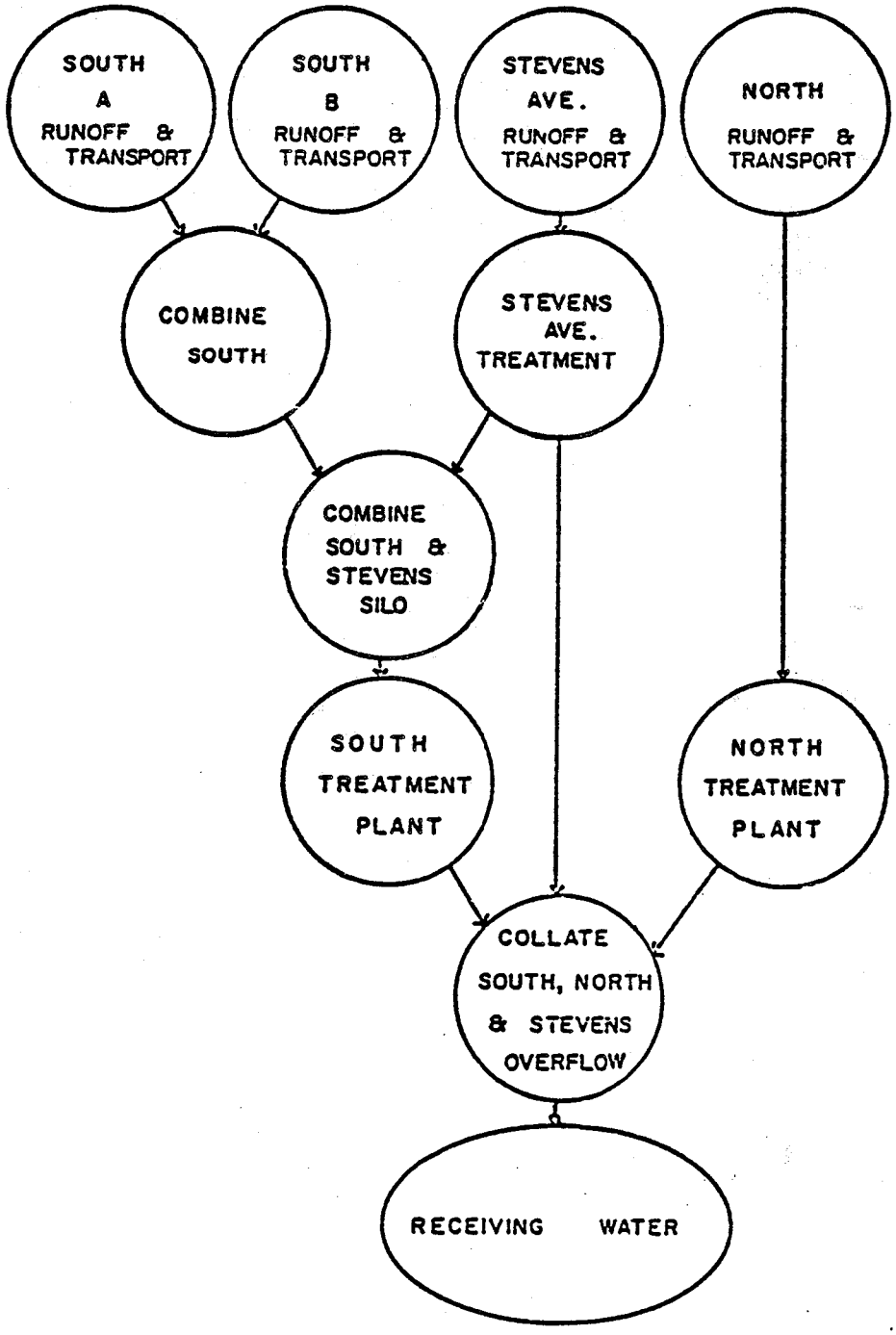


Figure 3-1. Combination of SWMM Runs for Overall Lancaster Simulation.

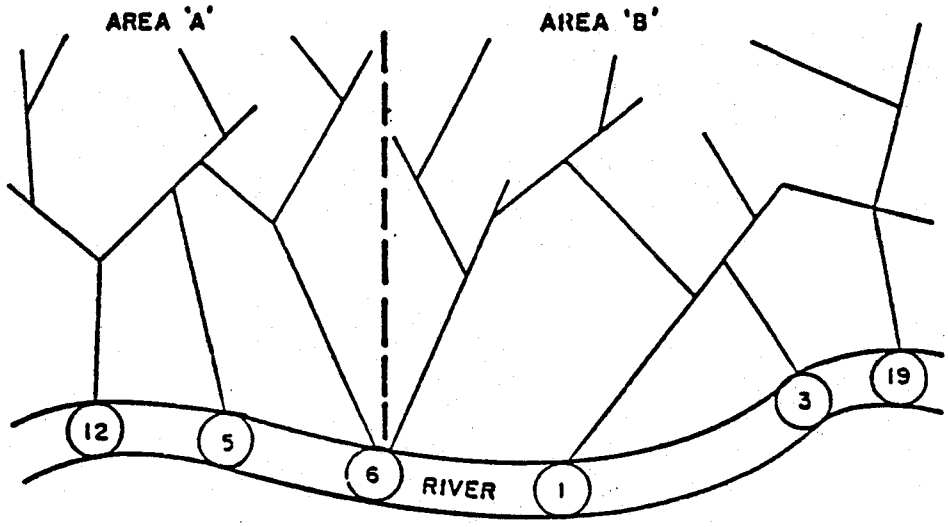


Figure 3-2. Hypothetical Drainage Network to Be Collated.

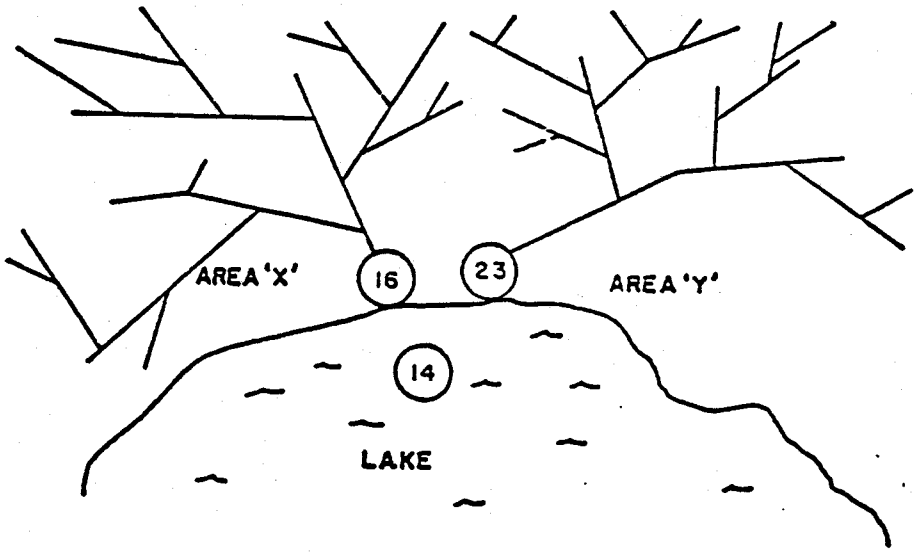


Figure 3-3. Hypothetical Drainage Network to Be Combined.

both files. The sequence (order) of numbers used in data group C2 need not correspond to the sequence on files JIN(K) and NSCRAT(1).

If parameter NUMR on data group C1 = 0 then all nodes will retain their same numbers, and data group C3 is not required. Otherwise, NUMR must equal NUMX (unless NUMX = 0 -- see below) and a corresponding new node number must be listed on data group C3 for every old number listed on data group C2. Of course, the same numbers may be reassigned as desired. Duplicate numbers may be assigned in data group C3. In this case, hydrographs and pollutographs at the common numbers will be summed, in the manner described earlier. For example, the collate option can be used to combine the two networks shown in Figure 3-3. For this case, the input data would be:

```
C1 2 2
C2 16 23
C3 14 14
```

If all nodes are to be extracted (NUMX = 0) and renumbering is desired for some (or all), set NUMR equal to the total number of distinct (i.e., not a duplicate number) nodes (including both files if collating). Data group C3 will contain the new numbers corresponding to the order of appearance of the distinct nodes on files JIN(K) and NSCRAT(K), respectively. Since this order may be difficult to determine (unless the ICOMB = 3 option is used to read file headers), it may be safer for the user to list all of the nodes on data group C2, followed by the new numbers on data group C3. In this manner exact correspondence can be assured.

ASCII File Output

If ICOMB = 4 (data group A1), interface file JIN will be converted to an ASCII or text file (with extracting and renumbering as an option). The file will be written in the form of Table 2-3. Every WRITE statement in Table 2-3 will correspond to one line of the file. With the exception of the Julian date, all numerical values will be written in E-format; the Julian date will be a 5-digit integer. One space will separate values on a line.

Quality Options

The two different input files may have different quality constituents, especially if a Runoff file is combined/collated with a Transport file, etc. The user is responsible for knowing the contents of each input file (possibly by running Combine with ICOMB = 2) and may specify in group C1 the constituents to be used for each. For instance, if BOD_5 is the first constituent to be placed on the output file, and if it is the third on file 1 and seventh on file 2, then NPOS2(1) = 3 and NPOS2(1) = 7. The description (name, units and type of units) will be copied from the first input file. Constituents not accessed will not be placed on the output file.

If a constituent is contained on one file but not the other, it may still be used. However, the file for which the constituent position (NPOS1 or NPOS2) is zero will be assumed to have zero concentration for that constituent.

If NPOLL = 0 in data group B2, no quality constituents will be placed on the new output file regardless of whether they are on the input files.

Timing

If the starting time (TZERO) is different for the two input files, the output file will begin at the earlier TZERO using zeroes for the other file until its series begins. Similarly, if one input file ends before the other, zeroes will be used until the end of the other file.

Files

The Combine Block uses one file (JIN(K)) when the file headers are read and printed. Three files are used if either the collate or combine options are used: two input interface files and one output interface files. The two input files are JIN(K) and NSCRAT(1). The output file is JOUT(K). (Obviously, this assumes that Combine is the Kth block called.) Two files, JIN(K) and JOUT(K), are used if ICOMB = 2. The Combine Block advances the block counter of the JIN and JOUT arrays, the same as all other blocks.

NSCRAT(1) may be used for scratch files in other blocks. Hence, following Combine, it may be necessary to end the SWMM run and restart the simulation in order to assign a different unit number to NSCRAT(1). Of course, in this case the resulting JOUT(K) file should be permanently saved using the @ option discussed in Section 2.

Table 3-1. Combine Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

   a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

   b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input <u>error</u> identification and are an aid to the EXTRAN user. Also 99999 lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 3-1 (continued). Combine Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
A1	Group identifier.	None
ICOMB	Program control. = 0, Collate only. = 1, Combine only. = 2, Extract (and optionally renumber) from a single file (JIN). = 3, Read the file headers of file JIN. = 4, Create an ASCII (text) file from the unformatted interface file (JIN).	0
* * * End of Input to the Combine Block if ICOMB = 3 * * *		
B1	Group identifier.	None
TITLE	Title, 2 lines to be placed as first title on output file (maximum of 80 characters per line).	Blank
B2	Group identifier.	Blank
NODEOT	Node number on output file for combined location. Enter zero if collating (ICOMB = 1).	None
NPOLL	Number of quality constituents to be placed on new file.	0
POLLUTANT IDENTIFICATION NOT REQUIRED IF NPOLL = 0		
B3	Group identifier.	None
NPOS1(1)	Constituent 1 position on file 1.	0
NPOS2(1)	Constituent 1 position on file 2.	0
.	.	.
.	.	.
.	.	.
NPOS1(NPOLL)	Constituent NPOLL position on file 1.	0
NPOS2(NPOLL)	Constituent NPOLL position on file 2.	0

Table 3-1 (continued). Combine Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Extraction/Renumbering Option	
C1	Group identifer.	None
NUMX	= Ø, Use all locations. > Ø, number of locations (nodes) to be extracted from one or two files.	Ø
NUMR	= Ø, do not renumber any locations. = NUMX, renumber according to data group C3. (If NUMX = Ø, NUMR can equal total number of nodes. See text.)	Ø
	Locations (nodes) to be Extracted	
	NOT REQUIRED IF NUMX = Ø ON DATA GROUP C1	
C2	Group identifier.	None
NODEX(1)	First node number.	None
.		
.		
.		
NODEX(NUMX)	Last node number.	None
	Numbers to be Assigned to Extracted Nodes	
	NOT REQUIRED IF NUMR = Ø ON DATA GROUP C1 VALUES MUST CORRESPOND TO NODES ENTERED IN DATA GROUP C2	
C3	Group identifier.	None
NODER(1)	Number for first renumbered node.	None
.		
.		
.		
NODER(NUMR)	Number for last renumbered node.	None

END OF COMBINE BLOCK

Program now returns to the Executive Block.

SECTION 4

RUNOFF BLOCK

BLOCK DESCRIPTION

Introduction

The Runoff Block has been developed to simulate both the quantity and quality runoff phenomena of a drainage basin and the routing of flows and contaminants to the major sewer lines. It represents the basin by an aggregate of idealized subcatchments and gutters or pipes. The program accepts an arbitrary rainfall or snowfall hyetograph and makes a step by step accounting of snowmelt, infiltration losses in pervious areas, surface detention, overland flow, channel flow, and the constituents washed into inlets, leading to the calculation of a number of inlet hydrographs and pollutographs.

The Runoff Block may be run for periods ranging from minutes to years. Simulations less than a few weeks will henceforth be called single event mode and longer simulations will be called continuous mode. With the slight exception of snowmelt, all computations are done identically for the two cases. The distinction between single event and continuous mode is kept mainly for ease of description and interpretation.

The overall catchment may be divided into a maximum of 200 subcatchments and 200 channel/pipes plus inlets. The user can modify these limitations by adjusting the variable NW and NG in the parameter statement of the INCLUDE file "TAPES.INC" and recompiling the program. Inlet flows and pollutographs may be placed on the interfacing file for input to subsequent blocks. However, these blocks have their own limitations on the number of inflow locations they will accept. See Section 2 for details. This section describes the operation of the Runoff Block and provides instructions on data preparation.

Program Operation

The relationships among the subroutines that make up the Runoff Block are shown in Figure 4-1. Subroutine RUNOFF is called by the Executive Block to gain entrance to the Runoff Block. The program prints "ENTRY MADE TO RUNOFF MODEL," initializes all variables to zero, and then calls subroutine HYDRO followed by PRINTR. Although BLOCK DATA is not an actual subroutine, it is automatically activated by RUNOFF and initializes some variables. Subroutine PRINTR reads the file headers, and then prints the table headings and results of the quantity and quality simulations.

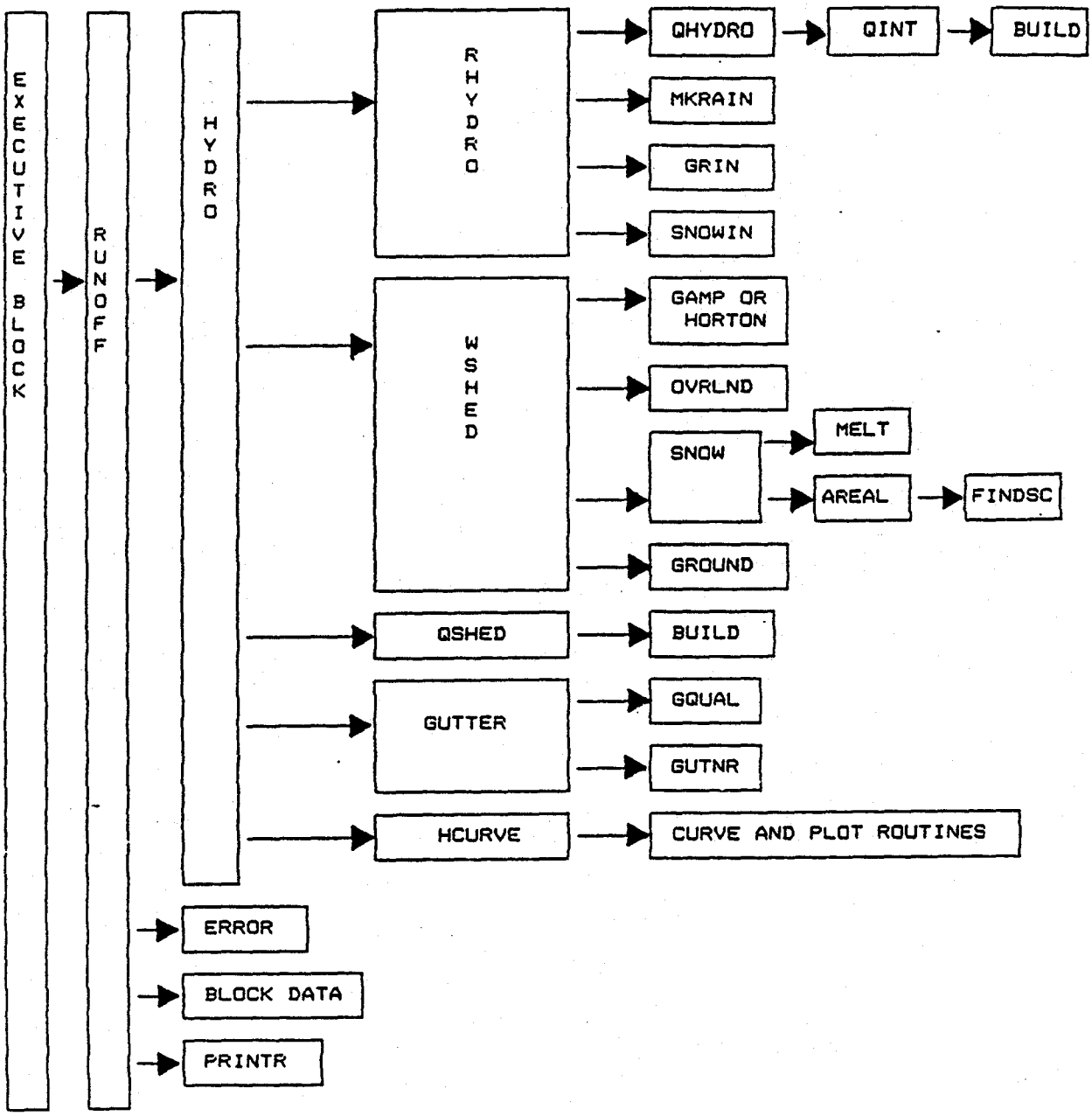


Figure 4-1. Structure of Runoff Block Subroutines.

Subroutine HYDRO computes the hydrograph ordinates and the watershed quality contributions with the assistance of 17 core subroutines, i.e., RHYDRO, GRIN, SNOWIN, QHYDRO, MKRAIN, QINT, QSHED, BUILD, WSHED, OVRLND, HORTON, GAMP, GUTTER, GUTNR, GQUAL, MELT, AREAL, AND FINDSC. RHYDRO reads the information concerning the inlet drainage basins. RHYDRO calls GRIN, MKRAIN, SNOWIN and QHYDRO to read groundwater, precipitation, snow information, and quality information, respectively. QINT and BUILD are then called to initialize the watershed constituent loads if water quality is simulated. HYDRO next sets up an ordering array to sequence the computational order for channel/pipes such that the computations proceed in a downstream direction.

HYDRO then computes the hydrograph ordinate for each time step by calling subroutine WSHED. WSHED calls either GAMP or HORTON to calculate infiltration. If snowmelt is simulated subroutine SNOW is called from WSHED. SNOW calls subroutines AREAL and MELT and subroutine FINDSC is called from AREAL. The runoff from a subcatchment is calculated by subroutine OVRLND and the subsurface flow contribution is calculated by subroutine GROUND. If quality is to be simulated, QSHED and BUILD are called to compute the watershed quality contributions from catchbasins, erosion, dust and dirt, and other sources. GUTTER is then called to compute the instantaneous water depth and flow rate for the channel/pipes and to route the flow. Water flowing into the inlet point is the sum of channel/pipe flow, direct drainage from subcatchments and direct groundwater inflow into the inlet. A continuity check is then made for the disposition of rainfall water in the form of runoff, detention, infiltration, and evaporation losses. The error in continuity is computed and printed as a percentage of precipitation. With the assistance of subroutine HCURVE, HYDRO plots the rainfall hyetograph, total infiltration, and the runoff hydrograph for the total drainage basin.

Interfacing and the Use of Disk Files

The Runoff Block transfers hydrographs and pollutographs for as many as 200 inlets and 10 constituents through an assigned file to other SWMM blocks (see Executive Block description). However, the other blocks may only accept part of this output. These restrictions may be circumvented by making a single run of the Runoff Block and generating a permanent data set (file) that will allow several runs of other blocks utilizing different portions of the output. If this is the first computational block, the title and values for the starting date and time and time step sizes will be used throughout all subsequent blocks.

Blocks, such as Extran and Transport, which may require a smaller time step than that used by the Runoff Block use a linear interpolation technique to generate the required input data from the interface file. Blocks such as the Storage/Treatment Block that may use a longer time step average the interface flows and loads over the longer time step.

Up to five scratch files are required for the single-event mode and as many as seven scratch files are required for the continuous mode; see Table 4-1. In the continuous mode the additional files are used to provide the program with a continuous feed of precipitation data so that there is effectively no limit on the length of the simulation.

Table 4-1 Runoff Off-line File Allocations

JIN(1)[a]	-	Input unit for precipitation. This data file was created earlier by the RAIN Block or saved in a previous run of the RUNOFF Block (see data group D1 description).
NSCRAT(1)	-	Scratch data file used when precipitation data are input on the E3 data group lines. Not required if precipitation is input on unit JIN(1).
NSCRAT(2)	-	Scratch data file used when precipitation data are input on the E3 data group lines. Not required if precipitation is input on unit JIN(1).
NSCRAT(3)	-	Data file used for storage of processed temperature, evaporation, and wind speed values from the Temp Block.
NSCRAT(4)	-	Scratch data file, always required. Used for temporary storage of output data to be printed.
NSCRAT(5)	-	Scratch data file, required if groundwater is simulated. Stores water table depths, groundwater flows and soil moisture contents for printout.
NSCRAT(6)	-	Scratch data, required if groundwater is simulated. Stores water table depths, groundwater flows and soil moisture contents for graphing by Graph Block.
JOUT(1)	-	Output unit for transfer of Runoff results to subsequent blocks. Required only if subsequent blocks are to be used or plotting is to be done using the Graph Block or statistics performed using the Statistics Block.

[a]Subscript "one" is used if Runoff is the first block run in a SWMM simulation. See explanation of Executive Block (Section 2).

DATA PREPARATION -- GENERAL INFORMATION

Introduction

Instructions on the use of the Runoff Block are divided into five subsections: general input and control data, meteorological data processing, surface quantity, surface quality and print control. The subsections follow the order of the input data groups shown in Table 4-31 at the end of this section. Many individual parameters are explained in more detail in the footnotes to Table 4-31. For further explanations of methods and techniques, the user

should refer to the documentation in the appendices to this report and to the original SWMM documentation (Metcalf and Eddy et al., 1971a).

Basic Runoff Data Sources

Importance of Runoff Block Data --

The Runoff Block forms the source of runoff and quality hydrographs and pollutographs for most SWMM applications. Although the other SWMM blocks allow direct input of special hydrographs and pollutographs either bypassing the interfacing file or in addition to it, in most cases these will be generated by the conversion of rainfall/snowmelt into runoff and pollutant loads in the Runoff Block. Hence, the input data for this block are probably the most important in the model.

Key data requirements and sources are mentioned during discussions of individual data groups later. However, the general types of data are discussed briefly at this point.

Meteorological Data --

Precipitation data are usually obtained from on-site gages maintained by an agency that has performed rainfall-runoff monitoring such as a local consulting firm, water authority, or city, county, state, provincial or federal agency. In the unfortunate event of a missing rain gage, precipitation data should be obtained from the nearest National Weather Service (NWS for U.S.) or Atmospheric Environment Service (AES for Canada) station. The fundamental data are precipitation hyetographs for the duration of the simulation. (See subsequent discussion for use of synthetic rainfall data.) When snowmelt is simulated, air temperatures and wind speed are needed in addition.

Surface Quantity Data --

Flow routing data are usually derived from topographic maps, aerial photos and drainage system plans. These are customarily obtained from the local agency responsible for drainage, usually the city or county. Especially for topographic maps, there is great variation in the quality of such data. Some cities, for instance, have 1:200 scale topographic maps complete with outlines of roads and structures. Slopes are easily derived from the one or two foot contours found on such maps. In some U.S. cities, the only contour information available may be the 1:24000 scale USGS quadrangle maps from which gross parameter estimation is often the only possibility. Seekers of basic quantity data must be prepared to spend several days at the municipal engineer's office to locate needed maps, plans etc. in public files.

A significant problem remains: the reliability of such data sources. Most municipal offices contain design drainage drawings, but recent as-built information is very rare. In older cities, design drawings may date back many decades and only serve as a guide to what actually exists in the field. This most often affects sewer slopes and cross sections (due to deterioration of old sewers). Finally, combined sewer regulators and other hydraulic control locations are often different from design drawings because of deterioration

and maintenance. In many instances, hydraulic connections exist that are not included on any plans because of pragmatic action of maintenance crews. In other cases, evident connections have been blocked off. In summary, all such data should be field checked.

Surface Quality Data --

Data required to formulate pollutographs are the most controversial of any SWMM input data. Such data and their possible sources are discussed later. At this point it is only re-emphasized that unless actual field sampling of runoff quality has been performed, typically by a government or pollution control agency, the credibility of predicted quality results cannot be established.

Default Parameters --

Very few default values for parameters are included in the model. However, the users may insert default parameters directly through the use of "default" and "ratio" options while entering data. The objective is to encourage the user to obtain reasonable values for all parameters on a site-specific basis, rather than to depend upon generalizations. Representative values and guidelines for selection of such parameters are included in this manual.

GENERAL AND CONTROL DATA (GROUPS A1 - B6)

The first four data groups are concerned with a label for the output and general operating parameters. The labels (titles) of group A1 will be placed on the interfacing file for future identification of the output. Most individual parameters are self-explanatory. However, further information on several parameters (e.g., infiltration) may be found in subsequent discussions of those topics. There is no distinction between single event and continuous simulation (except for snowmelt) in SWMM. The discerning user will notice the disappearance of parameter ICRAIN from earlier versions of SWMM. Single event and continuous simulations and modes will still be discussed but this is more of a semantic difference rather than a difference in input and programming. Ten hyetographs can be used for both single event and continuous simulations.

The user has more control over printing in SWMM4 by using the parameters on data group B2. The user can eliminate the printing of most input data by using IPRN(1) (see Table 4-31). IPRN(2) gives the user control over the plotting of rainfall hyetograph(s) and total inlet hydrograph. The user should avoid printing large amounts of unnecessary output and use parameter IPRN(3) on data group B2 judiciously (especially for long simulations). Control data and summary outputs are always printed.

The parameters of data group B3 govern the length of the wet time step (WET), the transitional time step(s) between wet and dry (WETDRY), the dry (DRY) time step, the time units of simulation, and the total simulation length. The exact number of time steps is no longer an input parameter. WET should be less than or equal to the rainfall interval entered on data group D1. It can be longer, but information is lost by averaging the rainfall over

a longer time period. A wet time step is a time step with precipitation occurring on <u>any</u> subcatchment. A transitional time step has no precipitation input on any subcatchment, but the subcatchment(s) still have water remaining in surface storage. A dry time step has no precipitation input or surface storage. However, it can have groundwater flow. The model is considered either globally wet, in the transitional period, or dry.

The time step should be smaller for periods of rapid change, i.e. during rainfall, and longer during periods of slower change, i.e. during transitional and dry time steps. Runoff computations use the concept of extrapolation to the limit (Appendix V) and can use any time step from 1 second to 1 year. The solution technique is stable and convergent for any length time step.

Typically the WET time step should be a fraction of the rainfall interval. Five minute rainfall should have wet time steps of 1, 2.5 or 5.0 minutes, for example. The rainfall intensity is constant over the wet time step when WET is a fraction of the rainfall interval. A smaller wet time step would be desirable when the subcatchment is small and the time of concentration is a fraction of the rainfall interval. When using one hour rainfall from the NWS wet time steps of 10 minutes, 15 minutes or longer can be used by the model.

The Runoff overland flow routing technique loses water through infiltration, evaporation, and surface water outflow during the transition periods. A subcatchment's surface storage and surface flow always decreases during the transition from a wet condition to a dry condition. A smooth curve or straight line are good models for the shape of the hydrograph. Transport or Extran usually have small time steps and use linear interpolation for input hydrographs with longer time steps. The transition time step, WETDRY, can be substantially longer than WET and generate a good overland flow hydrograph. For example, a WET of 5 minutes can be coupled with a WETDRY of 15 minutes or 30 minutes. When using hourly rainfall input a WET of 15 minutes can be coupled to a WETDRY of 2 hours or 3 hours.

The dry time step should be 1 day to a week. The dry time step is used to update the infiltration parameters, generate groundwater flow, and produce a time step value for the interface file. The dry time step should be day(s) in wet climates and days or week(s) in very dry climates. The synoptic analysis performed by the Rain Block will be of use in selecting the appropriate dry time step. Examine the average storm interevent duration in the storm summary table. The average storm interevent duration ranges from half a week to months depending on station location.

The model can achieve substantial time savings with judicious usage of WET, DRY, and WETDRY for both short and long simulations. As an example consider the time step saving using a WET of 15 minutes, a WETDRY of 2 hours, and a DRY of 1 day versus using a single time step of 1 hour for a year. Using Florida rainfall as input (average annual rainfall between 50 and 60 in. [1250 to 1500 mm]) gives 300 wet hours per year, flow for approximately 60 days per year, and 205 dry days per year. This translates to 1975 time steps. A constant hourly time step for one year requires 8760 time steps. This is greater than a 400 percent savings in time with a better representa-

tion of the flow hydrograph due to the 15 minute wet time step.

Data group B4 describes two global parameters pertaining to subcatchments: the rate of infiltration regeneration (REGEN), and percent imperviousness with no depression storage (PCTZER). This data group is optional and need not be entered by the user. These parameters are discussed in more detail later in conjunction with the subcatchment input parameters.

METEOROLOGICAL DATA (GROUPS C1-F1)

Snowmelt Data

General Parameters --

Groups C1 through F1 are used to read all pertinent meteorological data. Groups C1-C5 are concerned with snowmelt, if simulated. Additional snowmelt parameters are found in groups I1-I3. Snowmelt procedures are discussed in detail later.

In group C1, the watershed elevation is used only to compute average atmospheric pressure, which in turn has only a minimal effect on results. Hence, it is not a "sensitive" parameter. The free water holding capacity of a snow pack is the volume of water (as a depth, in inches) within the pack that can be held as liquid melt prior to releasing runoff. In the model it simply acts as an intermediate reservoir; the larger its volume, the greater the delay in the appearance of runoff following the conversion of snow to liquid water. Unfortunately, as is the case for most snowmelt parameters, very few data exist that permit estimation of this parameter in urban areas, let alone make distinctions among three types of snow-covered areas as required in group C1. However, some available information is summarized in Table 4-2.

In natural areas, a surface temperature (SNOTMP) of 34° to 35°F (1-2° C) provides the dividing line between equal probabilities of rain and snow (Eagleson, 1970; Corps of Engineers, 1956). However, parameter SNOTMP in group C1 might need to be somewhat lower in urban areas due to warmer surface temperatures.

The snow gage correction factor accounts for the error in snow gage measurements. The value of SCF is usually greater than 1.0 (the gage tends to underestimate the catch) and increases as a function of wind speed. Representative values are show in Figure 4-2 (Anderson, 1973). In practice, SCF can be used as a calibration factor to account for gains or losses of snow it cannot be determined from available data.

During non-melt periods (i.e., sub-freezing weather) the temperature of the snow pack follows the air temperature, but with a delay, since temperature changes cannot occur instantaneously. Heat exchange and temperature changes during this period are explained in Appendix II, with reference to equations II-15 and II-16. The weighting factor, TIPM, is an indicator of the thickness of the "surface" layer of the snow pack. Values of TIPM <= 0.1 give significant weight to temperatures over the past week or more and would indicate a

deeper layer (thus inhibiting heat transfer) than TIPM values greater than about 0.5 which would essentially only give weight to temperatures during the past day. In other words the pack will both warm and cool faster (i.e., track the air temperatures) with higher values of TIPM. Anderson (1973) states that TIPM = 0.5 has given reasonable results in natural catchments, although there is some reason to believe that lower values may be appropriate. No data exist for urban areas.

Table 4-2. Snowpack Free Water Holding Capacity
(Anderson, 1973; Corps of Engineers, 1956)

Model input (data group C1) is

$$FWFRAC = FW_{max}/WSNOW$$

where FWFRAC = free water holding capacity as a fraction of snowpack depth,
FW_{max} = maximum depth of free water stored in pack, inches, and
WSNOW = snowpack depth, inches water equivalent

Snowpack Conditions	FWFRAC
Typical deep pack (WSNOW > 10 in.)	0.02-0.05
Typical shallow early winter pack	0.05-0.25
Typical shallow spring pack or with slush layer	0.20-0.30

FWFRAC increases as pack density increases, pack depth decreases, slush layer increases, ground slope decreases.

Heat transfer within the snow pack is less during non-melt periods than during melt periods due to the presence of liquid water in the pack for the latter case. Parameter RNM simply multiplies melt coefficients (described for data groups I1-I3) to produce a lower "negative melt coefficient" for use during non-melt periods. A typical value for natural areas is 0.6, with values for urban areas likely to be somewhat higher because of the higher density of urban packs. The higher the value of RNM, the more rapid is the heat gain or loss of the pack in response to air temperature changes.

The catchment latitude and the longitude correction (described in footnote 8 to Table 4-31) are used only to compute hours of daylight for the catchment. Computations are insensitive to moderate errors in these values.

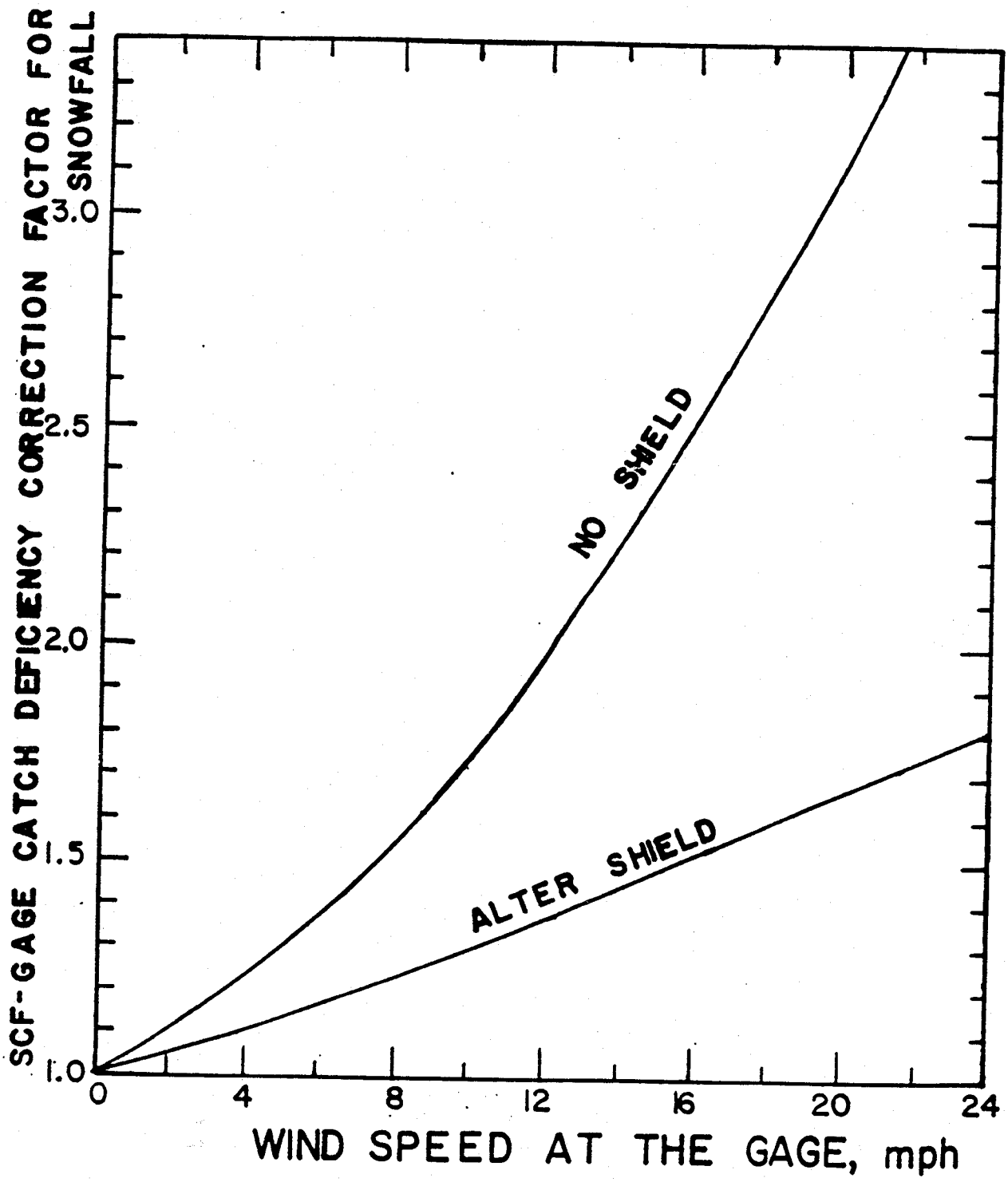


Figure 4-2. Gage Catch Deficiency Factor (SCF) Versus Wind Speed. (After Anderson, 1973 p. 5-20).

NWS Temperature Data --

Continuous SWMM requires a complete time history of daily maximum and minimum temperatures, from which hourly temperatures are synthesized by sinusoidal interpolation as described later. These max-min temperatures are supplied on the NWS TD-3200, "Surface Land Daily Cooperative Summary of Day." A magnetic tape containing these card images is available for most first-order NWS stations and others within the U.S. from the NOAA National Climatic Data Center in Asheville, NC (phone 704-259-0682). The entire Florida record of 40 years cost $236 in 1987. Such a record, corresponding to the precipitation record, is required for continuous simulation of snowmelt. Values are interpolated for missing dates. The Runoff Block uses the processed data from the Temp Block in its simulation. See Section 11 for more information and instructions in preparing the continuous temperature data file.

Wind Data --

Wind speeds, entered in group C2, are used only for melt calculations during periods of rainfall. The higher the values of wind speed, the greater are the convective and condensation melt terms. Of course, if the simulation covers a large city, the wind speeds entered in group C2 can only be considered gross estimates of what are in reality highly variable speeds. Average monthly speeds are often available from climatological summaries (e.g., NOAA, 1974).

An alternate source of wind speed data is TD-3200 from NOAA. The TEMP Block will read wind speed data from TD-3200 alone or in conjunction with temperature and evaporation data and create an interface file. The output of the Temp Block is input to the Runoff Block as file NSCRAT(3). Entering 999 in the first field of the C2 data line will trigger the input of the NOAA wind speed data from NSCRAT(3).

Areal Depletion Curves --

Areal depletion curves (ADC) account for the variation in actual snow covered area that occurs following a snowfall. They are explained in detail in Appendix II; a brief description is given here.

In most snowmelt models, it is assumed that there is a depth, SI, above which there will always be 100 percent cover. (Values of SI are input in data group I2.) In some models, the value of SI is adjusted during the simulation; in SWMM it remains constant. The amount of snow present at any time is indicated by the parameter WSNOW, which is the depth (water equivalent) over the snow covered areas of each subcatchment. This depth is non-dimensionalized by SI, called AWESI for use in calculating the fraction of area that is snow covered, ASC; a typical ADC for a natural catchment is shown in Figure 4-3. For values of the ratio AWESI = WSNOW/SI greater than 1.0, ASC = 1.0, that is, the area is 100 percent snow covered.

Some of the implications of different functional forms of the ADC may be seen in Figure 4-4. Since the program maintains snow quantities, the actual snow depth, WS, and area covered, AS, are related by continuity:

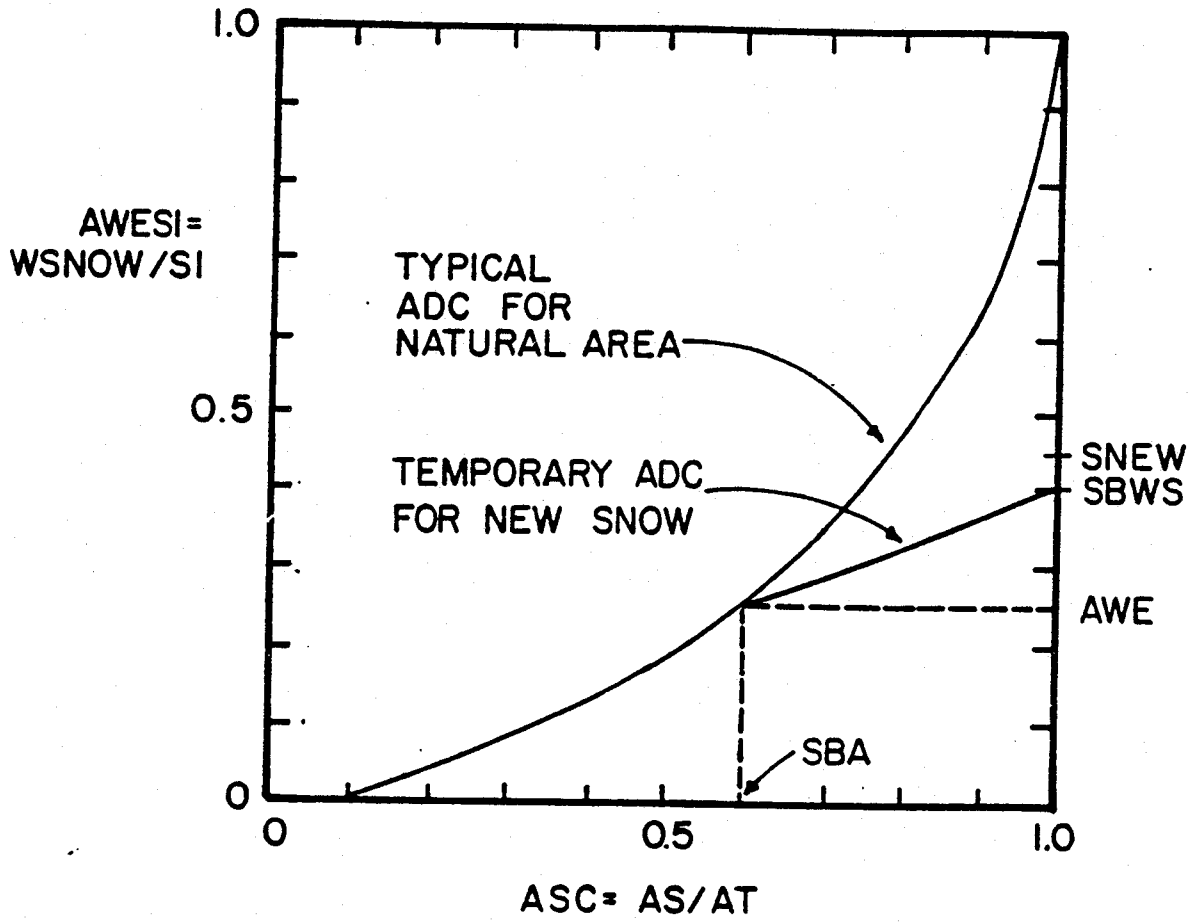


Figure 4-3. Actual Areal Depletion Curve for Natural Area. (After Anderson, 1973, p. 3-15).

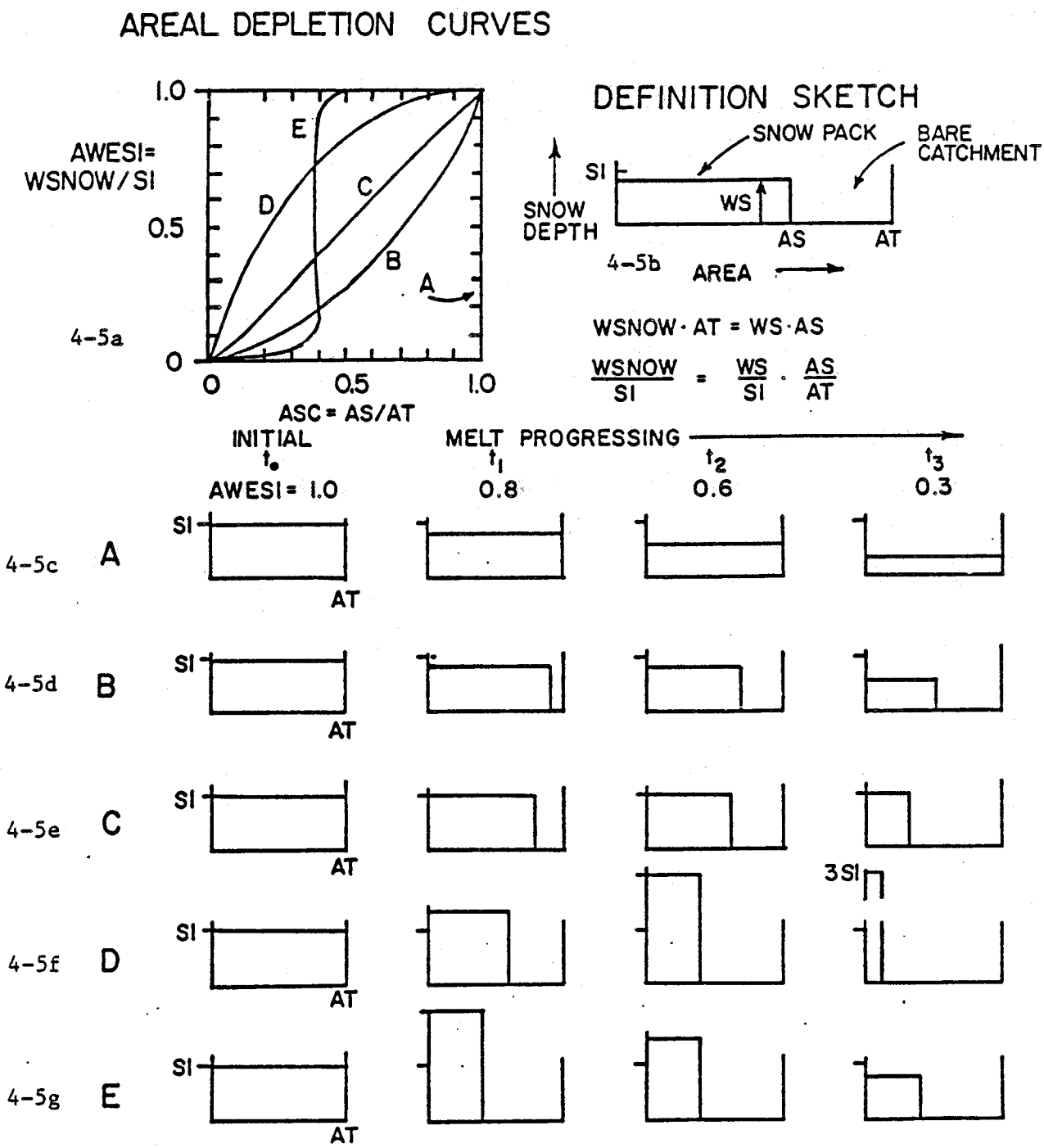


Figure 4-4. Effect on Snow Cover on Areal Depletion Curves.

$$WSNOW \cdot AT = WS \cdot AS \qquad (4\text{-}1)$$

where WSNOW = depth of snow over total area AT, ft water equivalent,
AT = total area, ft^2,
WS = actual snow depth, ft water equivalent, and
AS = snow covered area, ft^2.

In terms of parameters shown on the ADC, equation 4-1 may be rearranged to read

$$AWESI = WSNOW/SI = WS/SI \cdot AS/AT = WS/SI \cdot ASC \qquad (4\text{-}2)$$

Equation 4-2 can be used to compute the actual snow depth, WS, from known ADC parameters, if desired. It is unnecessary to do this in the program, but it is helpful in understanding the curves of Figure 4-4. Thus,

$$WS = AWESI/ASC \cdot SI \qquad (4\text{-}3)$$

Consider the three curves, B, C and D. For case B, AWESI is always less than ASC; hence, WS is always less than SI as shown in Figure 4-4d. For case C, AWESI = ASC, hence WS = SI, as shown in Figure 4-4e. Finally, for case D, AWESI is always greater than ASC; hence WS is always greater than SI, as shown in Figure 4-4f. Constant values of ASC at 100 percent cover and 40 percent cover are illustrated in Figures 4-4c, curve A, and Figure 4-4g, case E, respectively. At a given time (e.g., t_1 in Figure 4-4), the area of each snow depth-area curve is the same and equal to AWESI x SI, (e.g., 0.8 SI for time t_1).

Curve B on Figure 4-4a is the most common type of ADC occurring in nature, as shown in Figure 4-3. The convex curve D requires some mechanism for raising snow levels above the original depth, SI. In nature, drifting might provide such a mechanism; in urban area, plowing and windrowing could cause a similar effect. It is seen that such a convex curve acts to delay melt because of the inhibiting effect on heat transfer of deep snow packs. A complex curve could be generated to represent specific snow removal practices in a city. However, the program utilizes only one ADC curve for all impervious areas and only one ADC curve for all pervious areas. This limitation should not hinder an adequate simulation since the effects of variations in individual areas are averaged out in the city-wide scope of most continuous simulations.

The user must input the two ADC curves for impervious (group C3) and pervious (group C4) areas, as well as values of SI for each subcatchment (group I2). The program does not require the ADC curves to pass through the origin, AWESI = ASC = 0; they may intersect the abscissa at a value of ASC > 0 when ASC = 0.

The preceding paragraphs have centered on the situation where a depth of snow greater than or equal to SI has fallen and is melting. (The ADC curves are not employed until WSNOW becomes less than SI.) The situation when there is new snow is discussed in Appendix II.

Air Temperatures --

For a single event snowmelt simulation, air temperatures are input in data group C5. These may be obtained from instrumentation at the catchment or from the nearest NWS (U.S.) or AES (Canada) station. The temperatures are constant over the time interval DTAIR (group C5).

Precipitation Data

Choice of Rainfall Data --

Without doubt, rainfall data are the single most important group of hydrologic data required by SWMM. Yet, they are often prepared as an afterthought, without proper consideration of the implications of their choice. The following discussion will briefly describe options for rainfall input and their consequences. Only rainfall is considered since for snow it is the physics of snowmelt rather than snowfall which is important in determining runoff.

SWMM requires a hyetograph of rainfall intensities versus time for the period of simulation. For single event simulation this is usually a single storm, and data for up to ten gages may be entered (if the user is fortunate enough to have multiple gages for the catchment). For continuous simulation, hourly, 15-min or other continuous data from at least one gage are required; these are usually obtained from the nearest NWS (U.S.) or AES (Canada) station. Thus, for continuous simulation, the options are fewer since a satisfactory generator of, say, a synthetic hourly rainfall sequence is not usually available, and perhaps not even desirable. Hence, a historical rainfall sequence is usually used.

For single event simulation, on the other hand, synthetic design storm sequences are indeed an option in lieu of historical records. However, several pitfalls exist in the use of synthetic hyetographs that may not be obvious at first thought. As a prelude, consider the objectives of hydrologic quantity and quality modeling.

Modeling Objectives --

These were treated broadly in Section 1. Models might be used to aid in urban drainage design for protection against flooding for a certain return period (e.g., five or ten years), or to protect against pollution of receiving waters at a certain frequency (e.g., only one combined sewer overflow per year). In these contexts, the frequency or return period needs to be associated with a very specific parameter. That is, for rainfall one may speak of frequency distributions of interevent times, total storm depth, total storm duration or average storm intensity, all of which are different (Eagleson, 1970, pp. 183-190). Traditional urban drainage techniques often utilize frequencies of depths for given durations, taken from intensity-duration-frequency (IDF) curves, which are really conditional frequency distributions. But for the above objectives, and in fact, for almost all urban hydrology work, the frequencies of runoff and quality parameters are required, not those

of rainfall at all. Thus, one may speak of the frequencies of maximum flow rate, total runoff volume or duration or of total pollutant loads. These distributions are in no way the same as for similar rainfall parameters, although they may be related through analytical methods (Howard, 1976; Chan and Bras, 1979; Hydroscience, 1979). Finally, for pollution control, the real interest may lie in the frequency of water quality standards violations in the receiving water, which leads to further complications.

Ideally an analyst would develop costs and benefits for designs at several frequencies in preparation for an economic optimization. In practice, it is often difficult to accomplish this for even one case.

However, continuous simulation offers an excellent, if not the only method for obtaining the frequency of events of interest, be they related to quantity or quality. But continuous simulation has the disadvantages of a higher cost and the need for a continuous rainfall record. This has led to the use of a "design storm" or "design rainfall" or "design event" in a single event simulation instead. Of course, this idea long preceded continuous simulation, before the advent of modern computers. However, because of inherent simplifications, the choice of a design event leads to problems.

Design Events --

Two methods of obtaining design events are considered: 1) use of a historical sequence and 2) generation of a synthetic sequence. Synthetic sequences are usually constructed by the following steps (Arnell, 1982):

1. A storm duration is chosen, whether on an arbitrary basis or to coincide with the assumed catchment time of concentration, t_c, i.e., equilibrium time at which outflow equals a constant fraction of steady rainfall (or outflow equals rainfall on a catchment without losses). The latter method itself has difficulties because of the dependence of t_c on rainfall intensity and other parameters (Eagleson, 1970).

2. A return period is chosen in order to select the total storm depth for the specified duration from intensity-duration-frequency (IDF) curves.

3. A time history for the storm is assumed, usually on the basis of historical percentage mass curves. If peak intensities occur at the beginning of the storm, the hyetograph takes on the appearance of a decaying exponential curve. If the peak intensities occur near the middle, a "circus tent" hyetograph results (Figure 4-5). The hyetograph is shaped such that depths (or average intensities) for any duration centered about the peak match those from the IDF curve. Several shapes are commonly used (Arnell, 1982); in the U.S., the "Chicago storm" (Keifer and Chu, 1957) and the SCS Type-II distribution (SCS, 1972) are frequently encountered.

4. The continuous hyetograph of Figure 4-5 must then be discretized into a histogram for input to most models.

This procedure was apparently first detailed by Keifer and Chu (1957) and then by Tholin and Keifer (1960) in Chicago. It has since been emulated by

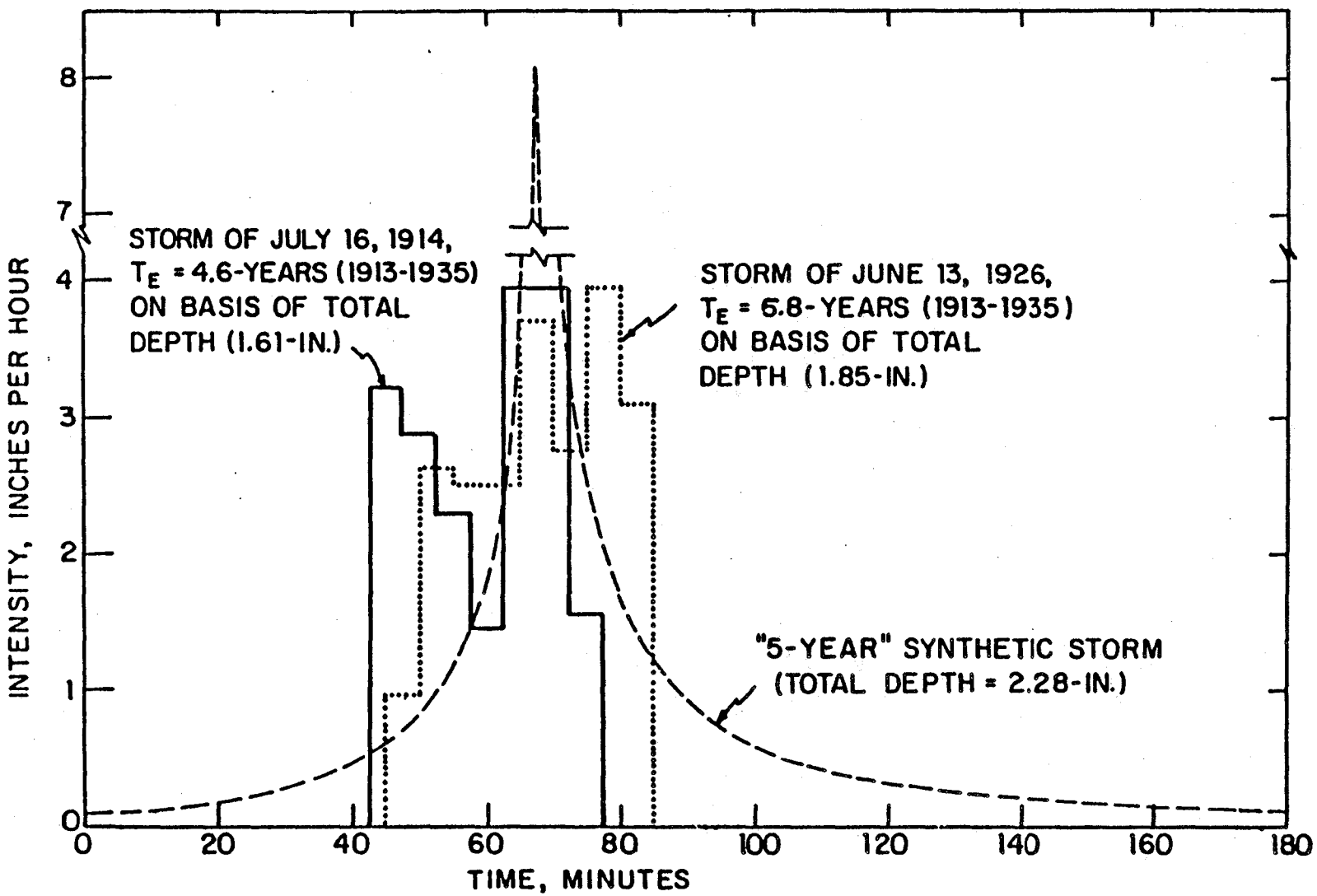


Figure 4-5. Comparison of Synthetic Versus Actual Storm Patterns, Chicago. (After McPherson, 1978, p. 111.)

many others (Arnell, 1982; Harremoes, 1983).

Many problems with this procedure for construction of synthetic hyetographs (McPherson, 1978; Patry and McPherson, 1979; Arnell, 1982; Harremoes, 1983; Adams and Howard, 1985) and with the underlying rational method and IDF curves on which it is based (McPherson, 1969) have been enumerated. For example:

1. IDF curves themselves may consist of components of several different storms. They in no way represent the time history of a real storm.

2. When frequencies are assigned to total storm depths (independent of duration) they generally do not coincide with the conditional frequencies of depth for the given duration obtained from IDF curves. For instance, the two historical storms shown on Figure 4-5 for comparison with the "5-year" synthetic storm of 2.28 in (58 mm) have return periods (based on total depth) of 4.6 and 5.8 years, but total depths of only 1.61 and 1.85 in (41 and 47 mm), respectively. Thus, IDF curves cannot be used to assign frequencies to storm volumes. If synthetic hyetographs are thence used for studies of detention storage or pollutant loads, where volumetric considerations are key, no frequency should be assigned to the results.

3. Although the time history assigned to a synthetic storm may represent an average of many storms, there is often considerable variability (see P. Bock, Discussion of Tholin and Keifer, 1960). If a frequency could be assigned to a synthetic storm, it would probably be considerably rarer than its nominal frequency, because the joint probability of all time sequences within the storm corresponding to those of an IDF curve is very low. The two historical storms shown on Figure 4-6 certainly do not mimic the synthetic storm.

4. Antecedent conditions must still be chosen arbitrarily when using a design event (either a synthetic or historical storm.) However, historical storms also provide their historical antecedent conditions. That is, a historical storm can be run in a single-event mode using several days of historical antecedent rainfall to generate realistic antecedent moisture conditions in the catchment. This is not possible with synthetic storms.

5. A synthetic design event is one that "never really happened." McPherson (1978) emphasizes the need to design with a real (historical) event to ensure credibility in the eyes of the public.

6. There is evidence that synthetic design events may produce an overdesign if the objective is a design for a given return period. Marsalek (1979a,b) has compared continuous simulation results of flood peaks and volumes versus return period with results obtained by single event simulations using the same model with input of n-year synthetic events of the type described earlier. Flood peaks are always higher for the synthetic events. Flood volumes are higher for most synthetic events, depending on the method of generation of the event, because the return periods assigned to the synthetic volumes are incorrect. The verdict is not clear, however. Huber et al. (1986) compared synthetic versus historical storms for simulation of peak flows for a 2000-ac catchment in Tallahassee, Florida. They found that a

larger peak was generated by a 22-yr historical storm than by a 25-yr SCS Type-II synthetic storm. In other words, synthetic storms are not always conservative.

Design Event Alternatives --

In spite of all of its problems, use of a design event may still be required. Fortunately, there are ways in which this may be accomplished satisfactorily.

Foremost among these is the use of continuous simulation as a screening tool. As stated earlier, continuous simulation for several years of a large catchment with inclusion of spatial detail can be time-consuming. Instead, representative smaller catchments may be simulated from which critical events may be selected for a more detailed, single event simulation. Thus, from a simple long-term continuous simulation, critical subsets may be identified for further analysis. Walesh and Snyder (1979) present ideas along this line, and Robinson and James (1984) and Huber et al. (1986) demonstrate the ideas.

Continuous simulation may also be used to "calibrate" a synthetic design event. That is, the design hyetograph may be adjusted such that it produces flows or volumes that correspond for its return period to those produced by a continuous simulation run. This has been done in studies in Northern Virginia (Shubinski and Fitch, 1976) and Denver (B. Urbonas, personal communication, 1979). Proper adjustment of antecedent conditions can also cause results from synthetic design events to match historical results (Wenzel and Voorhees, 1978).

In any event, several storm events should be processed for design considerations. These may be selected from a continuous simulation run, as suggested above, or chosen from the historical record on another basis. For urban drainage or flood control design, it may be desirable to choose a particular, well-known local rainfall event and make sure that a design will handle that storm.

Calibration of the model remains important for any application. It has been suggested (M. Terstriep, personal communication, 1979) that use of a synthetic design event for analysis of a new system may not be any worse than using historical data in an uncalibrated model.

The question of appropriate rainfall input for models has generated intense interest. Good discussions are given by McPherson (1978), Patry and McPherson (1979), Arnell (1982), James and Robinson (1982), Harremoes (1983) and Huber et al. (1986).

National Weather Service Precipitation Data --

Hourly precipitation values (including water equivalent of snowfall depths) are available for 40-year periods for most first-order NWS stations around the U.S. (Similar data are available in Canada from the Atmospheric Environment Service.) Magnetic tapes containing card images of NWS Tape Deck 3240, "Hourly Precipitation Data" are available from the NOAA National Weather

Records Center in Asheville, NC (phone (704) 259-0682). The cost for the entire state of Florida was $154 in 1984. Typically, purchasing the entire state record is actually cheaper than purchasing a single station due to extra processing costs for a one station retrieval.

Having obtained these data for a continuous simulation, they are read directly from the tape in the Rain Block. See input details in Section 10, which describes the Rain Block.

Atmospheric Environment Service Data --

A special package DATANAL is available from Computational Hydraulics Inc. to convert AES data tapes to the NWS format expected by SWMM (W. James, personal communication, 1987).

Special Input of Precipitation Data --

Precipitation input is significantly different in this version of SWMM. Important differences include: (1) free format input, (2) three input types, (3) variable precipitation intervals, (4) precipitation input may be intensity or volume, (5) rainfall print control, (6) fewer input values since zero rainfall need no longer be entered, and (6) the rainfall scratch file can be saved permanently.

For single event simulation, precipitation hyetographs may be input for up to ten gages using data groups D1 through E3. Any one of the ten gages may then be assigned to a subcatchment using parameter JK in the H1 data group.

Subroutine MKRAIN reads the input hyetographs input on data group E3. They are either temporarily or permanently saved on NSCRAT(1). MKRAIN also uses NSCRAT(2) as a temporary work file, making NSCRAT(2) a Runoff Block scratch file requirement. The user has the option of saving NSCRAT(1) as a permanent file for subsequent runs. This might be efficacious when a large amount (> 100 data points) are input in data group E3. The permanent file will save processing time on later calibration runs. There is no limitation on the number of precipitation data points.

The user saves the file permanently by using the @ function (discussed in Section 2) and selecting ROPT=2 on data group D1. The precipitation file has the same format as the precipitation file created by the Rain Block. The interested reader can find a description of a precipitation file in Section 10. The precipitation files are read by Subroutine HYDRO at the beginning of each time step.

Data group E1 defines the type of precipitation (KTYPE), precipitation values or pairs per line (KINC), precipitation print control (KPRINT), variable precipitation intervals (KTHIS), time units (KTIME), precipitation input type (KPREP), number of precipitation values (NHISTO), and the default rainfall interval (THISTO).

Precipitation can be read in three formats as described by parameter KTYPE. KTYPE = 0 is the old SWMM format with a constant precipitation inter-

val (THISTO). The problem with this format is that zeroes must be used to fill the "holes" for dry time steps. For example, the input

E3 1.0 0.0 0.0 0.0 2.0 3.0 1.0 0.4 0.5 0.0 KTYPE = 0 Example Input

means starting at time TZERO the first rainfall interval has an intensity of 1.0 in./hr, the second, third and fourth intervals have intensities of 0.0 in./hr, the fifth has intensity 2.0 in./hr, etc. Each interval is THISTO minutes long unless THISTO is modified by the E2 data group.

Using the other two input formats eliminates the necessity of entering zeroes. The starting time for the interval and the interval precipitation value are the only requirements. For example, the input

E3 0.0 1.0 100.0 0.5 KTYPE = 1 Example Input

means that the rainfall intensity starting at 0 minutes and lasting THISTO minutes is 1.0 in./hr. The rainfall intensity starting at minute 100 and lasting THISTO minutes is 0.5 in./hr. The hyetographs for each raingage are entered consecutively if KTYPE = 0 or 1. If KTYPE is 2, a starting time and a precipitation intensity for each raingage is entered on one line. For example, the input

E3 100.0 1.0 2.0 0.0 KTYPE = 2 Example Input

means starting at minute 100 the rainfall intensity for THISTO minutes is 1.0 in./hr for gage 1, 2.0 in./hr for gage 2, and 0.0 in./hr for gage 3. This format does require the input of zero rainfall at a gage if even one gage has measurable rainfall.

Input parameter KINC is the number of rainfall values per input line (KTYPE=0),or the number of time and precipitation pairs per line (KTYPE=1), and unnecessary for KTYPE=3. KINC equals NRGAG + 1 for KTYPE=3. The user should enter any number in the KINC field for KTYPE=3.

KPRINT controls the echo printing of the rainfall. Select KPRINT=1 to eliminate the echo printing. Only summary statistics by individual raingage will be printed. The summary table lists the total rainfall, maximum and minimum rainfall intensity or volume, and total rainfall duration for each raingage.

The time interval for input of hyetograph intensities, THISTO, (the same for all hyetographs) must be either equal to the wet computation time step, WET (group B3), or an integer multiple or integer fraction (e.g., 1/2, 1/5, etc.) thereof. If THISTO is an integer fraction of WET, the average intensity over time step DELT is used in computations. Realistically, THISTO should be at least equal to the wet time step. Information is lost by averaging over discrete rainfall intensities. The interrelationship between WET and THISTO is discussed later in the section on flow routing parameters.

Parameter KTHIS is the number of variable rainfall intervals input on data group E2. This option allows the user to mix rainfall intervals of dif-

fering lengths in a simulation, e.g. 5-minute rainfall between 15-minute or 1-hour rainfall intervals. An input of

```
E2   100.0  200.0   5.0    1000.0 2000.0  15.0        Variable THISTO input
```

means between 100 and 200 minutes the rainfall interval is 5 minutes, but between 1000 and 2000 minutes the rainfall interval is 15 minutes. The times are the minutes from the start of simulation. The time periods outside of these two ranges would have THISTO rainfall intervals. THISTO is always the default rainfall interval.

The precipitation input is either in units of intensity, in./hr [mm/hr], or the total rainfall volume over the rainfall interval, in. [mm]. The input type is selected by parameter KPREP. Runoff uses intensity units internally. The unit of time used by data groups E2 and E3 may be either minutes or hours and is selected by parameter KTIME on data group E1.

Temporal Rainfall Variations --

The required time detail for rainfall hyetographs is a function of the catchment response to rainfall input. Small, steep, smooth, impervious catchments have fast response times, and vice versa. As a generality, shorter time increment data are preferable to longer time increment data, but for a large (e.g., 10 mi^2 or 26 km^2) subcatchment (coarse schematization), even the hourly inputs usually used for continuous simulation may be appropriate.

The rain gage itself is usually the limiting factor. It is possible to reduce data from 24-hour charts from standard 24-hour, weighing-bucket gages to obtain 7.5-minute or 5-minute increment data, and some USGS float gages produce no better than 5-minute values. Shorter time increment data may usually be obtained only from tipping bucket gage installations.

The rainfall records obtained from a gage may be of mixed quality. It may be possible to define some storms down to 1 to 5 minute rainfall intensities, while other events may be of such poor quality (because of poor reproduction of charts or blurred traces of ink) that only 1-hr increments can be obtained. Variable precipitation intervals can be modeled by using data group E2 (see above). This will allow the interspersing of (for example) 5-minute, 15-minute, and hourly rainfall in a simulation.

Spatial Rainfall Variations --

Even for small catchments, runoff and consequent model predictions (and prototype measurements) may be very sensitive to spatial variations of the rainfall. For instance, thunderstorms (convective rainfall) may be very localized, and nearby gages may have very dissimilar readings. For modeling accuracy (or even more specifically, for a successful calibration of SWMM), it is essential that rain gages be located within and adjacent to the catchment, or a storm model such as RAINPAK (James and Scheckenberger, 1983) be used.

SWMM accounts for the spatial variability by the assignment of one of up to ten gages to a particular subcatchment. (Clearly, there is no point in the

input of more gage data than there are subcatchments.) If multiple gages are available, this is a much better procedure than is the use of spatially averaged (e.g., Thiessen weighted) data, because averaged data tend to have short-term time variations removed (i.e., rainfall pulses are "lowered" and "spread out"). In general, if the rainfall is uniform spatially, as might be expected from cyclonic (e.g., frontal) systems, these spatial considerations are not as important. In making this judgment, the storm size and speed in relation to the total catchment must be considered. It should be noted that a moving or "kinematic" storm may only be simulated in SWMM by using multiple gages. Storm motion may very significantly affect hydrographs at the catchment outlet (Yen and Chow, 1968; Surkan, 1974; James and Drake, 1980; James and Shtifter, 1981)).

Evaporation Data (Group F1)

An average monthly evaporation rate is required for the month being simulated in the single event mode, or for all months in the continuous mode. This rate is subtracted from rainfall and snowmelt intensities at each time step and is also used to replenish surface depression storage and provide an upper bound for soil moisture and groundwater evaporation. However, it is not used to account for sublimation from snow. Evaporation data may usually be obtained from climatological summaries (NOAA, 1974) or NWS or other pan measurements (e.g., from NWS Climatological Data or Farnsworth and Thompson, 1982). Single event simulations are usually insensitive to the evaporation rate, but evaporation can make up a significant component of the water budget during continuous simulation.

Evaporation can be input into the Runoff Block either by using data group F1, or by creating an evaporation time series using the Temp Block. If F1 is used the same monthly estimate for evaporation is used for all simulated years. The time series apprcach in the Temp Block allows yearly variation in evaporation. Daily, weekly, or monthly evaporation estimates can be read by the Temp Block. The evaporation time series is input into Runoff using NSCRAT(3) as the input file.

SURFACE QUANTITY DATA (GROUPS G1-I3)

Runoff Flow Routing Procedures and Options

Data groups G1 through I3 input data used to establish surface and subsurface flow routing and snowmelt parameters for the Runoff Block. Snowmelt and subsurface routing will be discussed subsequently. Surface flow routing is accomplished using four types of elements:

1. subcatchment elements (overland flow),
2. channel elements (trapezoidal or parabolic channel flow),
3. pipe elements (circular channel flow), and
4. control structures (weirs and orifices).

Subcatchment elements receive rainfall and snowmelt, account for losses due to evaporation and infiltration (via Horton's equation or the Green-Ampt equation), and permit surface depression storage to account for losses such as

ponding or retention on grass or pavement. "Losses" from infiltration may optionally be routed through a subsurface pathway (quantity simulation only), first into an unsaturated zone storage, then to a saturated zone storage from which baseflow into an inlet or channel/pipe may be generated (see Appendix X). Surface flow from subcatchments is always into channel/pipe elements or inlets. A tree-network of channel/pipes may be used to simulate smaller drainage elements of the sewer system. If they are used, they route hydrographs (and pollutographs) from subcatchments placed on the interfacing file for transmittal to subsequent SWMM blocks. However, the Runoff Block is often used by itself if the more sophisticated routing procedures of the Transport or Extended Transport Blocks are not required (discussed below).

Flow routing for both subcatchments and channel/pipes is accomplished by approximating them as non-linear reservoirs. This is simply a coupling of a spatially lumped continuity equation with Manning's equation. A detailed description is presented in Appendix VI. Should the capacity of a channel/pipe be exceeded, "surcharge" is indicated, and excess water is stored at the upstream end until the channel/pipe can accept it.

Input Data Preparation

Preparation of these input data requires two tasks: 1) discretization of the physical drainage system and 2) estimation of the coefficients necessary to characterize the catchment. These tasks require varying amounts of effort depending on the level of detail desired by the user.

Useful additional information for these tasks is contained in the short course proceedings prepared by the University of Massachusetts (Di Giano et al., 1977). The Runoff Block example is particularly good because of the emphasis on data reduction from typical municipal maps and plans. The SWMM user is encouraged to review these proceedings for alternative explanations and examples. Further useful information is contained in the references.

Discretization of the Catchment

Definition --

Discretization is a procedure for the mathematical abstraction of the physical drainage system. For the computation of hydrographs, the drainage basin may be conceptually represented by a network of hydraulic elements, i.e., subcatchments, channels and pipes. Hydraulic properties of each element are then characterized by various parameters, such as size, slope, and roughness coefficient.

Subcatchments represent idealized runoff areas with uniform slope. Parameters such as roughness values, depression storage and infiltration values are taken to be constant for the area and usually represent averages, although pervious and impervious areas have different characteristics within the model. If roofs drain onto pervious areas, such as lawns, they are usually considered part of the pervious area, although conceivably, they could be treated as miniature subcatchments themselves.

Discretization begins with the identification of drainage boundaries using a topographic map, the location of major sewer inlets using a sewer system map, and the selection of those channel/pipes to be included in the Runoff Block system. Note that discretization of the sewer system involves choices that affect elements to be used in either of the subsequent Transport or Extran Blocks (see below). An example will illustrate some of these points.

Example --

Two possible discretizations of the Northwood catchment in Baltimore (Tucker, 1968; Huber et al., 1981) are indicated in Figures 4-6 and 4-7 (Metcalf and Eddy et al., 1971a). A "fine" approach was used in Figure 4-6, resulting in 12 subcatchments and 13 pipes leading to one inlet. In Figure 4-7, a "coarse" discretization was used, resulting in five subcatchments and no channels or pipes. "Storm Conduits" shown in Figure 4-7 could either be simulated by the Transport or Extran Block or ignored, feeding all subcatchment flows to the one inlet. The outlet to the creek then represents the downstream point in the simulation. (This could lead, in a larger system, to inlets in the Transport Block.)

A comparison of hydrographs produced by the two methods is shown in Figure 4-8 (Metcalf and Eddy et al., 1971a), in which the differences are relatively minor. Additional calibration effort could bring the two schematizations into better agreement with each other and with the measured hydrograph. Techniques for this purpose are discussed later as are techniques for aggregation of subcatchments.

Required Amount of Detail --

It is anticipated that only a very coarse discretization will be used for continuous simulation. Although up to 200 subcatchments and channel/pipes or inlets are allowed, a typical hourly continuous simulation might include only one subcatchment and no channel/pipes. This economy in the amount of detail simulated is prompted to save computer time and because detail simply is not required for continuous simulation which serves as a screening and planning tool (see Appendix I). Moreover, reasonable agreement is possible between hydrographs produced by coarse and fine schematizations as will be discussed later under "subcatchment aggregation."

Should flow routing be desired during continuous simulation, Runoff Block channel/pipes ordinarily would be used. Although the Transport and Extran Blocks are intended primarily for single event analysis, they may also be employed, at the expense of slightly more interfacing effort. There are no limitations on the number of time steps for any block.

For a single event simulation, the amount of detail should be the minimum consistent with requirements for within-catchment information. Obviously, no information can be obtained about upstream surcharging if the upstream conduits are not simulated and subcatchments are not provided to feed them. In addition, sufficient detail needs to be provided to allow within-system control options to be tried for different areas and land uses. If, however, the

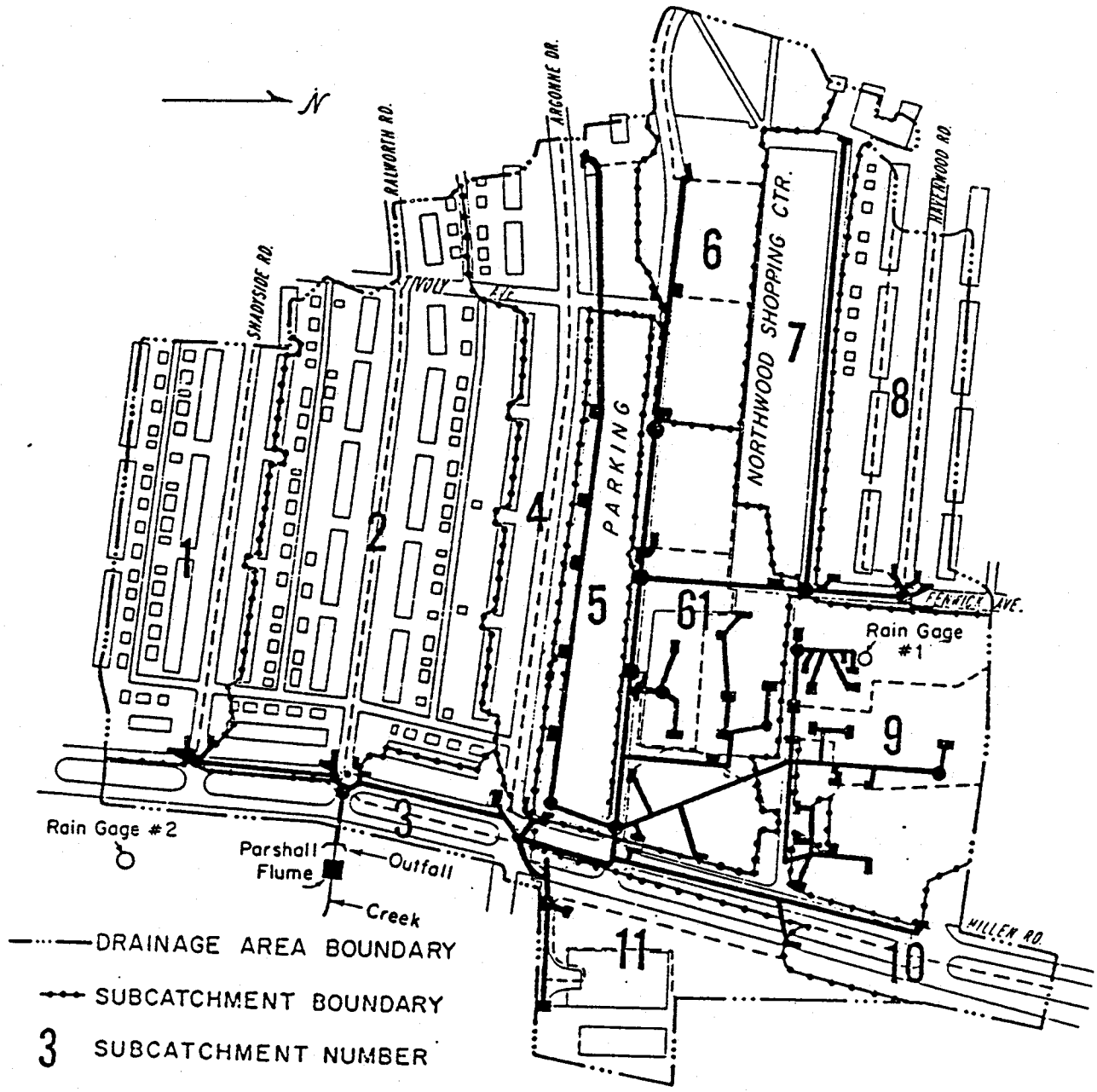


Figure 4-6. Northwood (Baltimore) Drainage Basin "Fine" Plan. (After Metcalf and Eddy et al., 1971a, p. 50)

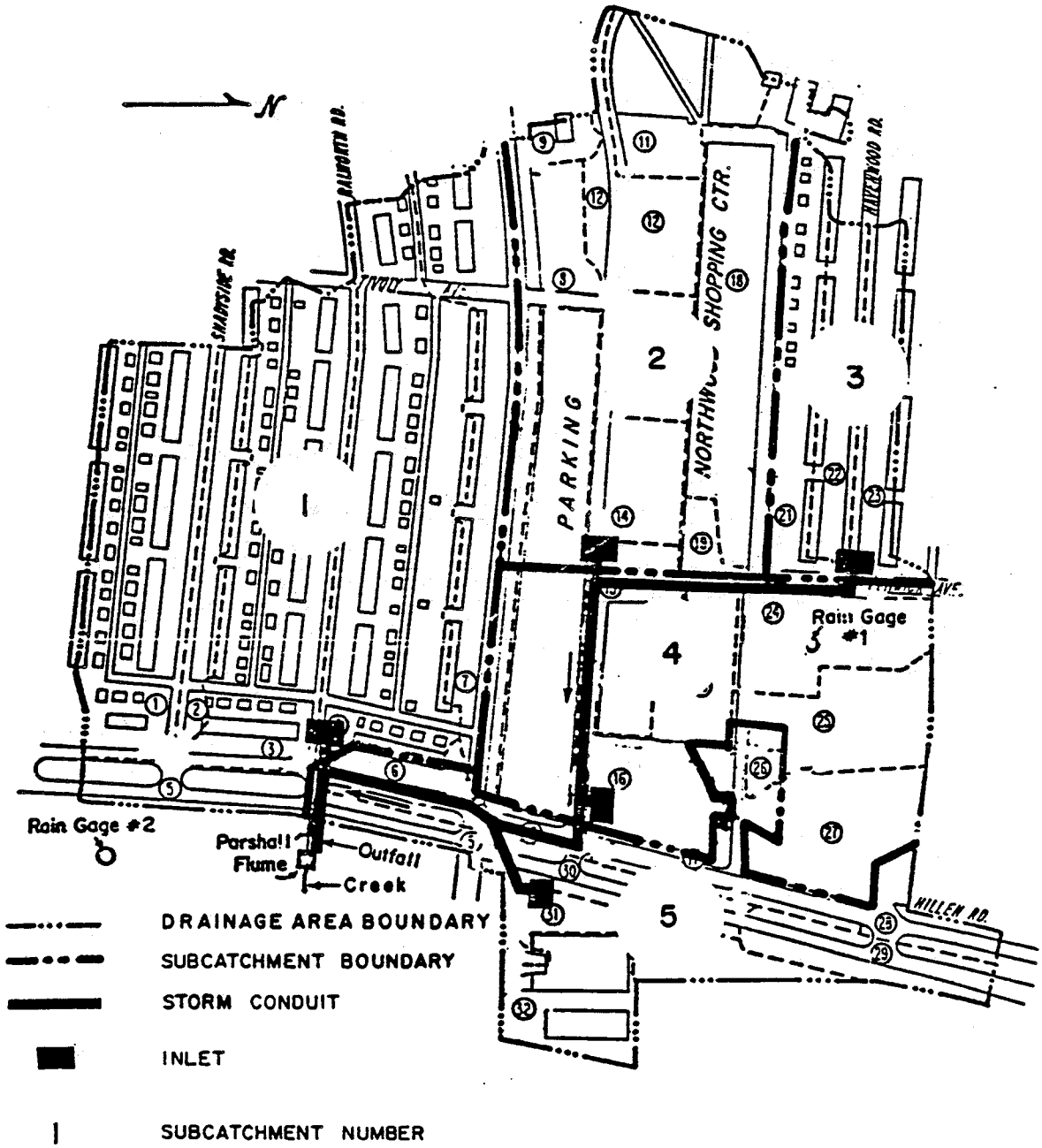


Figure 4-7. Northwood (Baltimore) Drainage Basin "Coarse" Plan. (After Metcalf and Eddy et al., 1971a, p. 51)

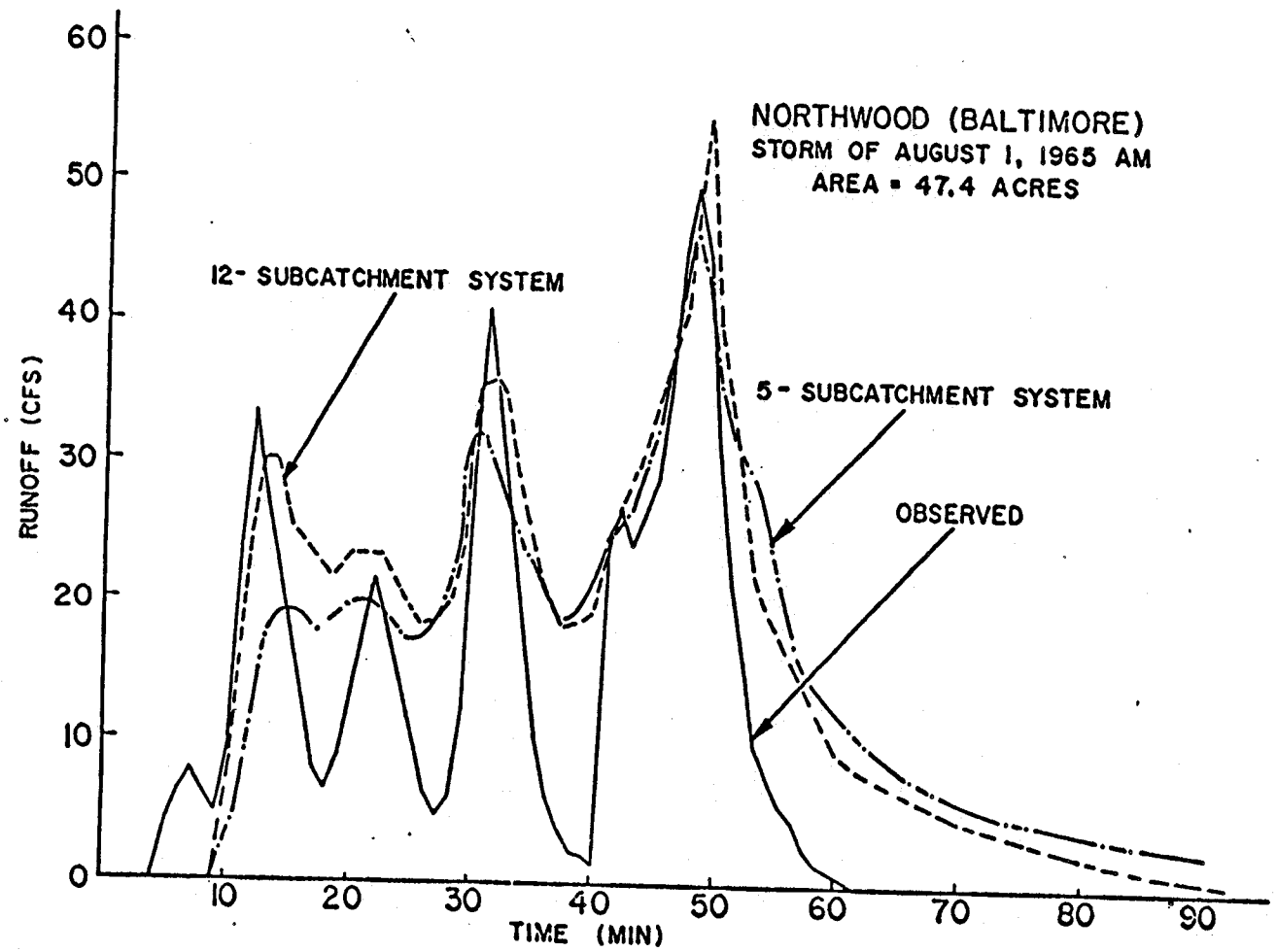


Figure 4-8. Effect of Coarse Subcatchment System, Northwood (Baltimore). (After Metcalf and Eddy et al., 1971a, p. 74)

primary objective is simply to produce a hydrograph and pollutograph at the outlet, utilizing a single raingage, then one subcatchment will often (but not always) serve as well as many.

A final constraint on the amount of detail is dictated by personnel requirements for data reduction. Once data resources (e.g., maps, plans) are gathered, discretization of the catchment can occupy one to three person-days (a longer time for more subcatchments) with perhaps an additional 15 to 30 minutes per subcatchment for their input parameters. Finally, there is not one "right" way to accomplish the discretization, especially since decisions at this stage can be compensated for during the later calibration phase.

Choice of Sewer System Flow Routing --

There are many criteria that influence the choice of the block used for sewer system routing: Runoff, Transport or Extended Transport. Several of these are given in Table 4-3; much more extensive information is contained in this manual and other SWMM documentation (Metcalf and Eddy et al., 1971a; Roesner et al., 1987) pertaining to each block.

Regarding flow routing methods, no backwater effects can be calculated (i.e., in an upstream direction) in the Runoff and Transport Blocks because each conduit element simply provides an inflow to a downstream element with no effect of the latter on the former. Thus, both Runoff and Transport routing act as a "cascade" of elements, each discharging into the next with no other interactions. On the other hand, the solution of the complete St. Venant (gradually varied flow) equations by the Extran Block provides for backwater effects and much more, as indicated in Table 4-3. This is at the cost of considerable extra complexity and computer time.

As a practical matter, the Runoff Block is often used to simulate smaller diameter pipes, e.g., less than 30 in (762 mm) and either the Transport or Extran Blocks for the larger trunk sewer system. The larger the catchment being simulated, the less important becomes the simulation of small conduits, far upstream. Conduits of less than a 12 in (305 mm) diameter are rarely simulated. Also, in spite of the fact that in the Runoff Block, trapezoidal conduits could be used to simulate street gutters, it should almost never be necessary to simulate flow in a roadside curb and gutter channel, unless the catchment is extremely small.

Numbering Schemes --

Subcatchments may be assigned any numbers between 1 and 9999. This is true also for channel/pipes and inlets except that the first number used for printing, and inlet numbers corresponding to Transport Block manholes must be less than or equal to 10,000. Other possible downstream external programs may have their own numbering requirements that should be recognized at this stage. Thus, inflows to such junctions must be numbered accordingly. To be on the safe side, it is often a good idea to reserve relatively low numbers for inlets, etc. that are transferred to subsequent blocks.

Table 4-3. Flow Routing Characteristics of Runoff, Transport and Extended Transport Blocks.

	Runoff Block	Transport Block	Extended Transport Block
1. Flow routing method	Non-linear reservoir, cascade of conduits	Kinematic wave, cascade of conduits	Complete equations, interactive conduit network
2. Relative computational expense for identical network schematizations	Low	Moderate	High
3. Attenuation of hydrograph peaks	Yes	Yes	Yes
4. Time displacement of hydrograph peaks	Weak	Yes	Yes
5. In-conduit storage	Yes	Yes	Yes
6. Backwater or downstream control effects	No	No[a]	Yes
7. Flow reversal	No	No	Yes
8. Surcharge	Weak	Weak	Yes
9. Pressure flow	No	No	Yes
10. Branching tree network	Yes	Yes	Yes
11. Network with looped connections	No	No	Yes
12. Number of pre-programmed conduit shapes	3	16	8
13. Alternative hydraulic elements (e.g., pumps, weirs, regulators)	No	Yes	Yes
14. Dry weather flow and infiltration generation (base flow)	No	Yes	Yes
15. Pollutograph routing	Yes	Yes	No
16. Solids scour/deposition	No	Yes	No
17. Card input of hydrographs/pollutographs	No	Yes	Yes

[a]Backwater may be simulated as a horizontal water surface behind a storage element.

Internally, the Runoff Block assigns subscripts (internal numbers) in the order in which the channel/pipes or subcatchment groups are read in. Some error messages use these numbers. It is not necessary to state specifically the inlets to be transferred to subsequent blocks, since all inlets at the downstream end of any subcatchment-channel/pipe flow routing chain are placed in that category and are printed out.

Within the above confines, considerable latitude exists for numbering schemes. Thus, subcatchments may feed channel/pipes with the same number; subcatchments or channel/pipes may be given numbers in a certain range (e.g., 200-299) based on certain characteristics; etc. The Transport Block numbering scheme allows even more latitude since it includes non-conduits (e.g., manholes).

Channel/Pipe Data (Groups G1 and G2)

Routing and Time Step Considerations --

The non-linear reservoir method of channel/pipe flow routing is described in Appendix V, as well as in the original documentation (Metcalf and Eddy et al., 1971a). Since the formulation produces a spatially "lumped" configuration (i.e., there is no dependence upon longitudinal distance for a given channel/pipe element), flows introduced at the "upstream end" of such an element are distributed horizontally over the entire water surface area. The implication is that a concentrated inflow into one "end" of a simulated channel/pipe is a reasonable approximation to the true situation in which channel/pipes receive distributed inflows along their lengths.

At each time step, an iterative (Newton-Raphson) scheme is used to solve the non-linear difference equation used to approximate the differential equation of the non-linear reservoir. The iterative scheme solves for the new channel/pipe depth based on the inflow, initial volume, and the outflow which is based on Manning's equation. The iteration is performed by Subroutine GUTNR and is globally convergent with no restrictions on time step size. The Newton-Raphson method has quadratic convergence and the number of iterations required in GUTNR is usually less than 3.

Three channel shapes are programmed in Runoff: trapezoidal channels, parabolic channels and circular pipes, as shown in Figure 4-9. This translates to five shapes since trapezoidal channels function as three channel shapes: (1) trapezoidal, (2) triangular, and (3) rectangular. A trapezoidal channel has a bottom width, maximum depth, and two side slopes. A triangular channel has no bottom width, maximum depth, and two side slopes. A rectangular or box channel has a bottom width, maximum depth, and side slopes of zero.

Parabolic channels can be used to approximate "natural channels." Parabolas are often used to characterize the cross sections of small and medium size channels (Chow, 1959). Only a top width (T) and maximum depth (D) are necessary to characterize the symmetric parabolic channel. The equation describing the parabolic channel is:

$$X^2 = k \cdot Y \tag{4-4}$$

where X = horizontal distance from channel center, ft [m],
Y = vertical distance from channel invert, ft [m], and
$k = T^2/(4 \cdot D)$.

Broad crested, narrow crested, V-notch weirs and orifices can be simulated by linking a trapezoidal channel, parabolic channel or circular pipe with an outflow equation. The volume of the channel is based on either a parabolic, trapezoidal or circular cross section. The weir or orifice outflow equation instead of Manning's equation is used in the non-linear convergence scheme. Data group G2 is used to input the control structure parameters. The weir or orifice is not a separate channel but a modification to the outflow of a modeled channel. Sample configurations are shown in Figure 4-10.

The broad and narrow crested weir equation used in Runoff is the standard weir equation:

$$Q = C \cdot L \cdot (h-h_c)^{1.5} \tag{4-5}$$

where Q = outflow, cfs [m^3/sec],
C = weir coefficient, $ft^{1/2}$/sec [$m^{1/2}$/sec],
L = weir length, ft [m],
h = hydraulic head, ft [m], and
h_c = weir crest, ft [m].

The triangular opening of a V-notch weir is assumed to have no upper limit. The equation for V-notched weirs used in Runoff is:

$$Q = C \cdot \tan(a/2) \cdot (h-h_c)^{2.5} \tag{4-6}$$

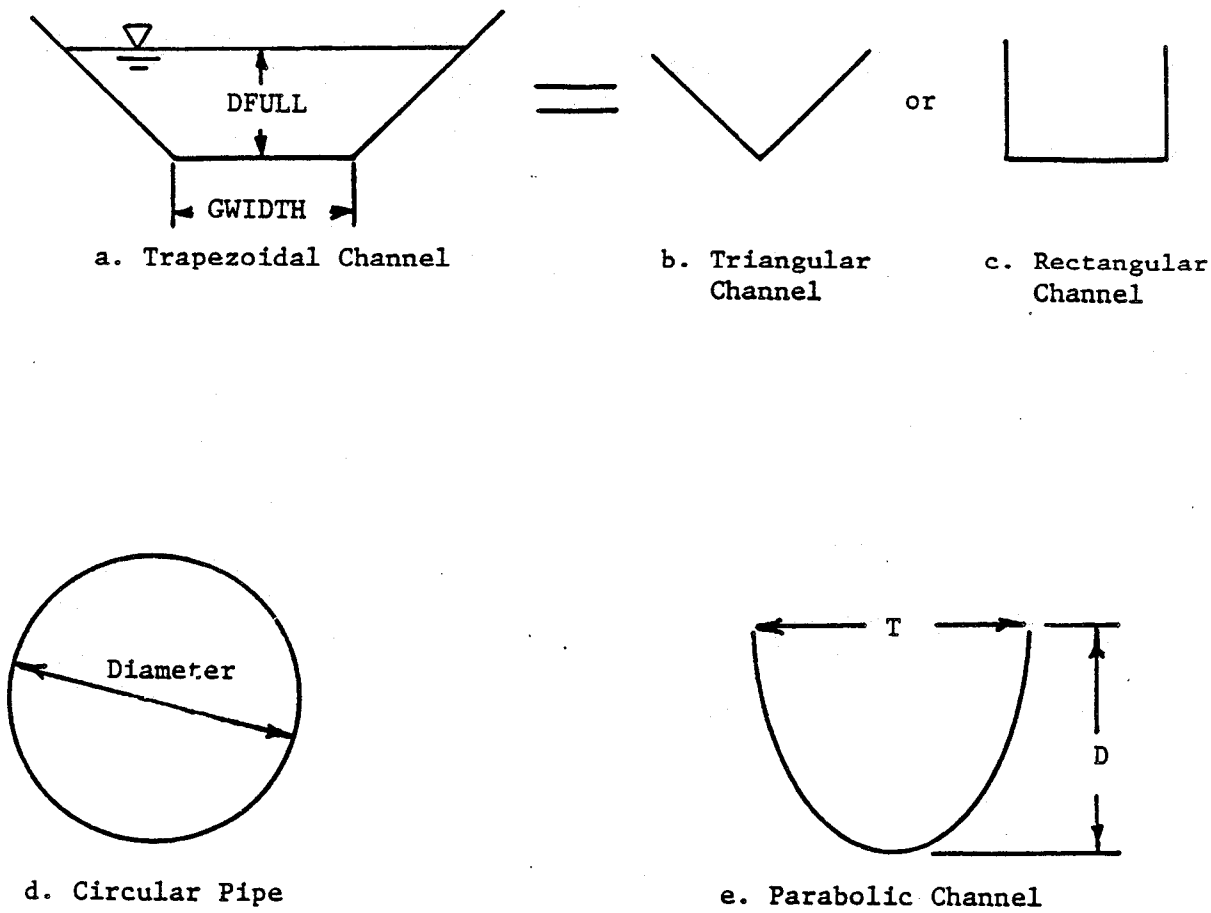
where, Q = outflow, cfs [m^3/sec],
C = weir coefficient, $ft^{1/2}$/sec [$m^{1/2}$/sec],
a = angle of notch (angle of opening), degrees,
h = hydraulic head, ft [m], and
h_c = weir crest (bottom of notch), ft [m].

The orifice is either: (1) a dropout or sump orifice, or (2) a side outlet orifice. A standard orifice equation is used for both types:

$$Q = C_d \cdot A \cdot [2 \cdot g \cdot (h-h_c)]^{0.5} \tag{4-7}$$

where Q = outflow, cfs [m^3/sec],
C_d = orifice discharge coefficient,
A = orifice cross sectional area, ft^2 [m^2],
g = gravitational acceleration = 32.2 ft/sec^2 or 9.8 m/sec^2,
h = hydraulic head above the orifice, ft [m], and
h_c = orifice centerline.

The weir or orifice crest height may be used to store water in a channel or pipe. If groundwater is simulated then the stored channel water affects



a. Trapezoidal Channel

b. Triangular Channel

c. Rectangular Channel

d. Circular Pipe

e. Parabolic Channel

Figure 4-9. Channels and Pipe of the Runoff Block

the groundwater flow via the tailwater flow equation. Trapezoidal and parabolic channels lose water through outflow and evaporation. Pipes lose water only through outflow.

Parameter Selection --

Most channel/pipe parameters are self explanatory and little interpretation is needed. The slope and roughness are combined into one parameter for further use in the program, using Manning's equation. Thus,

$$GCON = \frac{KM}{G6} \cdot G3^{1/2} \tag{4-8}$$

where GCON = routing parameter,
KM = 1.49 for units of feet and seconds and equals 1.0 for units of meters and seconds (not required by program),
G6 = Manning's roughness, n, and
G3 = invert slope.

Thus, equivalent changes in the routing can be made through changes in either the slope or roughness. An equivalent routing parameter is made for weirs and orifices using the weir coefficient and weir length (or notch angle), or the orifice coefficient and orifice cross sectional area.

Note that U.S. customary units (ft-sec) are used internally in the Runoff Block. When metric units are requested, input and output are converted to and from U.S. customary units to preserve ft-sec units internally. This scheme is also used in the Transport Block. However, metric calculations in the Extran and Storage/Treatment Blocks are used consistently throughout the program, when requested.

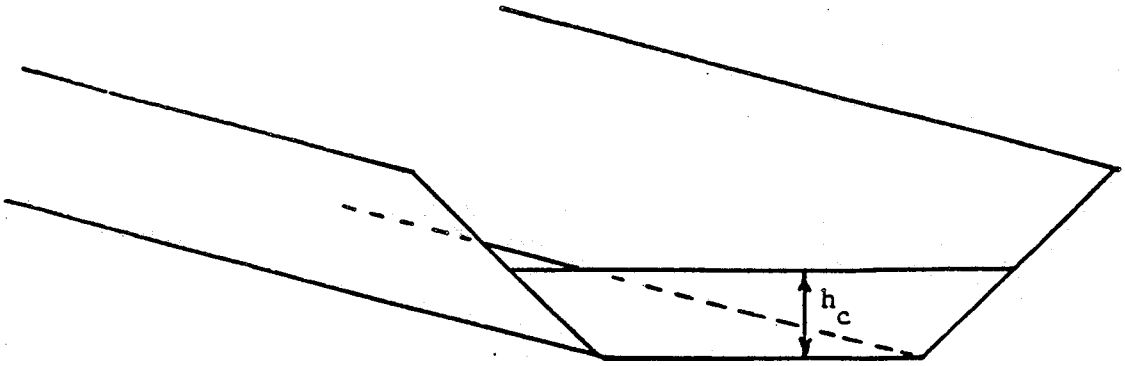
The invert slope is usually given on drainage maps or may easily be calculated from invert elevations and conduit lengths. Tables of Manning's roughness coefficient are given in many references; see for instance Chow (1959) or ASCE-WPCF (1969).

Subcatchment Surface Data (Group H1)

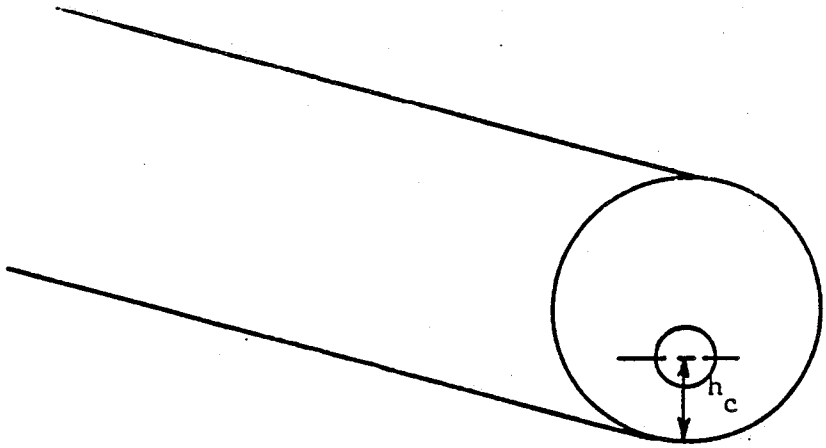
Subcatchment Schematization --

Many hydrologic models account for spatial variations by subdividing the overall catchment into subcatchments, predicting runoff from the subcatchments on the basis of their individual properties, and combining their outflows using a flow routing scheme. This procedure is followed in SWMM, in which subcatchments are idealized mathematically as spatially lumped, non-linear reservoirs, and their outflows are routed via the channel/pipe (or a subsequent Transport Block) network.

Each subcatchment is schematized as in Figure 4-11, in which three or four subareas (depending on whether snowmelt is simulated) are used to represent different surface properties as enumerated in Table 4-4. The slope of the idealized subcatchment is in the direction perpendicular to the width.



a. Trapezoidal channel with weir



b. Circular pipe with orifice

Figure 4-10. Example Weir and Orifice Configurations.

Flow from each subarea moves directly to a gutter/pipe or inlet and does not pass over any other subarea. (Thus, it is not possible to route runoff from roofs over lawn surfaces, for instance).

Table 4-4. Subcatchment Surface Classification

Subarea	Perviousness	Depression Storage	Snow Cover and Extent: Single Event	Snow Cover and Extent: Continuous
A1	Impervious	Yes	Bare	Normally bare, but may have snow cover over 100% of Subarea A1 plus Subarea A3.
A2	Pervious	Yes	Constant fraction, SNCP, of area is snow covered.	Snow covered subject to areal depletion curve.
A3	Impervious	No	Bare	Same as Subarea A1
A4	Impervious	Yes	100% covered.	Snow covered subject to areal depletion curve.

The width of the pervious subarea, A2, is the entire subcatchment width, whereas the widths of the impervious subareas, A1, A3, A4, are in proportion to the ratio of their area to the total impervious area, as implied in Figure 4-11. Specification of each subarea is through the use of parameters WAREA and WW(3) in Group H1, PCTZER in group B4 and SNN1 in group I1. If desired, any subcatchment may consist entirely of any one (or more) types of subareas.

Of course, real subcatchments seldom exhibit the uniform rectangular geometries shown in Figure 4-11. In terms of the flow routing, all geometrical properties are merely parameters (as explained below) and no inherent "shape" can be assumed in the non-linear reservoir technique. However, in terms of parameter selection, the conceptual geometry of Figure 4-11 is useful because it aids in explaining the flow routing.

Routing and Time Step Considerations --

The routing and time step discussion given earlier for channel/pipes applies almost identically for subcatchments. A detailed explanation of the non-linear reservoir equations is given in Appendix V. The routing is performed separately for each of the three of four subareas of the subcatchment. Convergence problems are rarely encountered during subcatchment routing because total subcatchment volumes (area times depth) are usually large compared to outflow volumes.

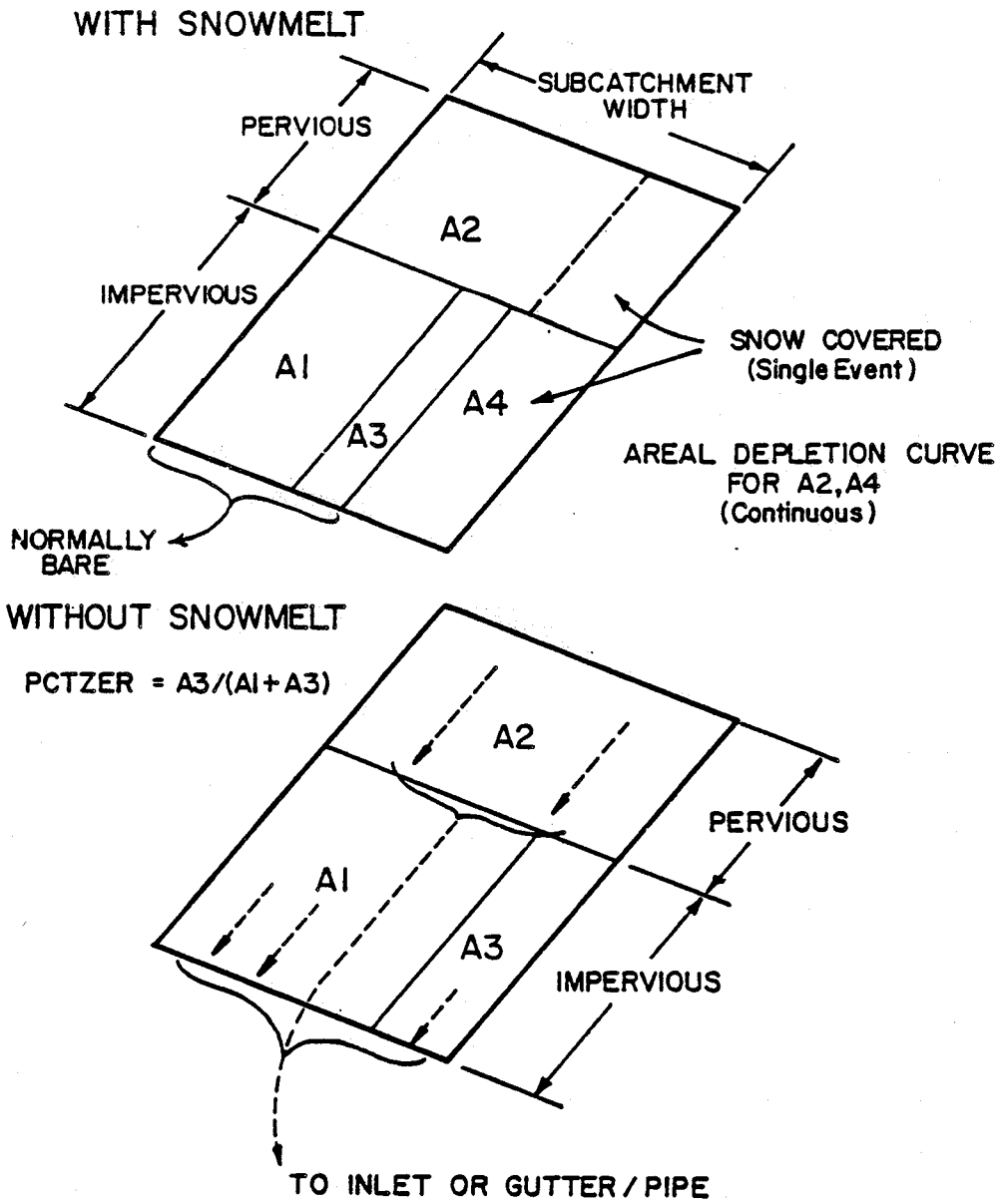


Figure 4-11. Subcatchment Schematization. Flows from pervious and total impervious subareas go directly to gutter/pipe or inlet. (E.g., flow from the pervious subarea does not travel over impervious area.)

Parameter selection is aided with reference to Figure 4-12 in which the subcatchment "reservoir" is shown in relation to inflows and outflows (or losses). The outflow to channel/pipes and inlets is computed as the product of velocity (from Manning's equation based on the difference between total depth and depression storage), depth and width,

is used for calibration

$$Q = W \frac{1.49}{n} (d - d_p)^{5/3} S^{1/2} \qquad (4\text{-}9)$$

where Q = WFLOW = subcatchment (or subarea) outflow, cfs,
W = WW(1) = subcatchment width, ft,
n = WW(5) or WW(6) = Manning's roughness coefficient,
d = WDEPTH = water depth, ft,
d_p = WSTORE = depth of depression (retention) storage, ft, and
S = WSLOPE = slope, ft/ft.

The FORTRAN parameters listed above are the Runoff Block parameters. When combined with the continuity equation (see Appendix V) and divided by the surface area, a new routing parameter is defined for the pervious and total impervious subcatchment areas and used in all subsequent calculations,

$$WCON = \frac{1.49\ W}{A\ n} S^{1/2} \qquad (4\text{-}10)$$

where WCON = routing parameter used in subroutine WSHED, ft-sec units, and
A = surface area of pervious or total impervious subarea, ft^2.

Note that the width, slope and roughness parameters are combined into one parameter. Thus, equivalent changes may be caused by appropriate alteration of any of the three parameters. Note also that the width and slope are the same for both pervious and impervious areas. Manning's roughness and relative area are the only parameters available to the modeler to characterize the relative contributions of pervious and impervious areas to the outlet hydrograph. (However, see further comments below on the subcatchment width.) Flows computed in the Runoff Block and transferred to subsequent blocks are instantaneous values at the end of a time step.

Subcatchment Width --

If overland flow is visualized (Figure 4-11) as running down-slope off an idealized, rectangular catchment, then the width of the subcatchment (data group H1) is the physical width of overland flow. This may be further seen in Figure 4-13 in which the lateral flow per unit width, q_L, is computed and multiplied by the width to obtain the total inflow into the channel. (As mentioned previously, the SWMM channel/pipes can only receive a concentrated inflow, however, and do not receive a distributed inflow in a specific fashion.) Note also in Figure 4-13 that for this idealized case, if the two sides of the subcatchment are symmetrical the total width is twice the length of the drainage channel.

Since real subcatchments will not be rectangular with properties of symmetry and uniformity, it is necessary to adopt other procedures to obtain the

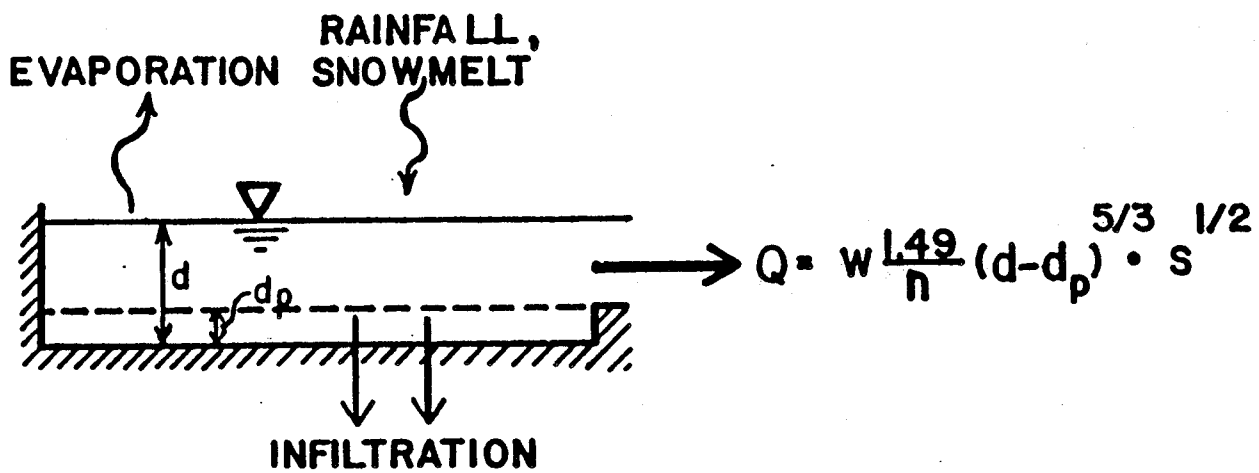
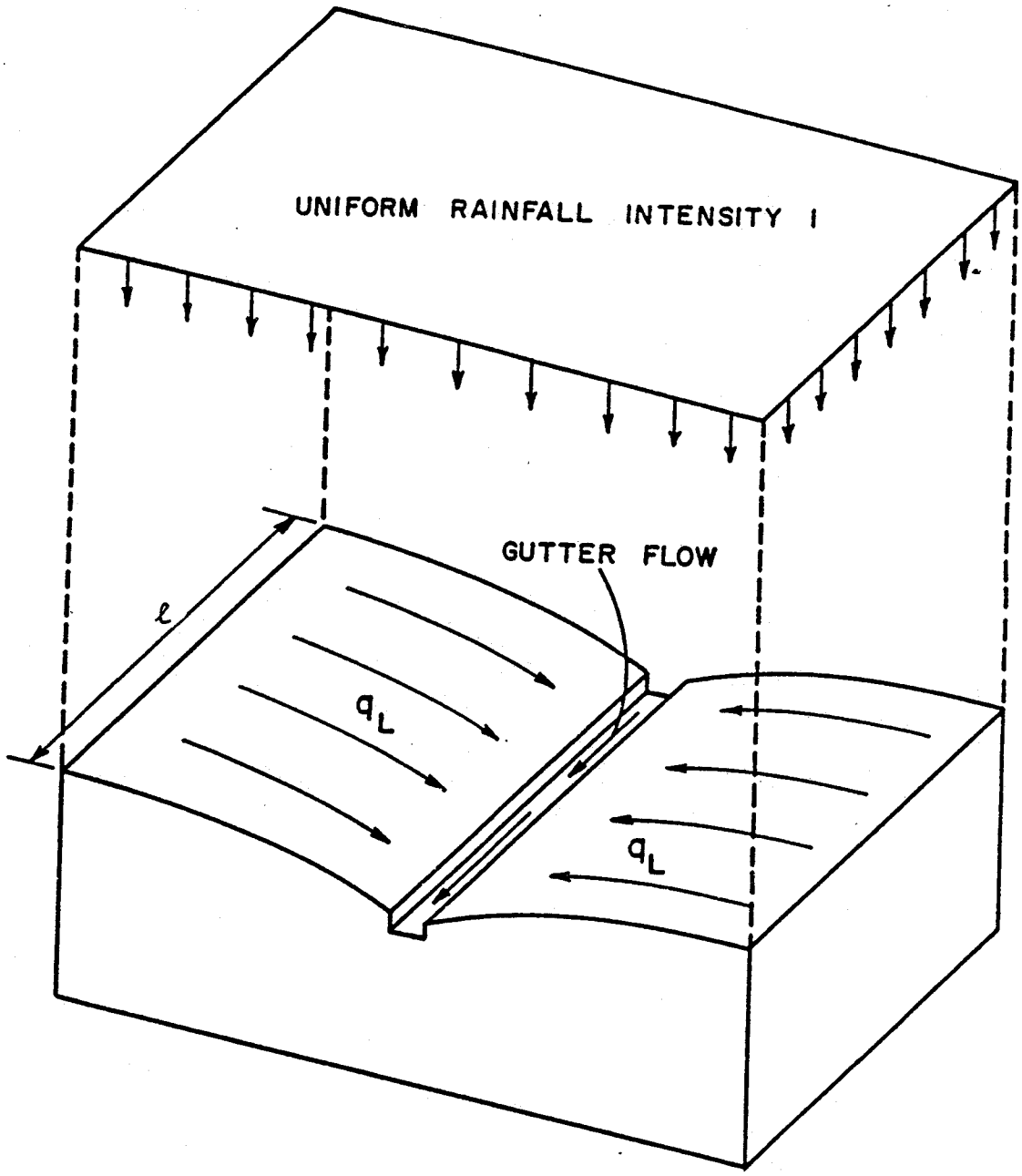


Figure 4-12. Non-linear Reservoir Representation of Subcatchment.



q_L = RATE OF OVERLAND FLOW/UNIT WIDTH.

W = 2ℓ = TOTAL WIDTH OF OVERLAND FLOW

Figure 4-13. Idealized Subcatchment-Gutter Arrangement Illustrating the Subcatchment Width.

width for more general cases. This is of special importance, because if the slope and roughness are fixed (see equation 4-10), the width can be used to alter the hydrograph shape.

For example, consider the five different subcatchment shapes shown on Figure 4-14. Catchment hydraulic properties, routing parameters and time of concentration are also given. The latter is calculated using the kinematic wave formulation (Eagleson, 1970, p. 340),

$$t_c = \left[\frac{L}{a\ i^{*m-1}}\right]^{1/m} \tag{4-11}$$

where t_c = time of concentration, sec,
L = subcatchment length ,ft,
i^* = rainfall excess (rainfall minus losses), ft/sec, and
a,m = kinematic wave parameters.

The kinematic wave formulation assumes that the runoff per unit width (velocity times depth) from the subcatchment is

$$q_L = a\ d^m \tag{4-12}$$

where q_L = flow per unit width, ft^2/sec, and
d = depth of flow, ft.

Parameters a and m depend upon the uniform flow equation used for normal flow. For Manning's equation,

$$a = (1.49/n) \cdot S^{1/2} \tag{4-13}$$

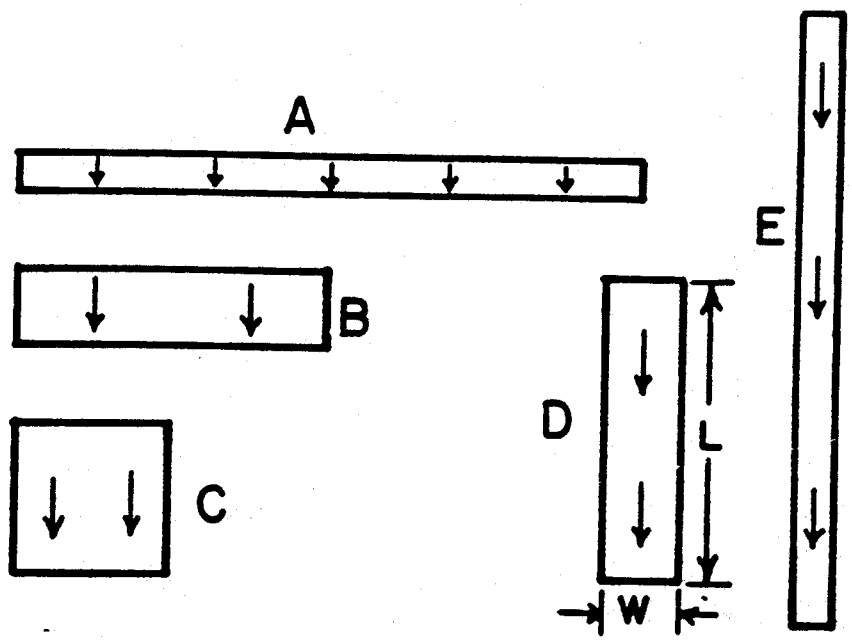
and

$$m = 5/3 \tag{4-14}$$

Note that the units of a depend upon the value of m, and for Manning's equation, feet-second units should be used for all calculations. The subcatchment length may be computed for the assumed rectangular shape simply by dividing the area by the width.

Finally, note the dependence of time of concentration upon the rainfall intensity. As i^* increases, t_c decreases. The calculation using equation 4-11 is consistent with the definition of t_c given earlier: t_c is the time to equilibrium, at which inflow equals outflow (for an impervious catchment). Equivalently, t_c is the time taken for the most remote portion of the catchment to contribute to flow at the outlet, which is the time taken by a wave (not a parcel of water) to travel from the remote point to the outlet.

Outflow hydrographs for continuous rainfall and for rainfall of duration 20 min are shown on Figure 4-15. These were computed by the Runoff Block nonlinear reservoir equations (Appendix V) using a time step of 5 min. Clearly, as the subcatchment width is narrowed (i.e., the outlet is constricted), the time to equilibrium increases. Thus, it is achieved quite rapidly for cases A and B and more slowly for cases C, D and E. The kinematic wave computation of



Slope = 0.01
Imperviousness = 100%
Depression Storage = 0
n = 0.02
Equilibrium outflow = i*A = 0.926 cfs

DELT = 5 min = 300 sec

i* = Rainfall = 1.0 in/hr = 0.000023148 ft/sec

Shape	A (ft^2)	W (ft)	L (ft)	t_c[a] (min)	WCON[b] (ft-sec units)
A	40,000	800	50	3.7	-0.149
B	40,000	400	100	5.7	-0.0745
C	40,000	200	200	8.6	-0.03725
D	40,000	100	400	13.0	-0.018625
E	40,000	50	800	19.7	-0.0093125

[a]Equation 4-7

[b]Equation 4-6

Figure 4-14. Different Subcatchment Shapes to Illustrate Effect of Subcatchment Width.

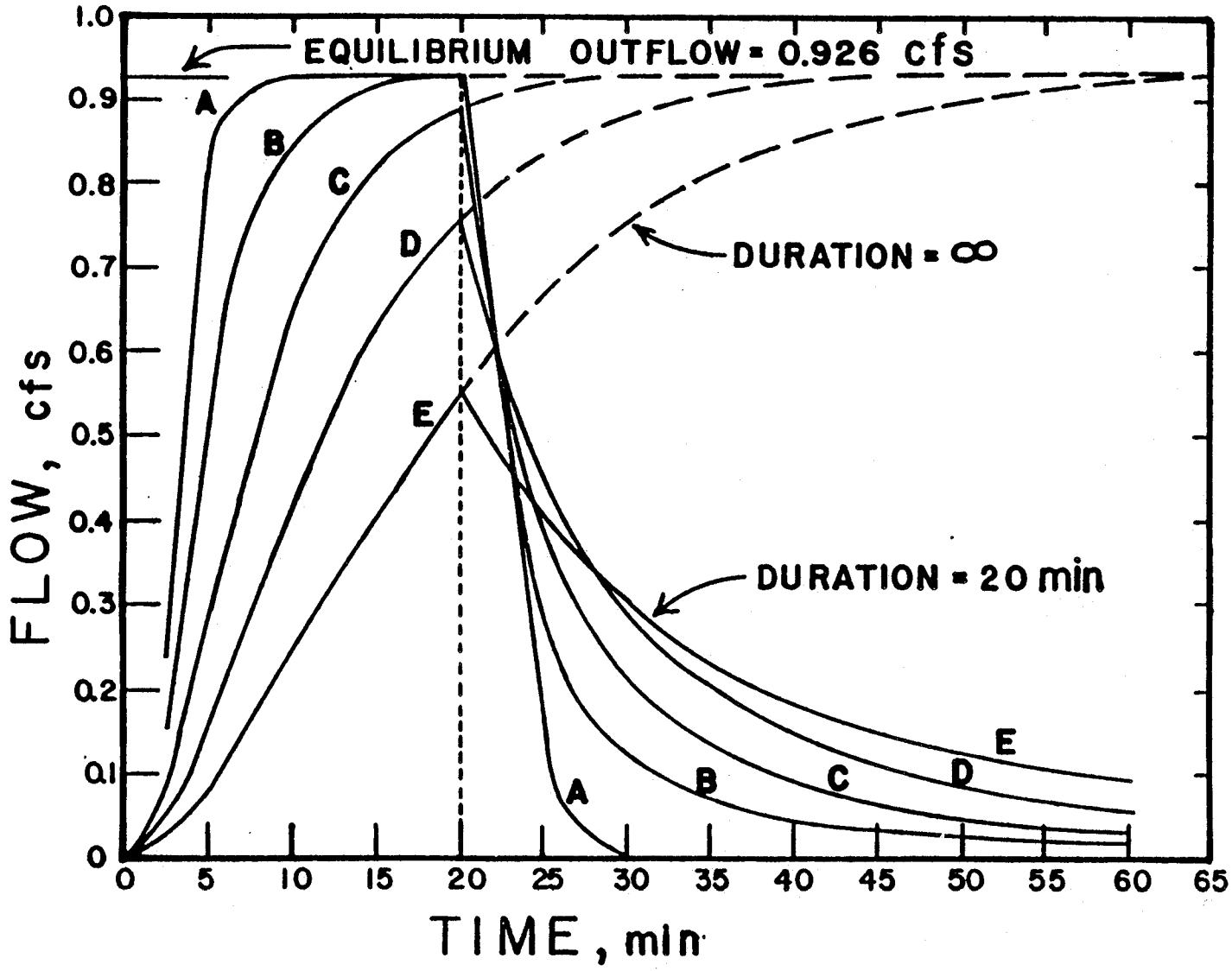


Figure 4-15. Subcatchment Hydrographs for Different Shapes of Figure 4-14.

t_c (Figure 4-14) is not particularly accurate for the non-linear reservoirs for which the asymptotic value of equilibrium outflow is approached exponentially. However, it may be used for guidance.

Two routing effects may be observed. A storage effect is very noticeable, especially when comparing hydrographs A and E for a duration of 20 min. The subcatchment thus behaves in the familiar manner of a reservoir. For case E, the outflow is constricted (narrow); hence, for the same amount of inflow (rainfall) more water is stored and less released. For case A, on the other hand, water is released rapidly and little is stored. Thus case A has both the fastest rising and recession limbs of the hydrographs.

A shape effect is also evident. Theoretically, all the hydrographs peak simultaneously (at the cessation of rainfall). However, a large width (e.g., case A) will cause equilibrium outflow to be achieved rapidly, producing a flat-topped hydrograph for the remainder of the (constant) rainfall. Thus, for a catchment schematized with several subcatchments and subject to variable rainfall, increasing the widths tends to cause peak flows to occur sooner. In general, however, shifting hydrograph peaks in time is difficult to achieve through adjustment of Runoff Block flow routing parameters. The time distribution of runoff is far and away the most sensitive to the time distribution of rainfall. Further discussion of the effect of subcatchment width on hydrograph shapes will be given below under "Subcatchment Aggregation and Lumping".

What is the best estimate of subcatchment width? If the subcatchment has the appearance of Figure 4-13, then the width is approximately twice the length of the main drainage channel through the catchment. However, if the drainage channel is on the side of the catchment as in Figure 4-14, the width is just equal to the length of the channel. A good estimate for the width can be obtained by first determining the maximum length of overland flow and dividing the area by this length.

Most real subcatchments will be irregular in shape and have a drainage channel which is off center, as in Figure 4-16. This is especially true of rural or undeveloped catchments. A simple way of handling this case is given by DiGiano et al. (1977). A skew factor is computed,

$$S_k = (A_2 - A_1)/A \tag{4-15}$$

where S_k = skew factor, $0 \leq S_k \leq 1$,
A_1 = area to one side of channel,
A_2 = area to other side of channel, and
A = total area.

The width is simply weighted between the two limits of l and $2l$ as

$$W = (2 - S_k) \cdot l \tag{4-16}$$

where W = subcatchment width, and
l = length of main drainage channel.

To reiterate, changing the subcatchment width changes the routing parame-

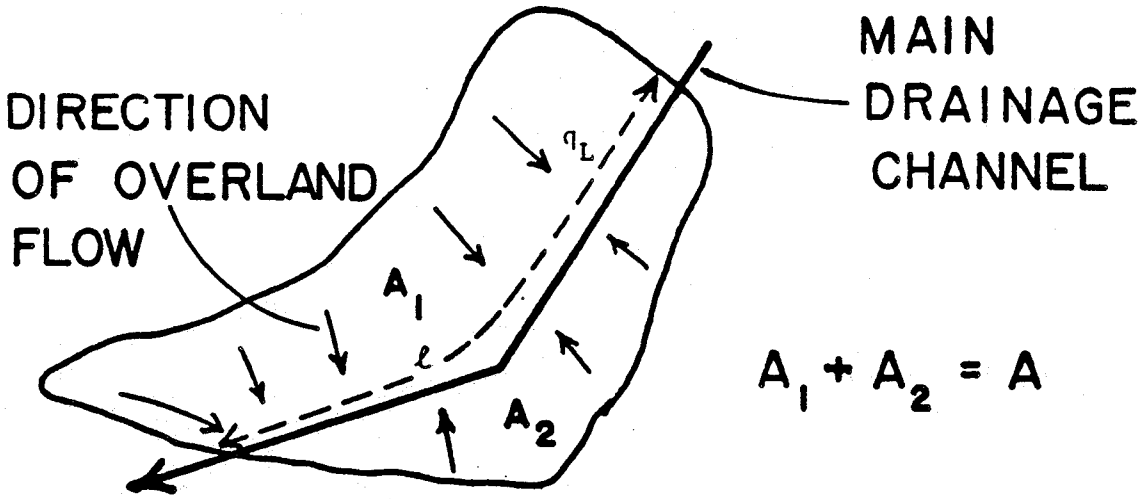


Figure 4-16. Irregular Subcatchment Shape for Width Calculation. (After DiGiano et al., 1977, p. 165.)

ter WCON of equation 4-10. Thus, identical effects to those discussed above may be created by appropriate variation of the roughness and/or slope.

Subcatchment Area --

In principle, the catchment and subcatchment area can be defined by constructing drainage divides on topographic maps. In practice, this may or may not be easy because of the lack of detailed contour information and the presence of unknown inflows and outflows. This may be most noticeably brought to the modeler's attention when the measured runoff volume exceeds the measured rainfall volume, if the latter is correct. Actually storm rainfall is seldom accurately measured over all subcatchments.

From the modeling standpoint, there are no upper or lower bounds on subcatchment area (other than to avoid convergence problems, as discussed earlier). Subcatchments are usually chosen to coincide with different land uses, with drainage divides, and to ease parameter estimation, i.e. homogeneous slopes, soils, etc. Further guidance is given later under subcatchment aggregation.

Imperviousness --

The percent imperviousness of a subcatchment is another parameter that can, in principle, be measured accurately from aerial photos or land use maps. In practice, such work tends to be tedious, and it is common to make careful measurements for only a few representative areas and extrapolate to the rest.

Care must be taken to ensure that impervious areas are hydraulically (directly) connected to the drainage system. For instance, if rooftops drain onto adjacent pervious areas, they should not be treated as a hydraulically effective impervious area in the Runoff Block. Such areas are noneffective impervious areas (Doyle and Miller, 1980). On the other hand, if a driveway drains to a street and thence to a stormwater inlet, the driveway would be considered to be hydraulically connected. Rooftops with downspouts connected directly to a sewer are definitely hydraulically connected.

Should rooftops be treated as "pervious," the real surrounding pervious area is subject to more incoming water than rainfall alone and thus might produce runoff sooner than if rainfall alone were considered. In the unlikely event that this effect is important (a judgment based on infiltration parameters) it could be modeled by altering the infiltration parameters or by treating such pervious areas as separate subcatchments, and increasing their rainfall by the ratio of roof area plus pervious to pervious alone. Since the roof areas would then not be simulated, continuity would be maintained.

Another method of estimating the effective impervious area given measured data is to plot the runoff (in. or mm) vs. rainfall (in. or mm) for small storms. The slope of the regression line is a good estimate of the effective impervious area (Doyle and Miller, 1980). Further information on the concept of hydraulically connected (or "hydraulically effective") impervious areas is contained in USGS studies (Jennings and Doyle, 1978) and documentation of the ILLUDAS model (Terstriep and Stall, 1974).

For continuous simulation in which very large subcatchments are being used, even spot calculations of imperviousness may be impractical. Instead, regression formulations have been developed in several studies (Graham et al., 1974; Stankowski, 1974; Manning et al., 1977; Sullivan et al., 1978). These typically relate percent imperviousness to population density, and are compared in Figure 4-17 (Heaney et al., 1977). The New Jersey equation (Stankowski, 1974) is perhaps the most representative:

$$I = 9.6\ PD_d^{(0.53\ -\ 0.0391\ \log10\ PDd)} \qquad (4\text{-}16)$$

where I = WW(3) = imperviousness, percent, and
PD_d = population density in developed portion of the urbanized area, person per acre.

The "developed portion" excludes large segments of undeveloped (i.e., natural or agricultural) lands that may lie within the area being simulated. Also note that the relationships shown in Figure 4-17 were all developed for large (city-wide) urban areas as a whole. Their use may be tenuous for smaller subbasins.

Slope --

The subcatchment slope should reflect the average along the pathway of overland flow to inlet locations. For a simple geometry (e.g., Figures 4-13 and 4-14) the calculation is simply the elevation difference divided by the length of flow. For more complex geometries, several overland flow pathways may be delineated, their slopes determined, and a weighted slope computed using a path-length weighted average. Such a procedure is described by DiGiano et al., 1977, pp. 101-102). Alternatively it may be sufficient to simulate what the user considers to be the hydrologically dominant slope for the conditions being simulated. Choose the appropriate overland flow length, slope, and roughness for this equivalent plane.

Manning's Roughness Coefficient, n --

Values of Manning's roughness coefficient, n, are not as well known for overland flow as for channel flow because of the considerable variability in ground cover for the former, transitions between laminar and turbulent flow, very small depths, etc. Most studies indicate that for a given surface cover, n varies inversely in proportion to depth, discharge or Reynold's number. Such studies may be consulted for guidance (e.g., Petryk and Bosmajian, 1975; Chen, 1976; Christensen, 1976; Graf and Chun, 1976; Turner et al., 1978; Emmett, 1978), or generalized values used (e.g., Chow, 1959; Crawford and Linsley, 1966; Huggins and Burney, 1982; Engman, 1986). Roughness values used in the Stanford Watershed Model (Crawford and Linsley, 1966) are given in Table 4-5 along with more recent values from Engman (1986). Engman also provides values for other agricultural land uses and a good literature review.

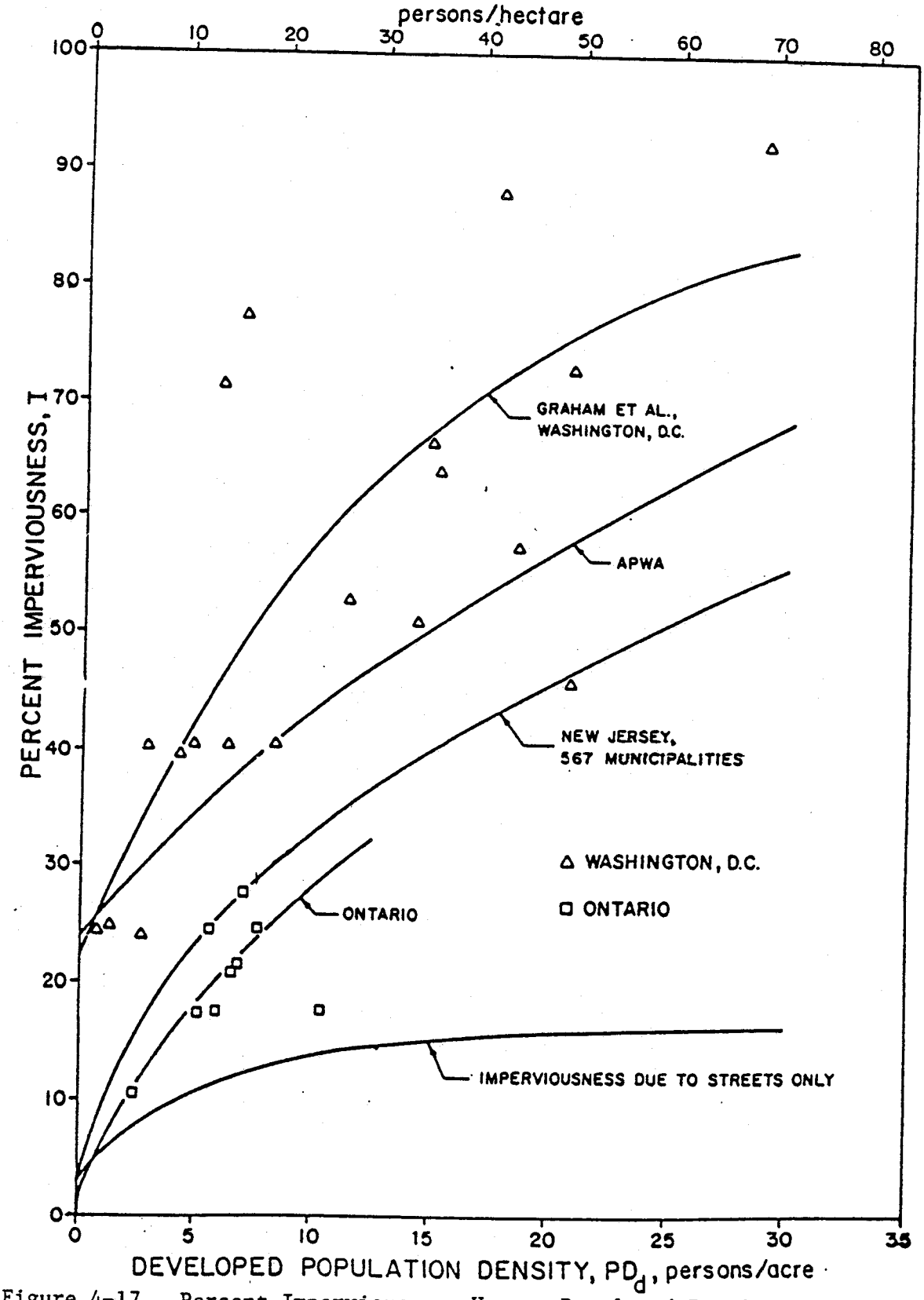


Figure 4-17. Percent Imperviousness Versus Developed Population Density for Large Urban Areas. (After Heaney, et al., 1977, p. 105)

Table 4-5. Estimates of Manning's Roughness Coefficients for Overland Flow

Source	Ground Cover	n	Range
Crawford and Linsley (1966)[a]	Smooth Asphalt	0.012	
	Asphalt of concrete paving	0.014	
	Packed clay	0.03	
	Light turf	0.20	
	Dense turf	0.35	
	Dense shrubbery and forest litter	0.4	
Engman (1986)[b]	Concrete or asphalt	0.011	0.01-0.013
	Bare sand	0.01	0.01-0.016
	Graveled surface	0.02	0.012-0.03
	Bare clay-loam (eroded)	0.02	0.012-0.033
	Range (natural)	0.13	0.01-0.32
	Bluegrass sod	0.45	0.39-0.63
	Short grass prairie	0.15	0.10-0.20
	Bermuda grass	0.41	0.30-0.48

[a]Obtained by calibration of Stanford Watershed Model.
[b]Computed by Engman (1986) by kinematic wave and storage analysis of measured rainfall-runoff data.

Depression Storage --

Depression (retention) storage is a volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas (see Figure 4-12); a good discussion is presented by Viessman et al. (1977). It represents a loss or "initial abstraction" caused by such phenomena as surface ponding, surface wetting, interception and evaporation. In some models, "depression storage" also includes infiltration in pervious areas. In the Runoff Block, water stored as depression storage on pervious areas is subject to infiltration (and evaporation), so that it is continuously and rapidly replenished. Water stored in depression storage on impervious areas is depleted only by evaporation. Hence, replenishment typically takes much longer.

As described earlier (e.g., Table 4-4), a percent "PCTZER" (data group B4) of the impervious area is assigned zero depression storage in order to promote immediate runoff. This percentage is the same for all subcatchments. Should variation among subcatchments be desired, PCTZER may be set to zero, and zero values for WSTORE entered in data group H1 as needed.

Depression storage may be derived from rainfall runoff data for impervious areas by plotting runoff volume (depth) as the ordinate against rainfall volume as the abscissa for several storms. The rainfall intercept at zero runoff is the depression storage. Data obtained in this manner from 18 urban European catchments (Falk and Niemczynowicz, 1978, Kidd, 1978a, Van den Berg, 1978) are summarized in Table 4-6. The very small catchments (e.g., less

Table 4-6 Recent European Depression Storage Data (Kidd, 1978b)

Catchment Name	Country	Area (ac)	Paved Area (ac)	Imperviousness (%)	Slope (%)	Depression Storage (in)	No. of Events	Reference
Lelystad Housing Area	Netherlands	4.94	2.17	44	0.5	0.059	10	Van den Berg, 1978
Lelystad Parking Lot[a]	Netherlands	1.73	1.73	100	0.5	0.035	10	"
Ennerdale Two	U.K.	0.088	0.079	89	3.1	0.020	6	Kidd, 1978a
Ennerdale Three	U.K.	0.022	0.022	100	3.0	0.016	9	"
Bishopdale Two	U.K.	0.146	0.111	76	2.4	0.018	11	"
Hyde Green One	U.K.	0.120	0.085	71	2.2	0.019	7	"
Hyde Green Two	U.K.	0.209	0.103	49	2.0	0.020	8	"
School Close One	U.K.	0.113	0.070	62	1.7	0.009	11	"
School Close Two	U.K.	0.177	0.097	55	0.9	0.026	11	"
Lund 1:75	Sweden	0.072	0.072	100	2.1	0.005	11	Falk and Niemczynowicz, 1978
Klostergarden 1:76	Sweden	0.081	0.081	100	0.9	0.041	11	"
Klostergarden 1:77	Sweden	0.083	0.083	100	2.3	0.020	13	"
Klostergarden 2:76	Sweden	0.020	0.020	100	3.3	0.019	11	"
Klostergarden 2:77	Sweden	0.019	0.019	100	4.1	0.013	12	"
Klostergarden 3:76	Sweden	0.076	0.076	100	3.1	0.022	11	"
Klostergarden 3:77	Sweden	0.102	0.102	100	2.3	0.022	13	"
Klostergarden 4:76	Sweden	0.068	0.068	100	1.6	0.020	10	"
Klostergarden 4:77	Sweden	0.069	0.069	100	1.9	0.022	13	"

[a]55% brick pavement. Other catchments have primarily asphalt pavement.

than 1 ac or 0.40 ha) were primarily roadway tributaries to stormwater inlets and catchbasins.

The data were aggregated and a regression of depression storage versus slope performed as part of a workshop (Kidd, 1978b). The data are plotted in Figure 4-18 along with the relationship developed by the workshop ,

$$d_p = 0.0303 \cdot S^{-0.49} , \quad (r = -0.85) \qquad (4\text{-}17)$$

where d_p = WSTORE = depression storage, in, and
S = WSLOPE = catchment slope, percent.

Viessman et al. (1977, p. 69) illustrate a similar but linear plot, a portion of which is shown in Figure 4-18, in which depression storage values for "four small impervious areas" near Baltimore, Maryland range from 0.06 to 0.11 in (1.5 to 2.8 mm), considerably higher than the European values shown in Figure 4-18. The reason for this discrepancy is not known, but it appears that the recent European data may be better suited to provide depression storage estimates, mainly because of their extent.

Separate values of depression storage for pervious and impervious areas are required for input in data group H1. Representative values for the latter can probably be obtained from the European data just discussed. Pervious area measurements are lacking; most reported values are derived from successful simulation of measured runoff hydrographs. Although pervious area values are expected to exceed those for impervious areas, it must be remembered that the infiltration loss, often included as an initial abstraction in simpler models, is computed explicitly in SWMM. Hence, pervious area depression storage might best be represented as an interception loss, based on the type of surface vegetation. Many interception estimates are available for natural and agricultural areas (Viessman et al., 1977, Linsley et al., 1949). For grassed urban surfaces a value of 0.10 in (2.5 mm) may be appropriate.

As mentioned earlier, several studies have determined depression storage values in order to achieve successful modeling results. For instance, Hicks (1944) in Los Angeles used values of 0.20, 0.15 and 0.10 in (5.1, 3.8, 2.5 mm) for sand, loam and clay soils, respectively, in the urban area. Tholin and Keifer (1960) used values of 0.25 and 0.0625 in (6.4 and 1.6 mm) for pervious and impervious areas, respectively, for their Chicago hydrograph method. Brater (1968) found a value of 0.2 in (5.1 mm) for three basins in metropolitan Detroit. Miller and Viessman (1972) give an initial abstraction (depression storage) of between 0.10 and 0.15 in (2.5 and 3.8 mm) for four composite urban catchments.

In SWMM, depression storage may be treated as a calibration parameter, particularly to adjust runoff volumes. If so, extensive preliminary work to obtain an accurate <u>a priori</u> value may be pointless since the value will be changed during calibration anyway.

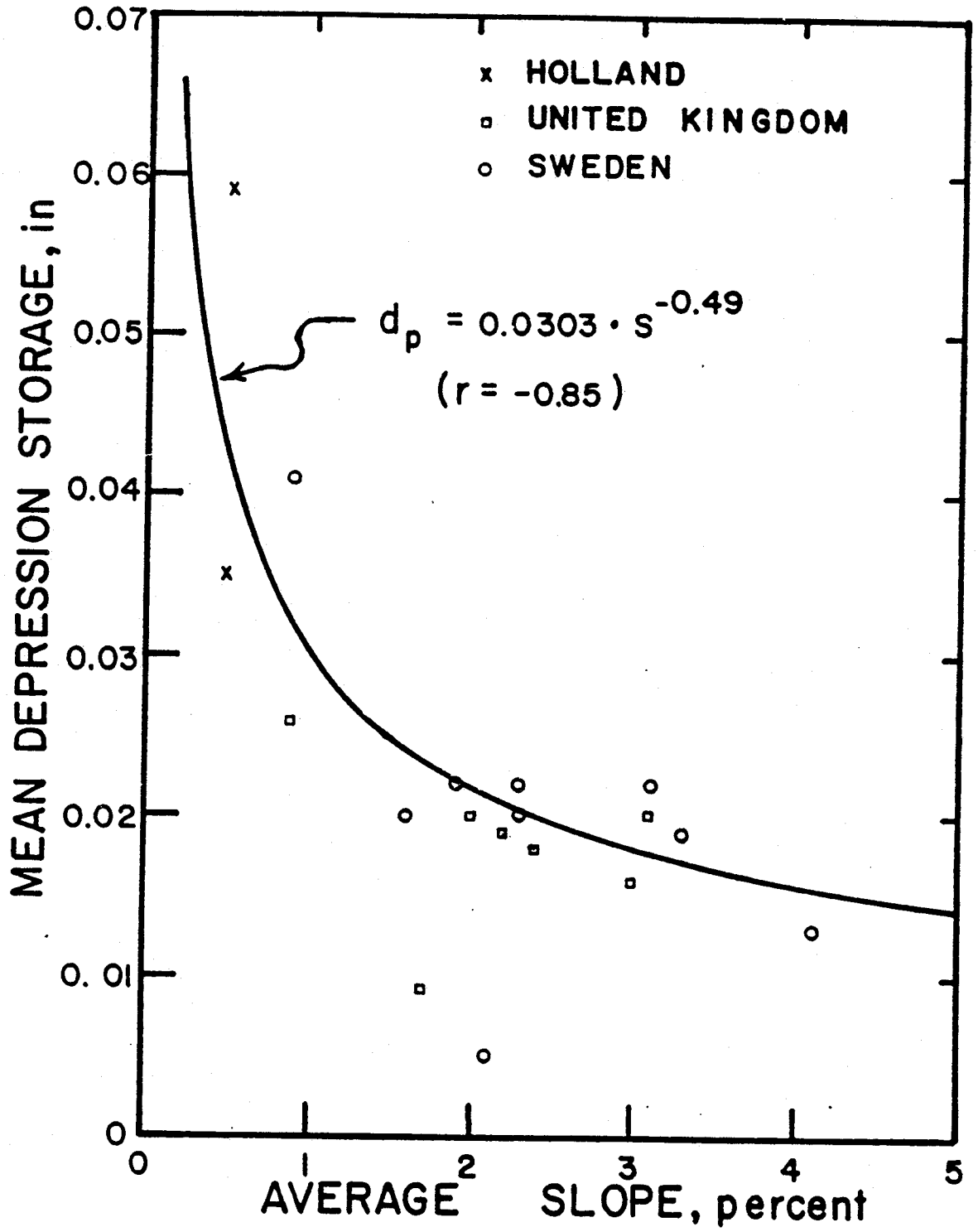


Figure 4-18. Depression Storage vs. Catchment Slope (after Kidd, 1978b). See Table 4-6 for catchment data.

Infiltration* --

Options--Infiltration from pervious areas may be computed by either the Horton (1933, 1940) or Green-Ampt (1911) equations described below. A complete description of the theoretical background and programming details for both is given in Appendix V. In SWMM, the method to be used for all subcatchments is determined by the input parameter INFILM (group B1). Parameters required by the two methods are quite different.

Horton Infiltration--Infiltration capacity as a function of time is given by Horton (1933, 1940) as

$$f_p = f_c + (f_o - f_c)\, e^{-kt} \qquad (4\text{-}18)$$

where f_p = infiltration capacity into soil, ft/sec,
f_c = minimum or ultimate value of f_p (WLMIN, ft/sec,
f_o = maximum or initial value of f_p (WLMAX), ft/sec,
t = time from beginning of storm, sec, and
k = decay coefficient (DECAY), sec^{-1}.

This equation describes the familiar exponential decay of infiltration capacity evident during heavy storms. However, the program does not use equation 4-18 directly; rather, the integrated form is used in order to avoid an unwarranted reduction in f_p during periods of light rainfall. Details are given in Appendix V.

Required parameters for data group H1 are f_o (WLMAX), f_c (WLMIN) and k (DECAY). In addition a parameter used to regenerate infiltration capacity (REGEN, group B2) is required for continuous simulation. Although the Horton infiltration equation is probably the best-known of the several infiltration equations available, there is little to help the user select values of parameters f_o and k for a particular application, (fortunately, some guidance can be found for the value of f_c). Since the actual values of f_o and k (and often f_m) depend on the soil, vegetation, and initial moisture content, ideally these parameters should be estimated using results from field infiltrometer tests for a number of sites of the watershed and for a number of antecedent wetness conditions. If it is not possible to use field data to find estimates of f_o, f_c, k and for each subcatchment, the following guidelines should be helpful.

The U.S. Soil Conservation Service (SCS) has classified most soils into Hydrologic Soil Groups, A, B, C, and D, dependent on their limiting infiltration capacities, f_c. (Well drained, sandy soils are "A"; poorly drained, clayey soils are "D.") A listing of the groupings for more than 4000 soil types can be found in the SCS Hydrology Handbook (1972, pp. 7.6-7.26); a similar listing is also given in the Handbook of Applied Hydrology (Ogrosky and Mockus, 1964, pp. 21.12-21.25), but the former reference also gives alternative groupings for some soil types depending on the degree of drainage of the subsoil. The soil type itself may be found in the U.S. from county SCS Soil

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*The infiltration section was prepared by Dr. Russell G. Mein, Monash University, Clayton, Victoria, Australia.

Survey maps.

The best source of information about a particular soil type is a publication entitled "Soil Survey Interpretations" available from a local SCS office in the U.S. Information on the soil profile, the soil properties, its suitability for a variety of uses, its erosion and crop yield potential, and other data is included on the sheet provided. A copy of the listing for Conestoga silt loam is shown in Figure 4-19. Parameter f_c is essentially equal to the saturated hydraulic conductivity, K_s, which is called "permeability" on the soil survey interpretation sheet. For Conestoga Silt Loam, a range of 0.63-2.0 in/hr (16-51 mm/hr) is shown.

Alternatively, values for f_c according to Musgrave (1955) are given in Table 4-7. To help select a value within the range given for each soil group, the user should consider the texture of the layer of least hydraulic conductivity in the profile. Depending on whether that layer is sand, loam, or clay, the f_c value should be chosen near the top, middle, and bottom of the range respectively. For example, the data sheet for Conestoga silt loam identifies it as being in Hydrology Group B which puts the estimate of f_c into the range of 0.15-0.30 in/hr (3.8-7.6 mm/hr), much lower than the K_s value discussed above. Examination of the texture of the layers in the soil profile indicates that they are silty in nature, suggesting that the estimate of the f_c value should be in the low end of the range, say 0.15-0.20 in/hr (3.8-5.1 mm/hr). A sensitivity test on the f_c value will indicate the importance of this parameter to the overall result.

Table 4-7. Values of f_c for Hydrologic Soil Groups (Musgrave, 1955)

Hydrologic Soil Group	f_c (in/hr)
A	0.45 - 0.30
B	0.30 - 0.15
C	0.15 - 0.05
D	0.05 - 0

Caution should be used in applying values from Table 4-7 to sandy soils (group A) since reported K_s values are often much higher. For instance, sandy soils in Florida have K_s values from 7 to 18 in/hr (180-450 mm/hr) (Carlisle et al., 1981). Unless the water table rises to the surface, ultimate infiltration capacity will be very high, and rainfall rates will almost always be less than f_c, leading to little or no overland flow from such soils.

For any field infiltration test the rate of decrease (or "decay") of infiltration capacity, k, from the initial value, f_o, depends on the initial moisture content. Thus the k value determined for the same soil will vary from test to test.

PA-60-L-5
REVISED 6-71
FILE CODE SOILS 12

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
HARRISBURG, PENNSYLVANIA

CECA CECI
CECB CECJ
CECH CECE
CECC CECD

SOIL SURVEY INTERPRETATIONS

Pennsylvania Date 7/28/71 Subject to Change SOIL: CONESTOGA silt loam

MLRA 148

MAP SYMBOLS: See Page [illegible]

BRIEF DESCRIPTION Deep, well drained upland soils formed from weathered micaceous or shaly limestone and calcareous schist and phylite. They have a silt loam surface layer, a silty clay loam subsoil. Bedrock occurs at about 75 inches.

Hydrology Group B Irrigation Group 1 Drainage Group: NA

ESTIMATED PHYSICAL AND CHEMICAL PROPERTIES

Depth To Bedrock (ft) 5+ Depth To Seasonal High Water Table (ft): 4+ Flood Hazard: None

Depth in Inches From Surface	Classification: USDA Texture	Unified	AASHO	Coarse Fraction Than 3 in	Percent Passing Sieve ---: No. 4 (4.7 mm)	No. 10 (2.0 mm)	No. 40 (.42 mm)	No. 200 (.074 mm)	Range in Permeability Inches/Hr	Available Moisture Capacity in/in of soil	Reaction pH	Shrink - Swell Potential
0-15	SIL	ML	A-4	-	90-100	90-100	80-100	60-90	0.63-2.0	.16-.20	4.5-6.5	low
15-43	SICL	ML,CL MH,CH	A-4, 5,6 7	0-5	90-100	90-100	80-100	60-90	0.63-2.0	.12-.16	4.5-5.5	low
43-75	SH SIL	CH,ML CL,MH CH	A-2 A-5 A-7	0-15	35-90	35-85	35-85	30-80	0.63-2.0	.06-.10	5.6-7.8	low
75+	- - - - - - -	- - -	- - -	- -	MICACEOUS LIMESTONE - -				- - - -	- - - -	- - - -	- - - -

SUITABILITY OF SOIL AS A SOURCE OF ---

TOPSOIL	SAND AND GRAVEL	ROADFILL
GOOD to 15 inches	UNSUITABLE	FAIR to POOR; A-4, 5, 6, 7

SOIL FEATURES AFFECTING SPECIFIED ENGINEERING USES

Use	Major Soil Feature Affecting Use
Highway and Road Location	Moderate potential frost action; cuts and fills needed
Ponds-Reservoir Area	Moderate perm.
Ponds-Embankments	Fair to poor stability and compaction; fair to poor resistance to piping
Drainage	NA
Sprinkler Irrigation	Moderate intake rate; moderate perm.; high available moisture capacity
Terraces or Diversions	Fair to poor stability
Grassed Waterways	High available moisture capacity; moderate fertility
Water Grading	Fair trafficability
Pipeline Construction and Maintenance	All features are favorable

SOIL LIMITATIONS FOR COMMUNITY DEVELOPMENT

Use	Phase	Degree of Limitation	Major Soil Feature Affecting Use
Septic Tank Filter Fields	0-6%	SLIGHT	HGWC
	6-12%	MODERATE	Slope; HGWC
	12-35%	SEVERE	Slope
Sewage Lagoons	0-3%	MODERATE	Moderate perm.
	3-6%	MODERATE	Slope; moderate perm.
	6-35%	SEVERE	Slope
Low Buildings With Basements	0-6%	SLIGHT	
	6-12%	MODERATE	Slope
	12-35%	SEVERE	Slope
Lawns and Landscaping	0-6%	SLIGHT	
	6-12%	MODERATE	Slope
	12-35%	SEVERE	Slope
Parking Lots and Streets in Subdivisions	0-3%	SLIGHT	
	3-6%	MODERATE	Slope
	6-35%	SEVERE	Slope
Sanitary Land Fills	0-6%	SLIGHT	
	6-12%	MODERATE	Slope
	12-35%	SEVERE	Slope

Figure 4-19a

Figure 4-19. Soil Conservation Service Soil Survey Interpretation for Conestoga Silt Loam (found near Lancaster, PA).

MERA 148 SOIL . COWESTOGA silt loam

SOIL LIMITATIONS FOR RECREATIONAL USES

Use	Phase	Degree of Limitation	Major Soil Features Affecting Use
Campsites - Tents	0-6%	SLIGHT	
	6-15%	MODERATE	Slope
	15-35%	SEVERE	Slope
Campsites Trailers	0-3%	SLIGHT	
	3-6%	MODERATE	Slope
	6-35%	SEVERE	Slope
Low Buildings Without Basements	0-6%	SLIGHT	
	6-15%	MODERATE	Slope
	15-35%	SEVERE	Slope
Paths and Trails	0-15%	SLIGHT	
	15-25%	MODERATE	Slope
	25-35%	SEVERE	Slope
Picnic and Play Areas	0-6%	SLIGHT	
	6-15%	MODERATE	Slope
	15-35%	SEVERE	Slope
Athletic Fields	0-3%	SLIGHT	
	3-6%	MODERATE	Slope
	6-35%	SEVERE	Slope
Golf Fairways	0-6%	SLIGHT	(moderate on eroded phase)
	6-15%	MODERATE	Slope (severe on eroded phase)
	15-35%	SEVERE	Slope

LAND CAPABILITY, SOIL LOSS FACTORS, AND ESTIMATED "B" MANAGEMENT YIELDS

Soil Phase	Capability	Soil Loss Factors			Corn bu.	Oats bu.	Wheat bu.	Soy-beans				Alfalfa Hay T.	Clover-Grass Hay T.	Pasture	
		K	T	T/K										Blue-Grass c.a.d.	Tall Grass-Legume c.a.d.
0-3%	I	.43	4	9.3	135	80	50	45				5.5	3.5	160	315
3-6%	IIe	.43	4	9.3	135	80	50	45				5.5	3.5	160	315
3-6% sev.	IIIe	.43	3	7.0	125	75	45	35				5.0	3.5	160	285
6-15%	IIIe	.43	4	9.3	125	75	45	35				5.0	3.5	160	285
6-15% sev.	IVe	.43	3	7.0	110	65	40	-				4.5	3.0	135	255
15-25%	IVe	.43	4	9.3	110	65	40	-				4.5	3.0	135	125
15-25% sev.	VIe	.43	3	7.0	-	-	-	-				-	-	115	-
25-35%	VIe	.43	4	9.3	-	-	-	-				-	-	115	-

WOODLAND

Soil Phase	1 - Slight 2 - Moderate 3 - Severe						Species To Favor in - -		Species and Site Index	Ord. Group
	Erosion Hazard	Equip. Restrict.	Seedling Mort.	Plant Compet. C	Plant Compet. H	Wind Throw Hazard	Natural	Plantation		
0-6%	1	1	1	3	2	1	RO A SM TP BW	YP BW L NSp WP	Ex. 85+ RO A SM Ex. 95+ TP	
6-15%	2	1	1	3	2	1				
15-35%	3	2	1	3	2	1				

WILDLIFE

Soil Phase	Wildlife Habitat Elements								Kinds of Wildlife Habitat		
	Grain and Seed Crops	Grass and Legumes	Wild Herb. Upland Plants	Hardwood Trees, Shrubs, Vines	Coniferous Woody Plants	Wild Herb. Wetland Plants	Shallow Water Dev.	Shallow Excavated Ponds	Openland Wildlife Habitat	Woodland Wildlife Habitat	Wetland Wildlife Habitat
0-3%	1	1	1	1	1	4	4	4	1	1	4
3-6%	2	1	1	1	1	4	4	4	1	1	4
6-15%	2	1	1	1	1	4	4	4	1	1	4
15-25%	3	2	1	1	1	4	4	4	2	1	4
25-35%	4	2	1	1	1	4	4	4	2	1	4

1 Good 2 Fair 3 Poor 4 Very Poor

Figure 4-19b

It is postulated here that, if f_o is always specified in relation to a particular soil moisture condition (e.g., dry) and for moisture contents other than this the time scale is changed accordingly (i.e., time "zero" is adjusted to correspond with the constant f_o), then k can be considered a constant for the soil independent of initial moisture content. Put another way, this means that infiltration curves for the same soil, but different antecedent conditions, can be made coincident if they are moved along the time axis. Butler (1957) makes a similar assumption.

Values of k found in the literature (Viessman et al., 1977; Linsley et al., 1975; Overton and Meadows, 1976; Wanielista, 1978) range from 0.67 to 49 $hr.^{-1}$ Nevertheless most of the values cited appear to be in the range 3-6 hr^{-1} (0.00083-0.00167 sec^{-1}). The evidence is not clear as to whether there is any relationship between soil texture and the k value although several published curves seem to indicate a lower value for sandy soils. If no field data are available, an estimate of 0.00115 sec^{-1} (4.14 hr^{-1}) could be used. Use of such an estimate implies that, under ponded conditions, the infiltration capacity will fall 98 percent of the way towards its minimum value in the first hour, a not uncommon observation. Table 4-8 shows the rate of decay of infiltration for several values of k.

Table 4-8. Rate of Decay of Infiltration Capacity for Different Values of k.

k value hr^{-1} (sec^{-1})	Percent of decline of infiltration capacity towards limiting value f_c after 1 hour.
2 (0.00056)	76
3 (0.00083)	95
4 (0.00115)	98
5 (0.00139)	99

The initial infiltration capacity, f_o depends primarily on soil type, initial moisture content, and surface vegetation conditions. For example, Linsley et al. (1982) present data which show, for a sandy loam soil, a 60 to 70 percent reduction in the f_o value due to wet initial conditions. They also show that lower f_o values apply for a loam soil than for a sandy loam soil. As to the effect of vegetation, Jens and McPherson (1964, pp. 20.20 - 20.38) list data which show that dense grass vegetation nearly doubles the infiltration capacities measured for bare soil surfaces.

For the assumption to hold that the decay coefficient k is independent of initial moisture content, f_o must be specified for the dry soil condition. The continuous version of SWMM automatically calculates the f_o value applicable for wetter conditions as part of the moisture accounting routine. However, for single-event simulation, the user must specify the f_o value for the

storm in question, which may be less than the value for dry soil conditions.

Published values of f_o vary depending on the soil, moisture, and vegetation conditions for the particular test measurement. The f_o values listed in Table 4-9 can be used as a rough guide. Interpolation between the values may be required.

Table 4-9. Representative Values for f_o.

A.	DRY soils (with little or no vegetation): Sandy soils: 5 in/hr Loam soils: 3 in/hr Clay soils: 1 in/hr
B.	DRY soils (with dense vegetation): Multiply values given in A. by 2 (after Jens and McPherson, 1964)
C.	MOIST soils (change from dry f_o value required for single event simulation only): Soils which have drained but not dried out (i.e., field capacity): divide values from A and B by 3. Soils close to saturation: Choose value close to f_c value. Soils which have partially dried out: divide values from A and B by 1.5-2.5.

For continuous simulation, infiltration capacity will be regenerated (recovered) during dry weather. SWMM performs this function whenever there are dry time steps -- no precipitation or surface water -- according to the following equation (see Figure V-3, Appendix V).

$$f_p = f_o - (f_o - f_c)\, e^{-k_d(t-t_w)} \qquad (4\text{-}19)$$

where k_d = decay coefficient for the recovery curve, sec^{-1}, and
t_w = hypothetical projected time at which $f_p = f_c$ on the recovery curve, sec.

In the absence of better knowledge of k_d, it is taken to be a constant fraction or multiple of k,

$$k_d = R\, k \qquad (4\text{-}20)$$

where R = constant ratio, probably << 1.0, (implying a "longer" drying curve than wetting curve). The parameter R is represented in the program by REGEN, group (B2).

On well-drained porous soils (e.g., medium to coarse sands), recovery of infiltration capacity is quite rapid and could well be complete in a couple of days. For heavier soils, the recovery rate is likely to be slower, say 7 to 14 days. The choice of the value can also be related to the interval between a heavy storm and wilting of vegetation. The value of k_d is then,

$$k_d = 0.02/D \tag{4-21}$$

where $k_d = R\,k$ = recovery curve decay coefficient, day^{-1}, and
D = number of days required for the soil to dry out (recover).

The factor of 0.02 in equation 4-21 assumes 98 percent recovery of infiltration capacity (i.e., $e^{-0.02} = 0.98$). The value of R may then be calculated from equation 4-20. For example, for $k = 4.14\ day^{-1}$ and drying times of 3, 7 and 14 days, values of R are 1.61×10^{-3}, 6.9×10^{-4} and 3.45×10^{-4} respectively.

Green-Ampt Infiltration--The second infiltration option is the Green-Ampt equation (1911) that, although not as well known as the Horton equation, has the advantage of physically based parameters that, in principle, can be predicted a priori. The Mein-Larson (1973) formulation of the Green-Ampt equation is a two-stage model. The first step predicts the volume of water, F_s which will infiltrate before the surface becomes saturated. From this point onward, infiltration capacity, f_p, is predicted directly by the Green-Ampt equation. Thus,

$$\text{For } F < F_s\text{: } f = i \text{ and } F_s = \frac{S_u\ IMD}{i/Ks - 1} \text{ for } i > K_s;$$

$$\text{No calculation of } F_s \text{ for } i \leq K_s \tag{4-22}$$

$$\text{For } F \geq F_s\text{: } f = f_p \text{ and } f_p = K_s\left(1 + \frac{S_u\ IMD}{F}\right) \tag{4-23}$$

where f = infiltration rate, ft/sec,
f_p = infiltration capacity, ft/sec,
i = rainfall intensity, ft/sec,
F = cumulative infiltration volume, this event, ft,
F_s = cumulative infiltration volume required to cause surface saturation, ft,
S_u = average capillary suction at the wetting front (SUCT), ft water,
IMD = initial moisture deficit for this event (SMDMAX), ft/ft, and
K_s = saturated hydraulic conductivity of soil, (HYDCON) ft/sec.

Infiltration is thus related to the volume of water infiltrated as well as to the moisture conditions in the surface soil zone. Full computational details are given in Appendix V.

Like the Horton equation, the Green-Ampt infiltration equation has three parameters to be specified S_u (SUCT), K_s (HYDCON) and IMD (SMDMAX). Again, estimates based on any available field data should take precedence over the following guidelines. No default values are provided.

The "Soil Survey Interpretation" sheet (see Figure 4-19) available for most soils from the SCS shows values of "permeability" (hydraulic conductivity) for the soil, K_s. However these values are taken from data for disturbed samples and tend to be highly variable. For example, for Conestoga silt loam the values range from 0.63 to 2.0 in/hr (16 to 51 mm/hr). A better guide for the K_s values is as given for parameter f_c for the Horton equation; theoretically these parameters (i.e., f_c and K_s) should be equal for the same soil. Note that, in general, the range of K_s values encountered will be of the order of a few tenths of an inch per hour.

The moisture deficit, IMD, is defined as the fraction difference between soil porosity and actual moisture content. Sandy soils tend to have lower porosities than clay soils, but drain to lower moisture contents between storms because the water is not held so strongly in the soil pores. Consequently, values of IMD for dry antecedent conditions tend to be higher for sandy soils than for clay soils. This parameter is the most sensitive of the three parameters for estimates of runoff from pervious areas (Brakensiek and Onstad, 1977); hence, some care should be taken in determining the best IMD value to use. Table 4-10, derived from Clapp and Hornberger (1973), gives typical values of IMD for various soil types.

Table 4-10. Typical Values of IMD (SMDMAX) for Various Soil Types

Soil Texture	Typical IMD at Soil Wilting Point
Sand	0.34
Sandy Loam	0.33
Silt Loam	0.32
Loam	0.31
Sandy Clay Loam	0.26
Clay Loam	0.24
Clay	0.21

These IMD values would be suitable for input to <u>continuous</u> SWMM; the soil type selected should correspond to the surface layer for the particular subcatchment. For <u>single event</u> SWMM the values of Table 4-10 would apply only to very dry antecedent conditions. For moist or wet antecedent conditions lower values of IMD should be used. When estimating the particular value it should be borne in mind that sandy soils drain more quickly than clayey soils, i.e., for the same time since the previous event, the IMD value for a sandy soil will be closer in value to that of Table 4-10 than it would be for a clayey

soil.

The average capillary suction, S_u, is perhaps the most difficult parameter to measure. It can be derived from soil moisture - conductivity data (Mein and Larsen, 1973) but such data are rare for most soils. Chu (1978) gives average values of the product of $S_u \cdot IMD$ for a range of soils, but these are not based on measurements. Fortunately the results obtained are not highly sensitive to the estimate of S_u (Brakensiek and Onstad, 1977). The approximate values which follow result from a survey of the literature (Mein and Larsen, 1973; Brakensiek and Onstad, 1977; Clapp and Hornberger, 1978; Chu, 1978). Published values vary considerably and conflict; however, a range of 2 to 15 in (50 to 380 mm) covers virtually all soil textures. Table 4-11 summarizes the published values. An excellent local data source can often be found in Soil Science departments at state universities. Tests are run on a variety of soils found within the state, including soil moisture versus soil tension data, with which to derive S_u. For example, Carlisle et al. (1981) provide such data for Florida soils along with information on K_s, bulk density and other physical and chemical properties.

Table 4-11. Typical values of Su (SUCT) for Various Soil Types.

Soil Texture	Typical Values for S_u (inches)
Sand	4
Sandy Loam	8
Silt Loam	12
Loam	8
Clay Loam	10
Clay	7

Generalized Green-Ampt parameters for U.S. locations are tabulated by Rawls et al. (1983). It is very difficult to give satisfactory estimates of infiltration equation parameters that will apply to all soils encountered. Which ever infiltration equation is used, the user should be prepared to adjust preliminary estimates in the light of any available data such as infiltrometer tests, measurements of runoff volume, or local experience.

Subcatchment Aggregation and Lumping

As discussed earlier, it is desirable to represent the total catchment by as few subcatchments as possible, consistent with the needs for hydraulic detail within the catchment. That is, if the only interest is in hydrographs and pollutographs at the catchment outlet, as is likely for continuous simulation, then one subcatchment should suffice for the simulation (although up to 30 can be used for continuous simulation). For a single event, detailed simulation, the number of subcatchments needed is a function of the amount of hydraulic detail (e.g., backwater, surcharging, routing, storage) that must be

modeled. In addition, enough detail must be simulated to allow non-point source controls to be evaluated (e.g., detention, street sweeping). Finally multiple subcatchments are the only means by which a moving (kinematic) storm may be simulated. Coupled spatial and temporal variations in rainfall can significantly alter predicted hydrographs (Yen and Chow, 1968; Surkan, 1974; James and Drake, 1980; James and Shtifter, 1981).

Clearly, the required volume of input data (and personal time) decreases as the number of subcatchments decreases. How then, can subcatchments be aggregated or "lumped" to provide hydrographs and pollutographs that are equivalent to more detailed simulations?

The most complete study of this question is contained in the Canadian SWMM report (Proctor and Redfern and J.F. MacLaren, 1976a) in which the effect of lumping is compared on real and hypothetical catchments. Similar work has been performed independently by Smith (1975). In both studies it is shown that a single equivalent lumped catchment can be formulated by proper adjustment of the subcatchment width.

In SWMM, Runoff and Transport simulation of the drainage network (i.e., conduits and channels) adds storage to the system and thus attenuates and somewhat delays the hydrograph peaks. When the drainage network is removed from the simulation, subcatchment runoff feeds "instantaneously" into inlets, with consequent higher and earlier hydrograph peaks. The key to aggregation of subcatchments is thus the replacement of the lost storage. This is best accomplished through variation of the subcatchment width, although the same effect could be achieved through variation of the slope or roughness (see discussion of equation 4-9). However, it is assumed that reasonable average values of the latter two parameters for the total catchment may be obtained by weighing individual subcatchment values by their respective areas. (For the roughness an area-weighted harmonic mean may be used, although it is probably an unnecessary refinement). Hence, the subcatchment width is a more logical parameter to be adjusted.

It was shown in the discussion of the subcatchment width, that reducing its value increases storage on the subcatchment. Hence, as subcatchments are aggregated and drainage network storage lost, the total catchments width, i.e., the sum of the subcatchment widths, must be reduced accordingly. This may be seen in Figure 4-20 for a very schematized drainage network in which the subcatchment widths are nominally twice the length of the drainage conduits (Smith, 1975). The lumped catchment could be represented by a single subcatchment, as in the bottom sketch of Figure 4-20, in which the width is approximately twice the length of the main drainage channel. Experience indicates (Smith, 1975; Proctor and Redfern and J.F. MacLaren, 1976a) that good results can be obtained with <u>no</u> channel/conduit network. However, the Canadian study (Proctor and Redfern and J.F. MacLaren, 1976a) does illustrate the routing effect of an "equivalent pipe" in the Transport Block. Note that if the storm duration is long compared to the catchment time of concentration, and if the rainfall intensity is constant, the peak flows obtained for either a lumped or detailed simulation will be about the same, since equilibrium outflow must ultimately result (see the discussion of Figure 4-15).

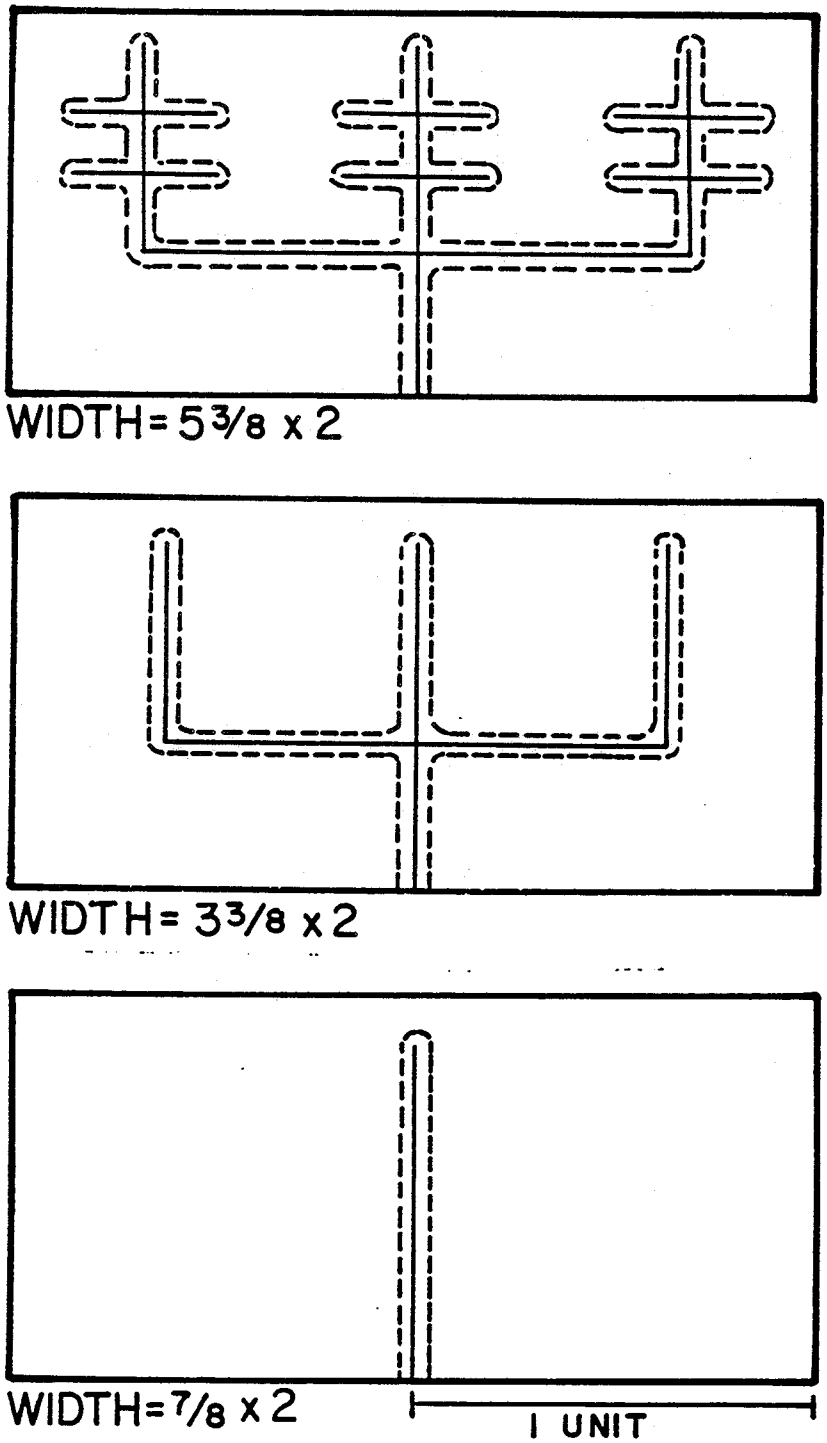


Figure 4-20. Effect of Changing the Level of Discretization on the Width of Overland Flow. (After Smith, 1975, p. 57.)

Several examples of lumping using real rainfall data on real catchments are shown by Proctor and Redfern and James F. MacLaren (1976a) and Smith (1975). An instructive example for the 2330 ac (943 ha) West Toronto area is taken from the former reference and shown in Figure 4-21. A Runoff-Transport simulation using 45 subcatchments and including the drainage network is compared with three Runoff-only simulations with no drainage network. The best agreement, in terms of matching of peak flows, between the detailed and lumped simulations occurred for a single subcatchment width of 60,000 ft (18,000 m) which is about 1.7 times the length of the main trunk conduit in the actual system. Even if a factor of two had been used (i.e., a width of 70,600 ft or 21,500 m) as a first guess, agreement would not be bad. The timing of the peaks for the single subcatchment representation is somewhat early, but adequate for most purposes. Recall that it is difficult to change the timing of subcatchment hydrograph peaks by changing only the width.

It is assumed that when subcatchments are aggregated, other parameters required in group H1 are simply areally weighted. When this is done, very little difference in runoff volume occurs between the aggregate and detailed representations. Differences that do result are usually from water that remains in storage and has not yet drained off of the lumped catchment, or from very slightly increased infiltration on the lumped catchment, again due to the longer presence of standing water on pervious areas (because of the reduced width).

To summarize, many subcatchments may be aggregated into a single lumped or equivalent subcatchment by using areally weighted subcatchment parameters and by adjustment of the subcatchment width. The lumped subcatchment width should be approximately twice the length of the main drainage channel (e.g., the trunk sewer) through the catchment in order to match hydrograph peaks. The effect on runoff volume should be minimal.

Runoff quality predictions are affected by aggregation of subcatchments to the extent that hydrographs and surface loadings are changed. When areal weighted averages of the latter are used for a lumped catchment, total storm loads are essentially the same as for a detailed simulation. Pollutographs of concentration versus time then vary only because of hydrograph variations.

Subsurface Flow Routing (Data Groups H2 - H4)

Introduction --

Routing of flows only (no quality) is performed by Subroutine GROUND and other subroutines. Full details are provided in Appendix X, but briefly, infiltration by either the Horton or Green-Ampt methods may be routed through an unsaturated zone lumped storage, followed by routing through a saturated zone lumped storage. Outflow may occur from the saturated zone to channel/pipes or may be "lost" (from the simulation) to deep groundwater. Evapotranspiration (ET) from both the upper and lower zone may also be simulated, and the groundwater table is dynamic: if it rises to the surface, the upper zone disappears and infiltration will be stopped; if it drops below the elevation of the bottom of the effluent channel/pipe, groundwater outflow will cease. The processes are illustrated schematically in Appendix X, Figure X-1.

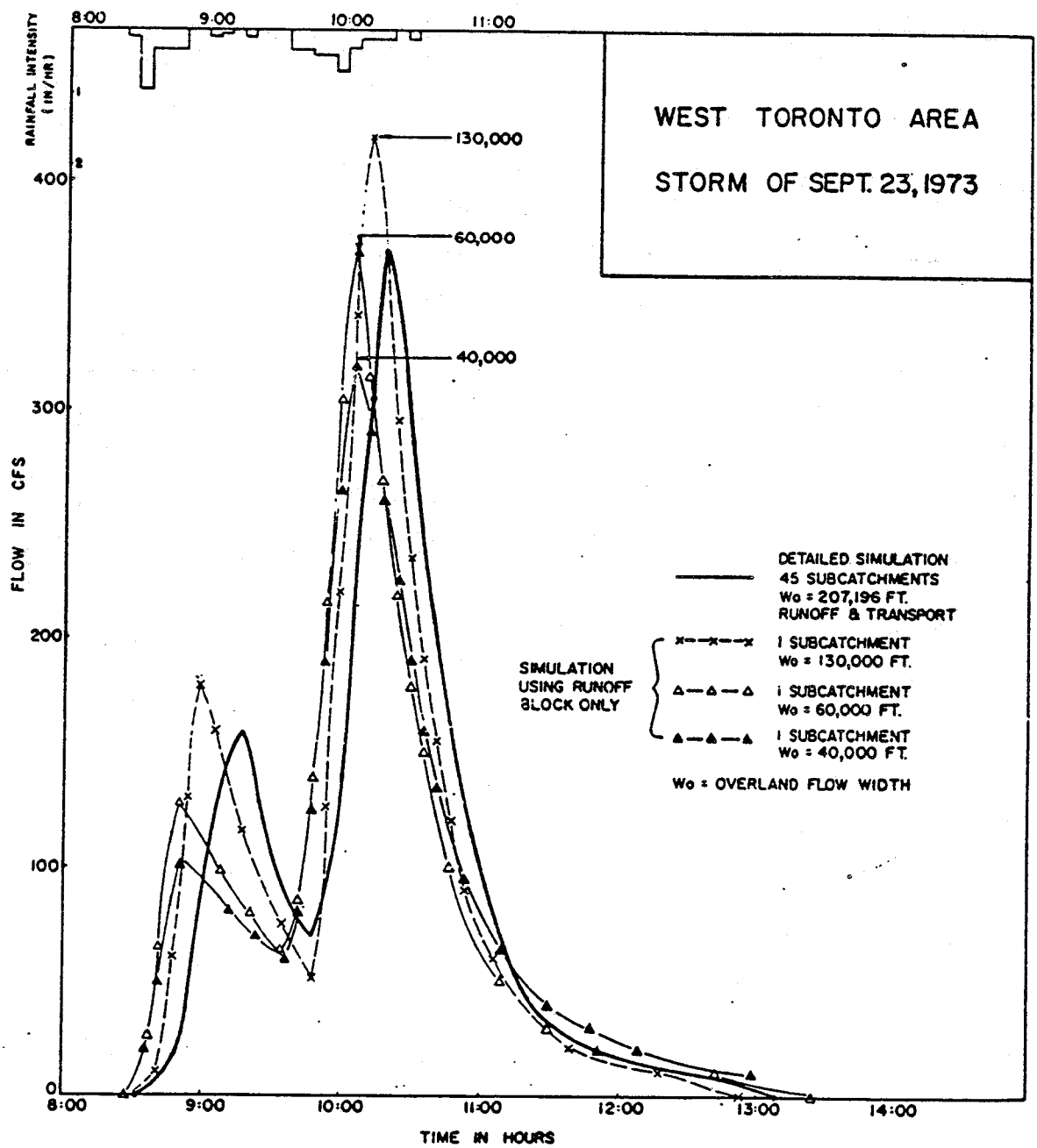


Figure 4-21. Effect on Hydrographs of Changing Subcatchment Width for West Toronto Area. (After Proctor and Redfern and J.F. MacLaren, 1976a, p. 216.)

If quality simulation is included, any water routed through the subsurface zones will be "clean" and act to dilute concentrations in downstream channel/pipes.

Data needs closely reflect soil properties. That is, data for subsurface flow routing involves parameters such as porosity, field capacity, hydraulic conductivity, water table elevation, etc. These data must be obtained from SCS or other sources. As mentioned previously in regard to infiltration parameters, state university Soil Science departments can often provide such information, e.g., Carlisle et al. (1981).

Subsurface routing for an individual subcatchment is indicated by the presence of an H2, H3 and H4 data group immediately following an H1 data group. Subsurface routing for up to any 100 subcatchments (herein called "subsurface subcatchments") can be simulated. The subcatchment number NMSUB on data line H2 must match the subcatchment number NAMEW on data line H1 immediately preceding it. Data groups H2 - H4 for subsurface subcatchments may be interspersed among the surface subcatchments; not all surface subcatchments are required to have a corresponding subsurface subcatchment.

Groundwater outflow may be routed to a channel/pipe; if this option is used, the channel/pipe number is denoted by NGWGW. If no channel/pipe number is indicated, groundwater outflow will be "lost" from the simulation, although it will be accounted for in the continuity check. The channel/pipe number does not have to be the same as for the surface runoff.

General Input and Elevations (Data Group H2) --

The variables ISFPF and ISFGF are flags that tell the program to save the data from that particular subsurface subcatchment for printouts and graphs, respectively. If ISFPF is 1, then NSCRAT(5) must be defined (greater than zero in the Executive Block); if ISFGF is 1, then NSCRAT(6) must be defined. An undefined scratch file will result in an error message followed by termination of execution.

Elevation variables (BELEV, GRELEV, STG, BC, and TW -- Figure X-1) can be referenced to some known benchmark, such as mean sea level, or they can be referenced to the bottom of the lower zone by setting GRELEV equal to zero. The option of referencing the elevation variables to some known benchmark was added so that, among other reasons, the user could easily compare his or her predicted stage data to measured stage data.

Groundwater Flow and Soil Parameters (Data Group H3) --

Groundwater outflow parameters A1, A2, A3, B1 and B2 are defined by equations X-24 and X-25. Because of the general nature of the two equations, a variety of functional forms can be approximated. For example, a linear reservoir can be selected by setting B1 equal to one and A2 and A3 equal to zero. The Dupuit approximation can be selected, within its usual limitations (Todd, 1980), as illustrated in the example in Appendix X.

Two methods can be used to simulate the effect of channel/pipe tailwater

elevations on groundwater outflow. The first method involves setting TW greater than BC (data group H2) and A2, B2 greater than zero (data group H3). It is also desirable to route the flow to a channel or pipe (otherwise, water will be lost from the simulation but accounted for in the continuity check), but this is not absolutely necessary. When this method is chosen, the user is actually supplying the average channel flow influence over the entire run; that is, parameter TW in equation X-25 will be constant for all time steps. This method is most applicable when the depth of the water in the channel is thought to remain fairly constant for the length of the run.

For the second method, TW must be less than zero, which makes it simply an indicator parameter. In addition, A2 and B2 must be greater than zero, and the groundwater flow must be routed to a previously defined trapezoidal channel or circular pipe. If this method is chosen, the program will use the elevation of the water surface in the channel or pipe at the end of the previous time step as the current time-step value for the variable TW (elevation of water surface in channel or pipe). The invert elevation of the channel/pipe is assumed to equal BC. Because of the fact that flow routing in the subsurface zone is not coupled with the channel/pipe routing, oscillations can occur in the groundwater flow as elevation D1 hovers near the variable tailwater elevation TW. This can usually be cured by reducing the simulation time step, WET or WETDRY. See the discussion in Appendix X.

Under-drains can be simulated as shown in the example in Appendix X. However, since groundwater flow from each subsurface subcatchment can only be routed to one pipe, a network of under-drain pipes must be replaced by one equivalent pipe for simulation purposes.

One very important rule to remember, regardless of the functional form chosen, is that groundwater flow should never be allowed to be negative. Although negative flow may be true for the actual system (i.e., bank recharge), it should not be allowed to happen in the model because there is currently no means of subtracting flow from the channel (since the channel flow routing is not coupled to the groundwater flow routing). An easy way to assure that groundwater flow remains positive is by making A1 greater than or equal to A2 and B1 greater than or equal to B2.

Saturated hydraulic conductivity, porosity, wilting point, and field capacity (HKSAT, POR, WP, and FC) are all measurable but difficult-to-obtain values. A discussion regarding saturated hydraulic conductivity was presented previously for the infiltration parameters (parameters HKSAT on data group H3 and HYDCON on data group H1 are treated separately in the program and need not be the same number). WP and FC are usually related to specific suction pressures. Table X-1 contains typical values for wilting point and field capacity (Linsley et al., 1982). SCS and university sources, especially agricultural extension offices in the U.S., often have these data.

For purposes of these groundwater routines, actual porosity and apparent porosity are considered to be equal, since no mechanism exists for adjusting for entrapped air and the difference is usually minor. Porosity is critical to this formulation because of its role in determining moisture storage. WP and FC are less important because they act only as threshold values at which

processes change.

Percolation and Evapotranspiration Parameters (Data Group H3) --

Water "percolates" from the unsaturated upper zone to the saturated lower zone. Parameters HCO and PCO are defined by equations X-21 and X-22, respectively. HCO can be estimated from an exponential fit of hydraulic conductivity to soil moisture, assuming such data are available. See Figure X-5 for example fits. Fitted or not, HCO is a sensitive calibration parameter for movement of unsaturated zone water into the saturated zone. PCO is the slope, PSI/ TH, of the soil tension versus moisture content curve. An average value can be used from data of the form of Figures X-2, X-3 and X-4. It can also be used for calibration, although it is likely that a better estimate of PCO can be obtained than for HCO.

The model includes a deep percolation term which is intended to account for losses through a confining layer, if they could be quantified. Parameter DP is defined by equation X-23. The functional form provides for a first order decay, typical of water table recession curves. Because of the uncertainty associated with this term, it is reasonable to use it for other saturated zone losses that can be quantified by calibration but less than adequately explained physically.

As explained in Appendix X, potential evaporation available for subsurface water loss is the difference between monthly (or other time interval) evaporation input to the Runoff Block (data group F1) and evaporation used by the surface routing. Upper zone ET is a fraction CET of this difference, by equation X-9. Lower zone ET removes the remaining fraction linearly as a function of depth to the water table according to equation X-12. Parameter DET is the maximum depth to the water table for which ET can occur. Subsurface ET can be "turned off" by setting CET = 0 and DET = 0.

Calibration --

Example runs are shown in Appendix X. Calibration is aided by examination of the output times series of water table elevation, soil moisture content and groundwater outflow hydrograph. These series are tabulated if parameter ISFPF = 1 in data group H2 and saved for plotting if parameter ISFGF = 1. Groundwater outflow can be routed to any channel/pipe, not necessarily the same one that receives the surface runoff for the subcatchment. In this way, the surface and subsurface flows can be routed separately, if desired.

<u>Snowmelt (Data Groups I1-I3)</u>

Overview of Procedures --

SWMM snowmelt routines are based on earlier work done on the Canadian SWMM study by Proctor and Redfern and James F. MacLaren (1976a, 1976b, 1977). Since snowmelt computations are explained in detail in Appendix II, only an outline is given here. Most techniques are drawn from Anderson's (1973) work for the National Weather Service (NWS). For continuous simulation, daily max-min temperatures from the NWS (see Section 11) are converted to hourly values

to sinusoidal interpolation, as explained earlier.

Urban snow removal practices may be simulated through "redistribution fractions" input for each subcatchment (discussed below), through alteration of the melt coefficients and base temperatures for the regions of each subcatchment, and through the areal depletion curves used for continuous simulation. Anderson's temperature-index and heat balance melt equations are used for melt computations during dry and rainy periods, respectively. For continuous simulation, the "cold content" of the pack is maintained in order to "ripen" the snow before melting. Routing of melt water through the snow pack is performed as a simple reservoir routing procedure, as in the Canadian study.

The presence of a snow pack is assumed to have no effect on overland flow processes beneath it. Melt is routed in the same manner as rainfall.

Subcatchment Schematization --

When snowmelt is simulated, a fourth subarea is added to each subcatchment as illustrated in Figure 4-11. The properties of each subarea are described in Table 4-4. The main purpose of the fourth subarea is to permit part of the impervious area (subarea A4) to be continuously snow covered (e.g., due to windrowing or dumping) and part (subareas A1 plus A3) to be "normally bare" (e.g., streets and sidewalks that are plowed). However, during continuous simulation, the normally bare portion can also have snow cover up to an amount WEPLOW (group I2) inches water equivalent (in. w.e.). (<u>All</u> snow depths and calculations are in terms of the equivalent depth of liquid water.) The snow covered and normally bare impervious areas are determined from fraction SNN1 (group I1). During single event simulation, subarea A4 retains 100 percent snow cover until it has all melted. During continuous simulation, an areal depletion curve, discussed earlier, is used.

Similarly, for single event simulation, a fraction SNN2 (group I1) of the pervious area remains 100 percent snow covered. During continuous simulation, the whole pervious area is subject to areal depletion curve.

Initialization --

Initial snow depths (inches water equivalent) may be entered using parameters SNN3, SNN4 (group I1) and SNN7 (group I2). This is likely to be the only source of snow for a single event simulation although snowfall values may be entered as negative precipitation in data group E2. During continuous simulation, the effect of initial conditions will die out, given a simulation of a few months.

No liquid runoff will leave the snow pack until its free water holding capacity (due to its porosity) has been exceeded. The available volume is a constant fraction, FWFRAC (group C1) of the snow depth, WSNOW. Hence, initial values of free water, FW, should maintain the inequality:

$$FW \leq FWFRAC \cdot WSNOW \quad (4\text{-}24)$$

Melt Equations --

During periods of no rainfall, snowmelt is computed by a degree-day or temperature index equation:

$$SMELT = DHM \cdot (TA - TBASE) \quad (4\text{-}25)$$

where SMELT = snowmelt rate, in. w.e./hr,
DHM = melt coefficient, in w.e./hr-°F,
TA = air temperature, °F, and
TBASE = snowmelt base temperature, °F.

There is no melt when TA $\leq$ TBASE. For single event simulation, the melt coefficient, DHM, remains constant. For continuous simulation it is allowed to vary sinusoidally from a minimum value on December 21 to a maximum value on June 21 (see Figure 4-22) in order to reflect seasonal changes.

Melt coefficients and base melt temperatures may be determined both theoretically and experimentally. Considering the former, it is possible to first write a snowmelt equation from a heat budget formulation that includes all relevant terms: change in snow pack heat storage, net short wave radiation entering pack, conduction of heat to the pack from underlying ground, net (incoming minus outgoing) longwave radiation entering pack, convective transport of sensible heat from air to pack, release of latent heat of vaporization by condensation of atmospheric water vapor, and advection of heat to snow pack by rain. (It is assumed here that the pack is "ripe", i.e., just at the melting point, so that rain will not freeze and release its latent heat of fusion.) The equation may then be linearized about a reference air temperature and reduced to the form of equation 4-22. Exactly this procedure is followed in a detailed example presented in Appendix III.

Alternatively, observed melt, in inches per time interval, may be plotted against temperature for that time interval, and a linear relationship developed of the form of equation 4-22. An often-cited such development for natural areas is illustrated in Figure 4-23 taken from the Corps of Engineers (1956). Viessman et al. (1977) also present a good discussion of degree-day equations. In the highly desirable but unlikely event that snowmelt data are available, the experimental procedure of Figure 4-23 is probably best for urban areas due to the considerable variation of snow pack and meteorological conditions that will be encountered, making reasonable theoretical assumptions more difficult.

For natural areas, considerable range in melt coefficients exits, on the order of 0.0006 to 0.008 in/hr-°F (0.03 to 0.4 mm/hr-°C). Although base melt temperatures are nominally near the freezing point (i.e., 32°F or 0°C) they may be considerably lower depending on the exposure of the site and meteorological conditions. For instance, for the linearization performed in Appendix III a base melt temperature of 9°F (-13°C) was computed, which is valid only

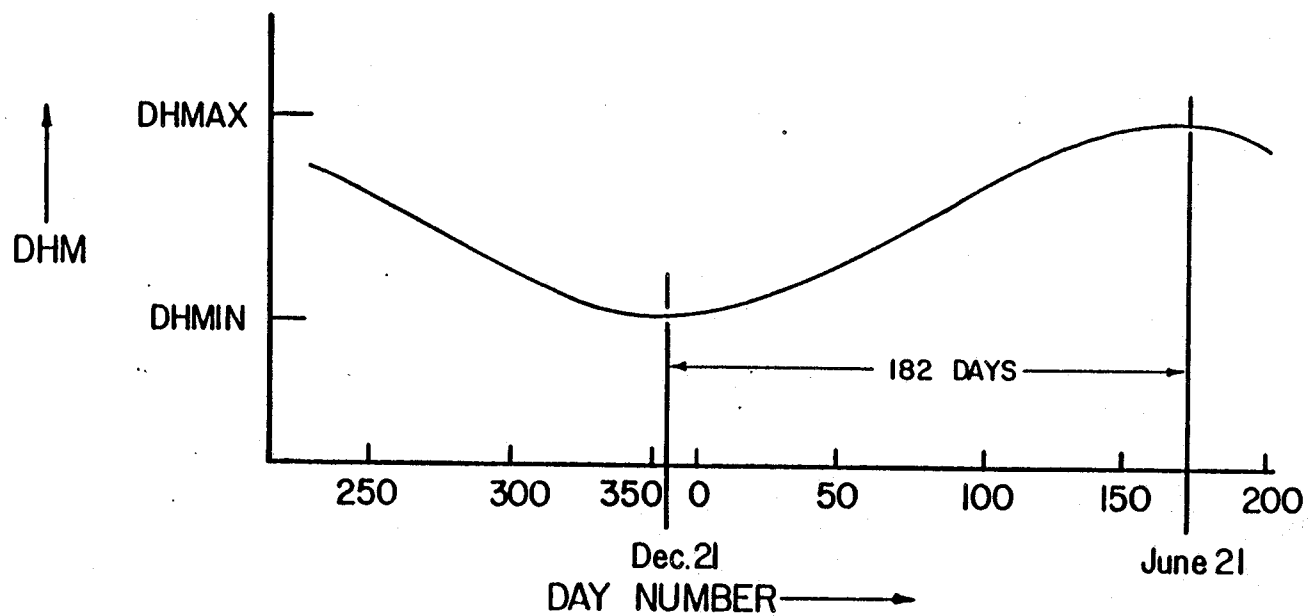


Figure 4-22. Seasonal Variation of Melt Coefficients for Continuous Simulation.

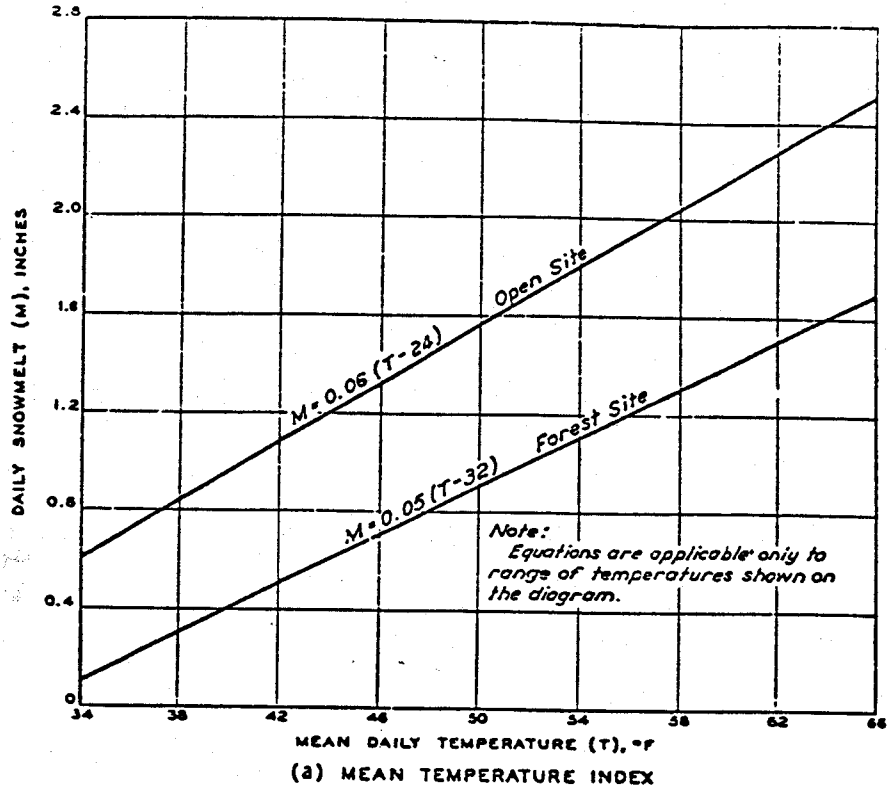


Figure 4-23. Degree-Day Equations for Snow Melt. (After Corps of Engineers, 1956, plate 6-4).

over the range of air temperatures used in the linearization (approximately 30 to 40°F or -1 to 5°C).

If the effects of snow removal practices (e.g., street salting) and land surface factors are known, different melt coefficients and base melt temperatures may be entered for the different snow covered subareas of a subcatchment. For instance, street salting lowers the freezing point in proportion to the concentration of the chemical. Handbook values (Chemical Rubber Co., 1976, pp. D218-D267) for freezing point depression are plotted versus concentration in Figure 4-24 for several common roadway salting chemicals. Thus, the base melt temperature computed for pure water might be lowered by an amount taken from Figure 4-24 if an idea is know about the likely concentration on the roadway. The concentration will depend upon the amount of chemical applied and the amount of snowfall and might not be easily computed. An interesting alternative would be to let SWMM predict it!

During periods (i.e., time steps) with rainfall, good assumptions can be made about relevant meteorological parameters for the complete heat balance melt equation. It then replaces the degree-day equation for "wet" time steps. Melt during these time steps is linearly proportional to air temperature and wind speed.

Areal Depletion Parameters --

In the earlier discussion of areal depletion curves it was noted that there would be 100 percent cover above a depth of SI inches water equivalent. Values of SI for impervious and pervious areas are read in group I2.

For natural areas, Anderson (1973) recommends that a distinction be made on the basis of areal homogeneity. For a very heterogeneous area there are likely to be areas that receive little snow, or else it will quickly melt. The value of SI for such areas might be about the maximum depth anticipated. For homogeneous areas a much lower value would be appropriate.

No specific information is available for urban areas; however, they are likely to be quite heterogeneous, especially if large, aggregated subcatchments are being used for the continuous simulation. Hence, a high value is probably indicated. Whichever values are used, they should be consistent with the form of the areal depletion curves entered in groups C3 and C4. In general (depending somewhat on the areal depletion curve), the higher the value of SI, the more "stacked up" on a catchment is the snow, and snowmelt will occur at a lower rate over a longer time.

Snow Redistribution --

The program allows (during continuous simulation) snow that falls on the normally bare impervious areas to be redistributed according to the fractions given as SFRAC in group I2. This is intended to simulate plowing and other snow removal practices in urban areas. Snow depths above WEPLOW inches water equivalent are thus redistributed according to Figure 4-25.

The value of WEPLOW depends upon the level of service given the parti-

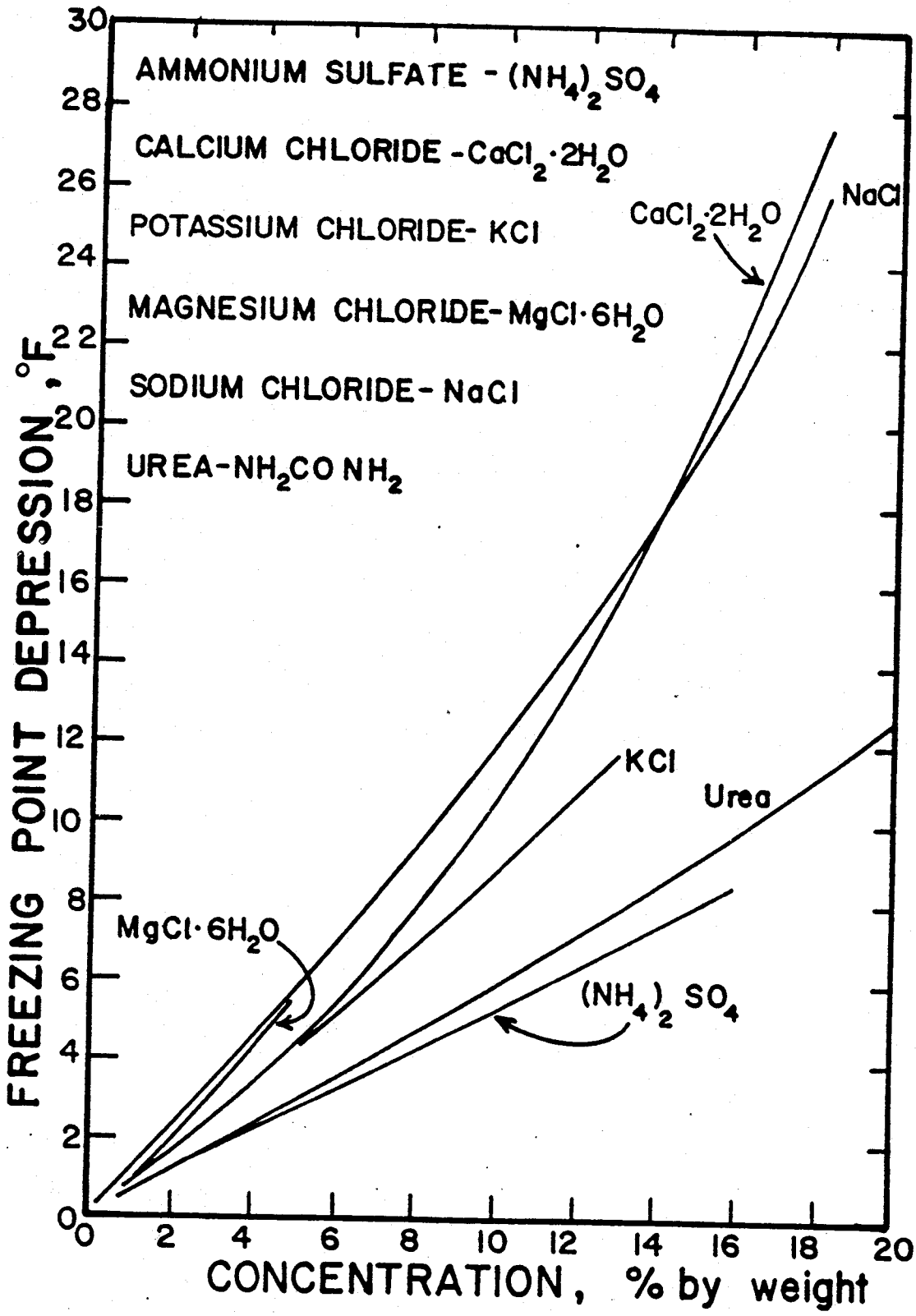


Figure 4-24. Freezing Point Depression Versus Roadway Salting Chemical Concentration. Compiled from data from CRC (1976).

A1 = IMPERVIOUS AREA WITH DEPRESSION STORAGE
A2 = PERVIOUS AREA
A3 = IMPERVIOUS AREA WITH ZERO DEPRESSION STORAGE
A4 = SNOW COVERED IMPERVIOUS AREA

A1 + A3 = NORMALLY BARE

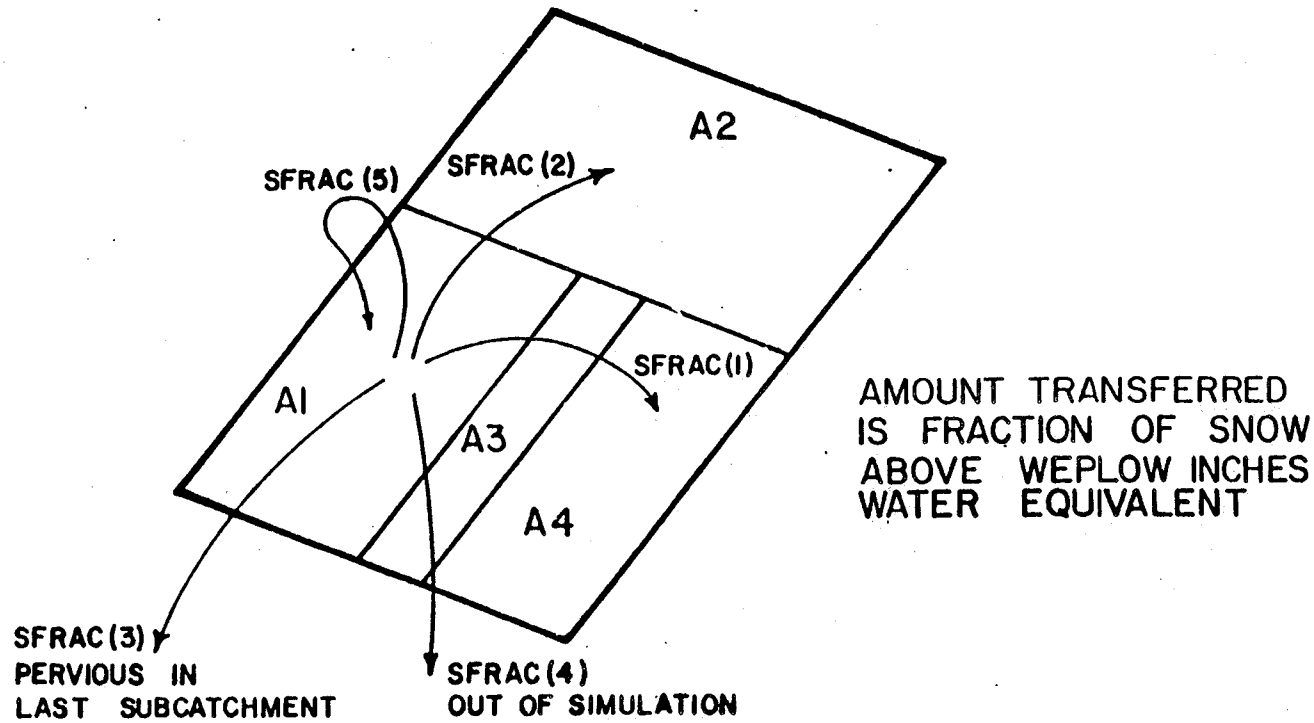


Figure 4-25. Illustration of Snow Redistribution Fractions.

cular impervious area. That is, at what snow depth do removal practices start? Some guidelines are provided by Richardson et al. (1974) in Table 4-12.

The five fractions SFRAC, should sum to 1.0 and are defined on the basis of the ultimate fate of the removed snow. For instance, if snow is plowed from a street onto an adjacent impervious or pervious area, fractions SFRAC(1) or SFRAC(2) would be appropriate. It may also be transferred to the last subcatchment (e.g., a dumping ground) or removed from the simulation (i.e., removed from the total catchment) altogether. Finally, it may be converted to immediate melt. Should variations in snow removal practices need to be simulated, different subcatchments can be established for different purposes and the fractions varied accordingly.

SURFACE QUALITY DATA (GROUPS J1-L1)

Preface to Quality Simulation

Simulation of urban runoff quality is a very inexact science if it can even be called such. Very large uncertainties arise both in the representation of the physical, chemical and biological processes and in the acquisition of data and parameters for model algorithms. For instance, subsequent sections will discuss the concept of "buildup" of pollutants on land surfaces and "washoff" during storm events. The true mechanisms of buildup involve factors such as wind, traffic, atmospheric fallout, land surface activities, erosion, street cleaning and other imponderables. Although efforts have been made to include such factors in physically-based equations (James and Boregowda, 1985), it is unrealistic to assume that they can be represented with enough accuracy to determine a priori the amount of pollutants on the surface at the beginning of the storm. Equally naive is the idea that empirical washoff equations truly represent the complex hydrodynamic (and chemical and biological) processes that occur while overland flow moves in random patterns over the land surface. The many difficulties of simulation of urban runoff quality are discussed by Huber (1985, 1986).

Such uncertainties can be dealt with in two ways. The first option is to collect enough calibration and verification data to be able to calibrate the model equations used for quality simulation. Given sufficient data, the equations used in SWMM can usually be manipulated to reproduce measured concentrations and loads. This is essentially the option discussed at length in the following sections. The second option is to abandon the notion of detailed quality simulation altogether and either use a constant concentration applied to quantity predictions (i.e., obtain storm loads by multiplying predicted volumes by an assumed concentration) (Johansen et al., 1984) or use a statistical method (Hydroscience, 1979; Driscoll and Assoc., 1981; EPA, 1983b; DiToro, 1984). Two ways in which constant concentrations can be simulated in SWMM are by using a rating curve (equation 4-41) with an exponent of 1.0 or by assigning a concentration to rainfall. Statistical methods are based in part upon strong evidence that storm event mean concentrations (EMCs) are lognormally distributed (Driscoll, 1986). The statistical methods recognize the frustrations of physically-based modeling and move directly to a stochastic result (e.g., a frequency distribution of EMCs), but they are even more de-

Table 4-12. Guidelines for Levels of Service in Snow and Ice Control. (Richardson et al., 1974.)

Road Classification	Level of Service	Snow Depth to Start Plowing (Inches)	Max. Snow Depth on Pavement (Inches)	Full Pavement Clear of Snow After Storm (Hours)	Full Pavement Clear of Ice After Storm Hours
1. Low-Speed Multilane Urban Expressway	• Roadway routinely patrolled during storms • All traffic lanes treated with chemicals • All lanes (including breakdown lanes) operable at all times but at reduced speeds • Occasional patches of well-sanded snow pack • Roadway repeatedly cleared by echelons of plows to minimize traffic disruption • Clear pavement obtained as soon as possible	0.5 to 1	1	1	12
2. High-Speed 4-Lane Divided Highways Interstate System ADT greater than 10,000	• Roadway routinely patrolled during storms • Driving and passing lanes treated with chemicals • Driving lane operable at all times at reduced speeds • Passing lane operable depending on equipment availability • Clear pavement obtained as soon as possible	1	2	1.5	12
3. Primary Highways Undivided 2 and 3 lanes ADT 500 -- 5000	• Roadway is routinely patrolled during storms • Mostly clear pavement after storm stops • Hazardous areas receive treatment of chemicals or abrasive • Remaining snow and ice removed when thawing occurs	1	2.5	2	24
4. Secondary Roads ADT less than 500	• Roadway is patrolled at least once during a storm • Bare left-wheel track with intermittent snow cover • Hazardous areas are plowed and treated with chemicals or abrasives as a first order of work • Full width of road is cleared as equipment becomes available	2	3	3	48

pendent on available data than methods such as those found in SWMM. That is, statistical parameters such as mean, median and variance must be available from other studies in order to use the statistical methods. Furthermore, it is harder to study the effect of controls and catchment modifications using statistical methods.

The main point is that there are alternatives to the approaches used in SWMM; the latter can involve extensive effort at parameter estimation and model calibration to produce quality predictions that may vary greatly from an unknown "reality." Before delving into the arcane methods incorporated in SWMM and other urban runoff quality simulation models, the user should try to determine whether or not the effort will be worth it in view of the uncertainties of the process and whether or not simpler alternative methods might suffice. The discussions that follow provide a comprehensive view of the options available in SWMM, which are more than in almost any other comparable model, but the extent of the discussion should not be interpreted as a guarantee of success in applying the methods.

Overview of Quality Procedures

For most SWMM applications, the Runoff Block is the origin of water quality constituents. Although effects of dry-weather flow and scour and deposition may be included in the Transport Block, (dry-weather flow quality may also be included in the Storage/treatment Block), the generation of quality constituents (e.g., pollutants) in the storm water itself can only be included in the Runoff Block.

Several mechanisms constitute the genesis of stormwater quality, most notably buildup and washoff. In an impervious urban area, it is usually assumed that a supply of constituents is built up on the land surface during dry weather preceding a storm. Such a buildup may or may not be a function of time and factors such as traffic flow, dry fallout and street sweeping (James and Boregowda, 1985). With the storm the material is then washed off into the drainage system. The physics of the washoff may involve rainfall energy, as in some erosion calculations, or may be a function of bottom shear stress in the flow as in sediment transport theory. Most often, however, washoff is treated by an empirical equation with slight physical justification. Methods for prediction of urban runoff quality constituents are reviewed extensively by Huber (1985, 1986).

As an alternative to the use of a buildup-washoff formulation, quality loads (i.e., mass/time) may be generated by a rating curve approach in which loads are proportional to flow raised to some power. Such an approach may also be justified physically and is often easier to calibrate using available data.

Another quality source is catchbasins. These are treated in SWMM as a reservoir of constituents in each subcatchment available to be flushed out during the storm.

Erosion of "solids" may be simulated directly be the Universal Soil Loss Equation (USLE). Since it was developed for long term predictions (e.g.,

seasonal or annual loads), its use during a storm event in SWMM is questionable. But it is convenient since many data are available to support it.

A final source of constituents is in the precipitation itself. Much more monitoring exists of precipitation quality at present than in the past, and precipitation can contain surprisingly high concentrations of many parameters. This is treated in SWMM by permitting a constant concentration of constituents in precipitation.

Many constituents can appear in either dissolved or solid forms (e.g., BOD, nitrogen, phosphorus) and may be adsorbed onto other constituents (e.g., pesticides onto "solids") and thus be generated as a portion of such other constituents. To treat this situation, any constituent may be computed as a fraction ("potency factor") of another. For instance, five percent of the suspended solids load could be added to the (soluble) BOD load. Or several particle size - specific gravity ranges could be generated, with other constituents consisting of fractions of each.

Up to ten quality constituents may be simulated in the Runoff Block. All are user supplied, with appropriate parameters for each. All are transferred to the interface file for transmittal to subsequent SWMM blocks, but not all may be used by the blocks; see the documentation for each block.

Up to five user supplied land uses may be entered to characterize different subcatchments. Street sweeping is a function of land use, and individual constituents. Constituent buildup may be a function of land use or else fixed for each constituent. Considerable flexibility thus exists.

When channel/pipes are included, quality constituents are routed through them assuming complete mixing within each gutter/pipe at each time step. No scour, deposition or decay-interaction during routing is simulated in the Runoff Block.

Output consists of pollutographs (concentrations versus time) at desired locations along with total loads, and flow-weighted concentration means and standard deviations. The pollutographs may be plotted using the Graph Block. In addition, summaries are printed for each constituent describing its overall mass balance for the simulation for the total catchment, i.e., sources, removals, etc. These summaries are the most useful output for continuous simulation runs.

In the following material, the processes described above are discussed in more detail. The various parameters are related to individual data groups as appropriate.

Quality Simulation Credibility

Although the conceptualization of the quality processes is not difficult, the reliability and credibility of quality parameter simulation is very difficult to establish. In fact, quality predictions by SWMM or almost any other surface runoff model are almost useless without local data for the catchment being simulated to use for calibration and validation. If such data are lack-

ing, results may still be used to compare relative effects of changes, but parameter magnitudes (i.e., actual values of predicted concentrations) will forever be in doubt. This is in marked contrast to quantity prediction for which reasonable estimates of hydrographs may be made in advance of calibration.

Moreover, there is disagreement in the literature as to what are the important and appropriate physical and chemical mechanisms that should be included in a model to generate surface runoff quality. The objective in the Runoff Block has been to provide flexibility in mechanisms and the opportunity for calibration. But this places a considerable burden on the user to obtain adequate data for model usage and to be familiar with quality mechanisms that may apply to the catchment being studied. This burden is all too often ignored, leading ultimately to model results being discredited.

In the end then, there is no substitute for local data, that is, rain, flow and concentration measurements, with which to calibrate and verify the quality predictions. Without such data, little reliability can be placed in the predicted magnitudes of quality parameters.

Required Degree of Temporal Detail

Early quality modeling efforts with SWMM emphasized generation of detailed pollutographs, in which concentrations versus time were generated for short time increments during a storm event (e.g., Metcalf and Eddy et al., 1971b). In most applications, such detail is entirely unnecessary because the receiving waters cannot respond to such rapid changes in concentration or loads. Instead, only the total storm event load is necessary for most studies of receiving water quality. Time scales for the response of various receiving waters are presented in Table 4-13 (Driscoll, 1979; Hydroscience, 1979). Concentration transients occurring within a storm event are unlikely to affect any common quality parameter within the receiving water, with the possible exception of bacteria. The only time that detailed temporal concentration variations might be needed within a storm event is when they will affect control alternatives. For example, a storage device may need to trap the "first flush" of pollutants.

The significant point is that calibration and verification ordinarily need only be performed on total storm event loads, or on event mean concentrations. This is a much easier task than trying to match detailed concentration transients within a storm event.

Quality Constituents

The number and choice of constituents to be simulated must reflect the user's needs, potential for treatment and receiving water impacts, etc. Almost any constituent measured by common laboratory or field tests can be included, up to a total of ten. The name and concentration units are entered in data group J3. These will be passed to subsequent blocks and are used as column headings for tabular output of concentrations, as illustrated in Figure 4-26. This heading style is used in both the Runoff and Transport Blocks.

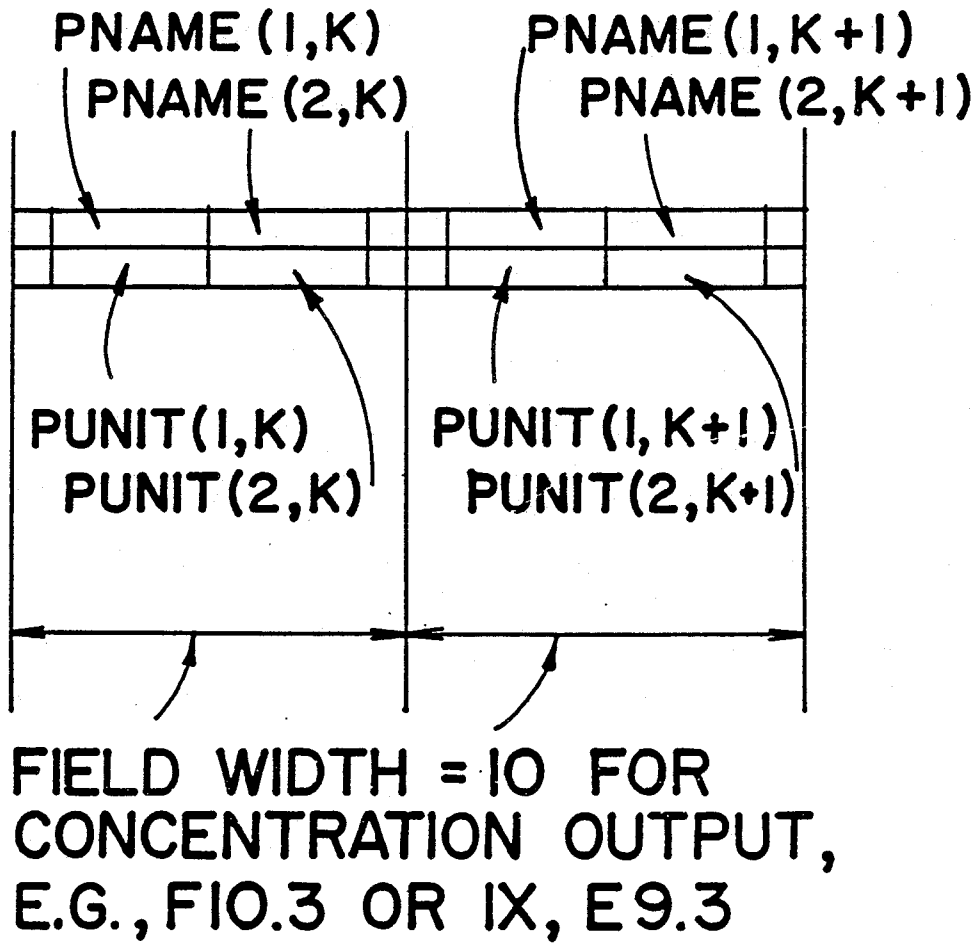


Figure 4-26. Layout of Quality Constituent Headings. Parameters PNAME and PUNIT are entered in card group J3, Table 4-31.

Options for concentration units are reasonably broad and broken into three categories, indicated by parameter NDIM in data group J3. Most constituents are measurable in units of milligrams per liter, mg/l. Although parameters such as metals, phosphorus or trace organics are often given as micrograms per liter, ug/l, the output of concentrations for NDIM = 0 is F10.3 (allowing for three decimal places), and it is expected to be compatible with reported values of such parameters. Thus, the use of mg/l should suffice for all parameters for which the "quantity" of the parameter is measured as a mass (e.g., mg).

Table 4-13. Required Temporal Detail for Receiving Water Analysis (After Driscoll, 1979 and Hydroscience, 1979)

Type of Receiving Water	Key Constituents	Response Time
Lakes, Bays	Nutrients	Weeks - Years
Estuaries	Nutrients, DO(?)	Days - Weeks
Large Rivers	DO, Nitrogen	Days
Streams	DO, Nitrogen Bacteria	Hours - Days Hours
Ponds	DO, Nutrients	Hours - Weeks
Beaches	Bacteria	Hours

A notable exception to the use of mass units is for bacteria, for which constituents such as coliforms, fecal strep etc. are given as a number or count per volume, e.g., MPN/l. Setting NDIM = 1 accounts for these units (or any other type of "quantity" per liter, including mass if desired). Concentration output for these constituents is given an E9.3 format.

A third category covers parameters with specialized concentration-type units such as pH, conductivity (umho), turbidity (JTU), color (PCU), temperature (^{o}C), etc. These are simulated using NDIM = 2. For these parameters, interpretation of concentration results is straightforward, but "total mass" or "buildup" is mostly conceptual. Since loads (e.g., mass/time) are transmitted in terms of concentration times flow rate, whichever concentration units are used, proper continuity of parameters is readily maintained. Of course, simulation of a parameter such as temperature could only be done to the zeroeth approximation in any event since all Runoff Block constituents are conservative.

Land Use Data (Group J2)

Each subcatchment must be assigned only one of up to five user supplied land uses. The number of the land use is used as a program subscript, so at least one land use data must be entered. Street sweeping is a function of land use and constituent (discussed subsequently). Constituent buildup may be a function of land use depending on the type of buildup calculation specified for each in group J3. The buildup parameters DDLIM, DDPOW, and DDFACT in group J2 are used only when constituent buildup will be a function of "dust and dirt" buildup. This is discussed in detail below.

The land use name, LNAME, will be printed in the output using eight columns. The land use types are completely arbitrary, but they could reflect those for which data are available and, of course, those found in the catchment, or an aggregate thereof.

Buildup

Background --

One of the most influential of the early studies of stormwater pollution was conducted in Chicago by the American Public Works Association (1969). As part of this project, street surface accumulation of "dust and dirt" (DD) (anything passing through a quarter inch mesh screen) was measured by sweeping with brooms and vacuum cleaners. The accumulations were measured for different land uses and curb length, and the data were normalized in terms of pounds of dust and dirt per dry day per 100 ft of curb or gutter. These well known results are shown in Table 4-14 and imply that dust and dirt buildup is a linear function of time. The dust and dirt samples were analyzed chemically, and the fraction of sample consisting of various constituents for each of four land uses was determined, leading to the results shown in Table 4-15.

Table 4-14. Measured Dust and Dirt (DD) Accumulation in Chicago by the APWA in 1969 (APWA, 1969).

Type	Land Use	Pounds DD/dry day per 100 ft-curb
1	Single Family Residential	0.7
2	Multi-Family Residential	2.3
3	Commercial	3.3
4	Industrial	4.6
5	Undeveloped or Park	1.5

From the values shown in Tables 4-14 and 4-15, the buildup of each constituent (also linear with time) can be computed simply by multiplying dust and dirt by the appropriate fraction. Since the APWA study was published

during the original SWMM project (1968-1971), it represented the state of the art at the time and was used extensively in the development of the surface quality routines (Metcalf and Eddy et al., 1971a, Section 11). In fact, the formulation and data may still be used in SWMM should the user wish to rely upon highly site specific results for Chicago. Needless to say, unless the application is in Chicago this is not recommended. Several useful studies have been conducted since the pioneering APWA work which permit much more selectivity.

Table 4-15. Milligrams of Pollutant Per Gram of Dust and Dirt (Parts Per Thousand By Mass) For Four Chicago Land Uses From 1969 APWA Study (APWA, 1969).

	Land Use Type			
Parameter	Single Family Residential	Multi-Family Residential	Commercial	Industrial
BOD5	5.0	3.6	7.7	3.0
COD	40.0	40.0	39.0	40.0
Total Coliforms[a]	1.3×10^6	2.7×10^6	1.7×10^6	1.0×10^6
Total N	0.48	0.61	0.41	0.43
Total PO4 (as PO4)	0.05	0.05	0.07	0.03

[a]Units for coliforms are MPN/gram.

Of course, the whole buildup idea essentially ignores the physics of generation of pollutants from sources such as street pavement, vehicles, atmospheric fallout, vegetation, land surfaces, litter, spills, anti-skid compounds and chemicals, construction, and drainage networks. Lager et al. (1977a) and James and Boregowda (1985) consider each source in turn and give guidance on buildup rates. But the rates that are (optionally) entered into the Runoff Block only reflect the aggregate of all sources.

Available Studies --

The 1969 APWA study (APWA, 1969) was followed by several more efforts, notably AVCO (1970) reporting extensive data from Tulsa, Sartor and Boyd (1972) reporting a cross section of data from ten US cities, and Shaheen (1975) reporting data for highways in the Washington, D.C. area. Pitt and Amy (1973) followed the Sartor and Boyd (1972) study with an analysis of heavy metals on street surfaces from the same ten US cities. More recently, Pitt (1979) reports on extensive data gathered both on the street surface and in runoff for San Jose. A drawback of the earlier studies is that it is difficult to draw conclusions from them on the relationship between street surface accumulation and stormwater concentrations since the two were seldom measured simultaneously.

Amy et al. (1975) provide a summary of data available in 1974 while Lager

et al. (1977a) provide a similar function as of 1977 without the extensive data tabulations given by Amy et al. Perhaps the most comprehensive summary of surface accumulation and pollutant fraction data is provided by Manning et al. (1977) in which the many problems and facets of sampling and measurements are also discussed. For instance, some data are obtained by sweeping, others by flushing; the particle size characteristics and degree of removal from the street surface differ for each method. Some results of Manning et al. (1977) will be illustrated later. Surface accumulation data may be gleaned, somewhat less directly, from references on loading functions that include McElroy et al. (1976), Heaney et al. (1977) and Huber et al. (1981a).

Ammon (1979) has summarized many of these and other studies, specifically in regard to application to SWMM. For instance, there is evidence to suggest several buildup relationships as alternatives to the linear one, and these relationships may change with the constituent being considered. Upper limits for buildup are also likely. Several options for both buildup and washoff are investigated by Ammon, and his results are partially the basis for formulations in this version of SWMM. Jewell et al. (1980) also provide a useful critique of methods available for simulation of surface runoff quality and ultimately suggest statistical analysis as the proper alternative. Many of the problems and weakness with extensive data and present modeling formulations are pointed out by Sonnen (1980) along with guidelines for future research.

To summarize, many studies and voluminous data exist with which to formulate buildup relationships, most of which are purely empirical and data-based, ignoring the underlying physics and chemistry of the generation processes. Nonetheless, they represent what is available, and modeling techniques in SWMM are designed to accommodate them in their heuristic form.

Buildup Formulations --

Most data, as will be seen, imply linear buildup since they are given in units such as lb/ac-day or lb/100 ft curb-day. As stated earlier, the Chicago data that were used in the original SWMM formulation assumed a linear buildup. However, there is ample evidence that buildup can be nonlinear; Sartor and Boyd's (1972) data are most often cited as examples (Figure 4-27). More recent data from Pitt (Figure 4-28) for San Jose indicate almost linear accumulation, although some of the best fit lines indicated in the figure had very poor correlation coefficients, ranging from $0.35 \leq r \leq 0.9$. Even in data collected as carefully as in the San Jose study, the scatter (not shown in the report) is considerable. Thus, the choice of the best functional form is not obvious. Whipple et al. (1977) have criticized the linear buildup formulation included in the original SWMM, although it is somewhat irrelevant since the user may insert his/her own desired initial loads, calculated by whatever procedure desired, in data group L1. However, this is a useful option only for single-event simulation.

The proper choice of the proper functional form must ultimately be the responsibility of the user. The program provides three options for dust and dirt buildup (Table 4-16) and three for individual constituents (Table 4-17), namely:

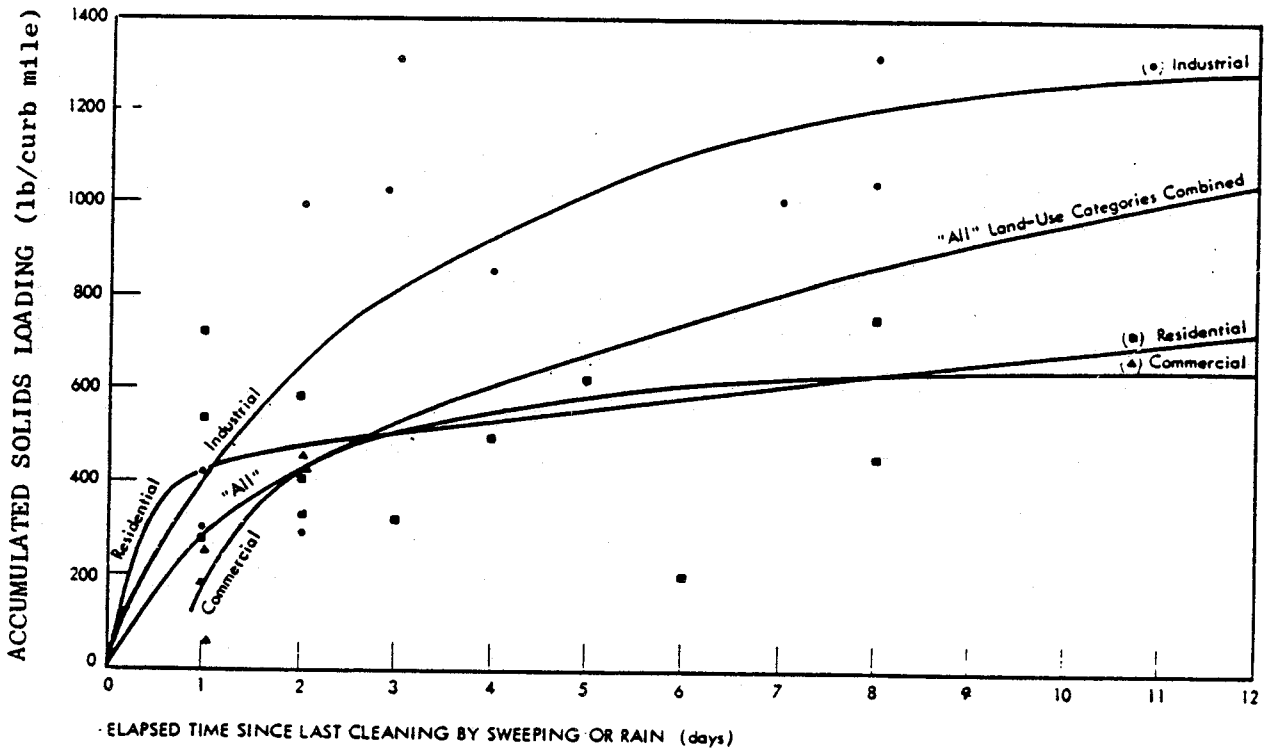


Figure 4-27. Non-linear Buildup of Street Solids. (After Sartor and Boyd, 1972, p. 206.)

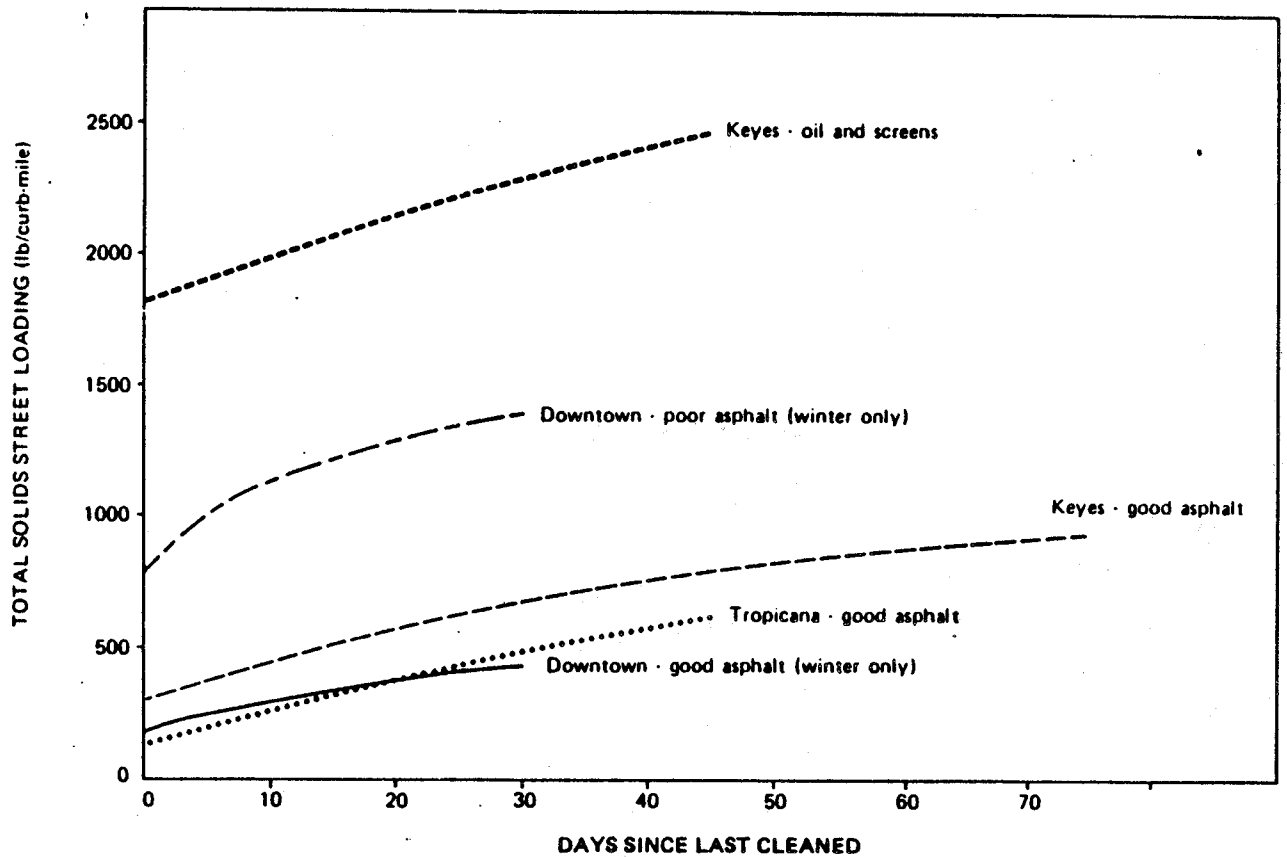


Figure 4-28. Buildup of Street Solids in San Jose. (After Pitt, 1979, p. 29.)

Table 4-16. Buildup Equations and Units for Dust and Dirt.

Enter parameters on Card Group J2.

DD = Dust and Dirt, lb. t = time, days.

For metric input substitute kg for lb, ha for ac and km for 100-ft.

METHOD (Card Group J2)	Type	Equation	Equation Number
0	Power-Linear	$DD = DDFACT \cdot t^{DDPOW}$ $DD \leq DDLIM$	(4-23)
1	Exponential	$DD = DDLIM \cdot (1-e^{-DDPOW \cdot t})$	(4-24)
2	Michaelis-Menton	$DD = DDLIM \cdot t/(DDFACT+t)$	(4-25)

Units for Card Input of:

METHOD	JACGUT	DDLIM	DDPOW	DDFACT
0	0	$lb \cdot (100\ ft\ curb)^{-1}$	Dimensionless	$lb \cdot (100\ ft\text{-}curb)^{-1} \cdot day^{-DDPOW}$
	1	$lb \cdot ac^{-1}$	Dimensionless	$lb \cdot ac^{-1} \cdot day^{-DDPOW}$
	2	lb	Dimensionless	$lb \cdot day^{-DDPOW}$
1	0	$lb \cdot (100\ ft\ curb)^{-1}$	day^{-1}	Not Used
	1	$lb \cdot ac^{-1}$	day^{-1}	Not Used
	2	lb	day^{-1}	Not Used
2	0	$lb \cdot (100\ ft\ curb)^{-1}$	Not Used	day
	1	$lb \cdot ac^{-1}$	Not Used	day
	2	lb	Not Used	day

Parameters DDLIM, DDPOW, and DDFACT are single subscripted by land use, J.

Table 4-17. Buildup Equations for Constituents.

Enter Parameters on Card Group J3.

PSHED = Constituent quantity. t = time, days.

For parameter units, see Table 4-17.

KALC (Card Group J3)	Type	Equation	Equation Number
1	Power-Linear	$PSHED = QFACT(3) \cdot t^{QFACT(2)}$	(4-26)
		$PSHED \leq QFACT(1)$	
2	Exponential	$PSHED = QFACT(1) \cdot (1 - e^{-QFACT(2) \cdot t})$	(4-27)
3	Michaelis-Menton	$PSHED = \frac{QFACT(1) \cdot t}{(QFACT(3) + t)}$	(4-28)

Parameters QFACT are doubly subscripted. Second subscript is constituent number, K.

Table 4-18. Units for Card Input of Constituent Parameters, Card Group J3.

Define Q_1 and Q_2 ≡ Constituent quantity as follows:

NDIM	Q
0	Q_1 = lb, Q_2 = mg
1	$Q_1 = Q_2 = 10^6$ · Other quantity, e.g., 10^6·MPN
2	$Q_1 = Q_2$ = Concentration x ft^3, e.g., JTU · ft^3

For metric input substitute kg for lb, m^3 for ft^3, ha for ac and km for 100-ft.

For KALC = 4, buildup parameters are not required.

For KALC = 0, QFACT(J,K) = Q_2/g_{DD} for J = 1 to JLAND and g_{DD} = grams dust and dirt. (E.g., see Table 4-14)

Otherwise:

KALC	KACGUT	QFACT(1,K)	QFACT(2,K)	QFACT(3,K)
1	0	Q_1·(100 ft-curb)$^{-1}$	Dimensionless	Q_1·(100 ft-curb)$^{-1}$·day$^{-QFACT(2,K)}$
	1	Q_1·ac^{-1}	Dimensionless	Q_1·ac^{-1}·day$^{-QFACT(2,K)}$
	2	Q_1	Dimensionless	Q_1·day$^{-QFACT(2,K)}$
2	0	Q_1·(100 ft-curb)$^{-1}$	day^{-1}	Not Used
	1	Q_1·ac^{-1}	day^{-1}	Not Used
	2	Q_1	day^{-1}	Not Used
3	0	Q_1·(100 ft-curb)$^{-1}$	Not Used	day
	1	Q_1·ac^{-1}	Not Used	day
	2	Q_1	Not Used	day

QFACT(4,K) and QFACT(5,K) not required for KALC ≠ 0.

1. power-linear,
2. exponential, or
3. Michaelis-Menton.

Linear buildup is simply a subset of a power function buildup. The shapes of the three functions are compared in Figure 4-29 using the dust and dirt parameters (group J2) as examples, and a strictly arbitrary assignment of numerical values to the parameters. Exponential and Michaelis-Menton functions have clearly defined asymptotes or upper limits. Upper limits for linear or power function buildup may be imposed if desired. "Instantaneous buildup" may be easily achieved using any of the formulation with appropriate parameter choices. For instance, if it were desired to always have a fixed amount of dust and dirt available, DDLIM, at the beginning of any storm event (i.e., after any dry time step during continuous simulation), then linear buildup could be used with DDPOW = 1.0 and DDFACT equal to a large number $\geq$ DDLIM/DELT. Linear buildup is fastest in terms of computer time.

It is apparent in Figure 4-29 that different options may be used to accomplish the same objective (e.g., nonlinear buildup); the choice may well be made on the basis of available data to which one of the other functional forms have been fit. If an asymptotic form is desired, either the exponential or Michaelis-Menton option may be used depending upon ease of comprehension of the parameters. For instance, for exponential buildup the exponent (i.e., DDPOW for dust and dirt of QFACT(2,K) for a constituent) is the familiar exponential decay constant. It may be obtained from the slope of a semi-log plot of buildup versus time. As a numerical example, if its value were 0.4 day^{-1}, then it would take 5.76 days to reach 90 percent of the maximum buildup (see Figure 4-29).

For Michaelis-Menton buildup the parameter DDFACT for dust and dirt (or QFACT(3,K) for a constituent) has the interpretation of the half-time constant, that is, the time at which buildup is half of the maximum (asymptotic) value. For instance, DD = 50 lb at t = 0.9 days for curve 4 in Figure 4-29. If the asymptotic value is known or estimated, the half-time constant may be obtained from buildup data from the slope of a plot of DD versus t · (DDLIM-DD), using dust and dirt as an example. Generally, the Michaelis-Menton formulation will rise steeply (in fact, linearly for small t) and then approach the asymptote slowly.

The power function may be easily adjusted to resemble asymptotic behavior, but it must always ultimately exceed the maximum value (if used). The parameters are readily found from a log-log plot of buildup versus time. This is a common way of analyzing data, (e.g., Miller et al., 1978; Ammon, 1979; Smolenyak, 1979; Jewell et al., 1980; Wallace, 1980).

Prior to the beginning of the simulation, buildup occurs over DRYDAY days for both single event and continuous simulation. During the simulation, buildup will occur during dry time steps (runoff less than 0.0005 in./hr or 0.013 mm/hr) only for continuous simulation.

For a given constituent, buildup may be computed 1) as a fraction of dust

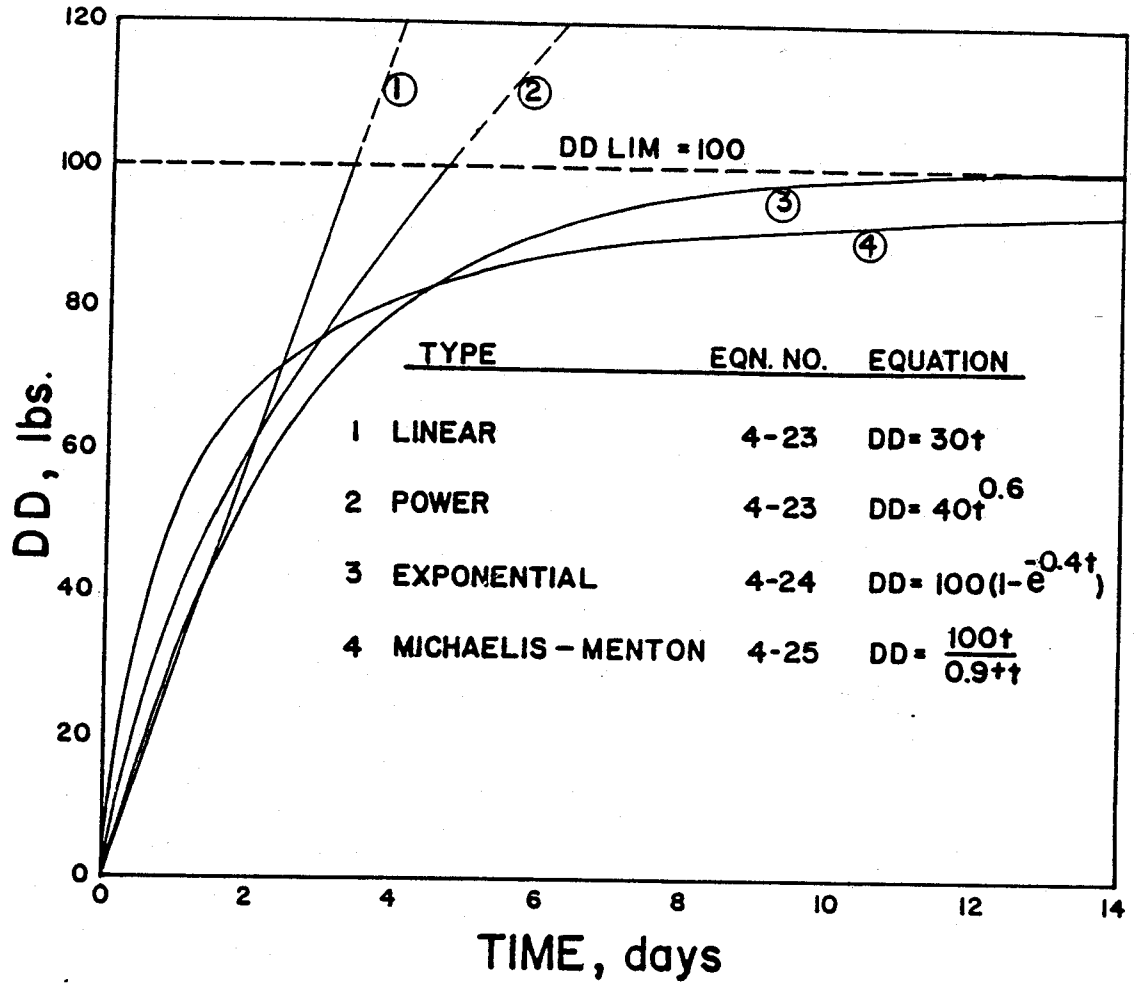


Figure 4-29. Comparison of Linear and Three Non-linear Buildup Equations. "Dust and dirt," DD, is used as an example. Numerical values have been chosen arbitrarily.

and dirt, or 2) individually for the constituent. If the first option is used (KALC = 0 in data group J3) then the rate of buildup will depend upon the fraction and the functional form used for a given land use. In other words, the functional form could vary with land use for a given constituent. If the second option is used ($1 \leq KALC \leq 3$ in data group J3) the buildup function will be the same for all land uses (and subcatchments) for a given constituent. Of course, each constituent may use any of the options. Catchment characteristics (i.e., area or gutter length) may be included through the use of parameters JACGUT (group J2) or KACGUT (group J3), as described in Tables 4-16 and 4-18.

Units for dust and dirt buildup parameters are reasonably straightforward and explained in Table 4-16. For example, if linear buildup was assumed using the Chicago APWA data (APWA, 1969), values for DDFACT could be taken directly from Table 4-13 for different land uses. Parameters JACGUT would equal zero. A limiting buildup (DDLIM) of so many lb/100 ft-curb could be entered if desired, and for linear buildup, DDPOW = 1.0.

Units for constituent buildup parameters depend upon parameter NDIM, that is, the units for the buildup parameters depend upon the units of the constituent. When NDIM = 0 and the constituent concentration is simply mg/l (mass per volume), then buildup units are straightforward and given as pounds. When NDIM = 1, concentrations are given as some other quantity per volume, usually a bacteria count such as MPN/l. In this case buildup is simply in millions of MPN. The scaling is included to facilitate entry of large numbers.

When NDIM = 2, constituent concentrations are given in specialized units such as pH, JTU, PCU, ^{o}C, etc. "Buildup" of such parameters is rarely referred to; instead, a much more viable option is the use of a rating curve that gives load (i.e., concentration times flow) directly as a function of flow (discussed subsequently). However, the buildup option may be used with such constituents if desired. Within the Runoff Block, concentrations are ultimately computed in subroutine GUTTER by dividing a load (quantity per second) by a flow rate (cubic feet per second). Thus, if the quantity has units of concentration times cubic feet, the proper conversion will be made. This is the reason for the peculiar units requested in Table 4-18. Such an analysis is straightforward and analogous to computations of total mass in pounds (obtained by summing flow rate times concentration) for constituents measured in mg/l.

Buildup Data --

Data with which to evaluate buildup parameters are available in most of the references cited earlier under "available studies." Manning et al. (1977) have perhaps the best summary of linear buildup rates; these are presented in Table 4-19. It may be noted that dust and dirt buildup varies considerably among three different studies. Individual constituent buildup may be taken conveniently as a fraction of dust and dirt from the entries in Table 4-18, or they may be computed explicitly. It is apparent that although a large number of constituents have been sampled, little distinction can be made on the basis of land uses for most of them.

Table 4-19. Nationwide Data on Linear Dust and Dirt Buildup Rates and on Pollutant Fractions. (After Manning et al., 1977, pp. 138-140.)

Pollutant		Land Use Categories				
		Single Family Residential	Multiple Family Residential	Commercial	Industrial	All Data
Dust and Dirt Accumulation lb/curb-mi/day kg/curb-km/day						
Chicago[1]	Mean	35(10)	109(31)	181(51)	325(92)	158(44)
	Range	19-96(5-27)	62-153(17-43)	71-326(80-151)	284-536(80-151)	19-536(5-15)
	No. of Obs	60	93	126	55	334
Washington[2]	Mean	--	--	134(38)	--	134(38)
	Range	--	--	35-365(10-103)	--	35-365(10-103)
	No. of Obs	--	--	22	--	22
Multi-City[3]	Mean	182(51)	157(44)	45(13)	288(81)	175(49)
	Range	3-950(1-268)	8-770(2-217)	3-260(1-73)	4-1,500(1-423)	3-1,500(1-423)
	No. of Obs	14	8	10	12	44
All Data	Mean	62(17)	113(32)	116(47)	319(90)	159(45)
	Range	3-950(1-268)	8-770(2-217)	3-365(1-103)	4-1,500(1-423)	3-1,500(1-423)
	No. of Obs	74	101	158	67	400
BOD mg/kg	Mean	5,260	3,370	7,190	2,920	5,030
	Range	1,720-9,430	2,030-6320	1,280-14,540	2,820-2,950	1,288-14,540
	No. of Obs	59	93	102	56	292
COD mg/kg	Mean	39,250	41,970	61,730	25,080	46,120
	Range	18,300-72,800	24,600-61,300	24,800-49 8,410	23,000-31,800	18,300-498,410
	No. of Obs	59	93	102	38	292
Total N-N (mg/kg)	Mean	460	550	420	430	480
	Range	325-525	356-961	323-480	410-431	323-480
	No. of Obs	59	93	80	38	270
Kjeldahl N (mg/kg)	Mean	--	--	640	--	640
	Range	--	--	230-1,790	--	230-1,790
	No. of Obs	--	--	22	--	22
NO_3 (mg/kg)	Mean	--	--	24	--	24
	Range	--	--	10-35	--	10-35
	No. of Obs	--	--	21	--	21
NO_2-N (mg/kg)	Mean	--	--	0	--	15
	Range	--	--	0	--	0
	No. of Obs.	--	--	15	--	15
Total PO_4 (mg/kg)	Mean	--	--	170	--	170
	Range	--	--	90-340	--	90-340
	No. of Obs	--	--	21	--	21

Table 4-19. (Continued)

Pollutant:		Land Use Categories				
		Single Family Residential	Multiple Family Residential	Commercial	Industrial	All Data
PO_4-P	Mean	49	58	60	26	53
(mg/kg)	Range	20-109	20-73	0-142	14-30	0-142
	No. of Obs	59	93	101	38	291
Chlorides	Mean	--	--	220	--	220
(mg/kg)	Range	--	--	100-370	--	100-370
	No. of Obs	--	--	22	--	22
Asbestos	Mean	--	--	57.2×10^6 (126×10^6)	--	57.2×10^6 (126×10^6)
fibers/lb	Range	--	--	$0\text{-}172.5 \times 10^6$ ($0\text{-}380 \times 10^6$)	--	$0\text{-}172.5 \times 10^6$ ($0\text{-}380 \times 10^6$)
(fibers/kg)	No. of Obs	--	--	16	--	16
Ag	Mean	--	--	200	--	200
(mg/kg)	Range	--	--	0-600	--	0-600
	No. of Obs	--	--	3	--	3
As	Mean	--	--	0	--	0
(mg/kg)	Range	--	--	0	--	0
	No. of Obs	--	--	3	--	3
Ba	Mean	--	--	38	--	38
(mg/kg)	Range	--	--	0-80	--	0-80
	No. of Obs	--	--	8	--	8
CD	Mean	3.3	2.7	2.9	3.6	3.1
(mg/kg)	Range	0-8.8	0.3-6.0	0-9.3	0.3-11.0	0-11.0
	No. of Obs	14	8	22	13	57
Cr	Mean	200	180	140	240	180
(mg/kg)	Range	111-325	75-325	10-430	159-335	10-430
	No. of Obs	14	8	30	13	65
Cu	Mean	91	73	95	87	90
(mg/kg)	Range	33-150	34-170	25-810	32-170	25-810
	No. of Obs	14	8	30	13	65
Fe	Mean	21,280	18,500	21,580	22,540	21,220
(mg/kg)	Range	11,000-48,000	11,000-25,000	5,000-44,000	14,000-43,000	5,000-48,000
	No. of Obs	14	8	10	13	45
Hg	Mean	--	--	0.02	--	0.02
(mg/kg)	Range	--	--	0-0.1	--	0-0.1
	No. of Obs	--	--	6	--	6
Mn	Mean	450	340	380	430	410
(mg/kg)	Range	250-700	230-450	160-540	240-620	160-700
	No. of Obs	14	8	10	13	45
Ni	Mean	38	18	94	44	62
(mg/kg)	Range	0-120	0-80	6-170	1-120	1-170
	No. of Obs	14	8	30	13	65

Table 4-19. (Continued)

Pollutant		Land Use Categories				
		Single Family Residential	Multiple Family Residential	Commercial	Industrial	All Data
Pb (mg/kg)	Mean	1,570	1,980	2,330	1,590	1,970
	Range	220-5,700	470-3,700	0-7,600	260-3,500	0-7,600
	No. of Obs	14	8	29	13	64
Sb (mg/kg)	Mean	--	--	54	--	54
	Range	--	--	50-60	--	50-60
	No. of Obs	--	--	3	--	3
Se (mg/kg)	Mean	--	--	0	--	0
	Range	--	--	0	--	0
	No. of Obs	--	--	3	--	3
Sn (mg/kg)	Mean	--	--	17	--	17
	Range	--	--	0-50	--	0-50
	No. of Obs	--	--	3	--	3
Sr (mg/kg)	Mean	32	18	17	13	21
	Range	5-110	12-24	7-38	0-24	0-110
	No. of Obs	14	8	10	13	45
Zn (mg/kg)	Mean	310	280	690	280	470
	Range	110-810	210-490	90-3,040	140-450	90-3,040
	No. of Obs	14	8	30	13	65
Fecal Strep No./gram	Geo. Mean	--	--	370	--	370
	Range	--	--	44-2,420	--	44-2,420
	No. of Obs	--	--	17	--	17
Fecal Coli No./gram	Geo. Mean	82,500	38,800	36,900	30,700	94,700
	Range	26-130,000	1,500-1,000,000	140-970,000	67-530,000	26-1,000,000
	No. of Obs	65	96	84	42	287
Total Coli No./gram	Geo. Mean	891,000	1,900,000	1,000,000	419,000	1,070,000
	Range	25,000-3,000,000	80,000-5,600,000	18,000-3,500,000	27,000-2,600,000	18,000-5,600,000
	No. of Obs	65	97	85	43	290

As an example, suppose options METHOD = 0 and KALC = 0 are chosen in groups J2 and J3 and "all data" are used from Table 4-19 to compute dust and dirt parameters. Since the data are given as lb x curb-mile^{-1} x day^{-1}, linear buildup is assumed and commercial land use DD buildup (average for all data) would be DDFACT = 2.2 lb / (100-ft curb - day) (i.e., 2.2 = 116/52.8, where 52.8 is the number of hundreds of feet in a mile). DDPOW would equal 1.0 and no data are available to set an upper limit, DDLIM. Parameter JACGUT = 0 so that the loading rate will be multiplied by the curb length for each subcatchment. Constituent fractions are available from the table. For instance, QFACT values for commercial land use would be 7.19 mg/g for BOD5, 0.06 mg/g for total phosphorus, 0.00002 mg/g for Hg, and 0.0369 106 MPN/g for fecal coliforms. Direct loading rates could be computed for each constituent as an alternative. For instance, with KALC = 1 for BOD5 and KACGUT = 0, parameter QFACT(3,K) would equal 2.2 x 0.00719 = 0.0158 lb / (100-ft curb - day).

It must be stressed once again that the generalized buildup data of Table 4-19 are merely informational and are never a substitute for local sampling or even a calibration using measured concentrations. They may serve as a first trial value for a calibration, however. In this respect it is important to point out that concentrations and loads computed by the Runoff Block are usually linearly proportional to buildup rates. If twice the quantity is available at the beginning of a storm, the concentrations and loads will be doubled. Calibration is probably easiest with linear buildup parameters, but it depends on the rate at which the limiting buildup, i.e., DDLIM or QFACT(1,K), is approached. If the limiting value is reached during the interval between most storms, then calibration using it will also have almost a linear effect on concentrations and loads. If is apparent that the interaction between the interevent time of storms (i.e., dry days) and the effect of buildup is accomplished using the rate constants DDPOW and DDFACT for dust and dirt and QFACT(2,K) and QFACT(3,K) for constituents. This is discussed further subsequently under "Overall Sensitivity to Quality Parameters."

Almost all of the above loading data are from samples of storm water, not combined sewage. Although some loadings may be inferred from concentration measurements of combined sewage (e.g., Huber et al., 1981a; Wallace, 1980), they are not directly related to most surface accumulation measurements. Thus, if buildup data alone are used in combined sewer areas, buildup rates will probably be multiples of the values listed, for example in Table 4-18. The proper factor will most easily be found by calibration with local concentration measurements. Alternatively, the dry-weather flow mixing and scour routines in the Transport Block may be used to increase combined sewer concentrations. However, mixing of dry-weather flow with storm water has a negligible effect on concentrations during high flows, and the scour routine is highly empirical and adds a second calibration step. Hence, the easiest option for combined sewers is probably to calibrate as described earlier. Calibration may also be achieved using the rating curve approach.

When snowmelt is simulated, some of the ten constituents may be used to represent deicing chemicals; several common roadway "salts" are listed in Figure 4-24. Applications of such chemicals varies depending upon depth of snowfall and local practice. Loading rates are discussed in Appendix II and in other references (Proctor and Redfern and J.F. MacLaren, 1976a, 1976b;

Field et al., 1973; Richardson et al., 1974; Ontario Ministry of the Environment, 1974). For instance, guidelines of the type proposed by Richardson et al. (1974) are used in many cities and are given in Table 4-20. Summaries are also given by Manning et al. (1977) and Lager et al. (1977a).

Since for most deicing chemicals the principal source is direct application during snow events, there is little or no buildup during snow-free periods. Parameter LINKUP (group J3) may be used to simulate this effect for continuous simulation. Of course, for single event simulation, buildup may be computed directly be the user and input in data group L1 or computed by any of the equations just discussed. Since there is only one storm simulated (ordinarily) there is no need for inter-storm buildup.

Washoff

Definition --

Washoff is the process of erosion or solution of constituents from a subcatchment surface during a period of runoff. It the water depth is more than a few millimeters, processes of erosion may be described by sediment transport theory in which the mass flow rate of sediment is proportional to flow and bottom shear stress, and a critical shear stress can be used to determine incipient motion of a particle resting on the bottom of a stream channel, e.g., Graf (1971), Vanoni (1975). Such a mechanism might apply over pervious areas and in street gutters and larger channels. For thin overland flow, however, rainfall energy can also cause particle detachment and motion. This effect is often incorporated into predictive methods for erosion from pervious areas (Wischmeier and Smith, 1958) and may also apply to washoff from impervious surfaces, although in this latter case, the effect of a limited supply (buildup) of the material must be considered.

Washoff Formulation --

Ammon (1979) reviews several theoretical approaches for urban runoff washoff and concludes that although the sediment transport based theory is attractive, it is often insufficient in practice because of lack of data for parameter (e.g., shear stress) evaluation, sensitivity to time step and discretization and because simpler methods usually work as well (still with some theoretical basis) and are usually able to duplicate observed washoff phenomena. Among the latter, the most oft-cited results are those of Sartor and Boyd (1972), shown in Figure 4-30, in which constituents were flushed from streets using a sprinkler system. From the figure it would appear that an exponential relationship could be developed to describe washoff of the form:

$$POFF(t) = PSHED_o(1 - e^{-kt}) \qquad (4\text{-}32)$$

where POFF = cumulative amount washed off at time, t,
$PSHED_o$ = initial amount of quantity on surface at t = 0, and
k = coefficient.

POFF is shown as the ordinate of Figure 4-30. Alternatively, since the amount remaining, PSHED(t), equals $PSHED_o$-POFF, then:

Table 4-20. Guidelines for Chemical Application Rates for Snow Control. (Richardson et al., 1974.)

WEATHER CONDITIONS			APPLICATION RATE (Pounds of material per mile of 2-lane road or 2-lanes of divided)			
Temperature	Pavement Conditions	Precipitation	Low-and High-Speed Multilane Divided	Two and Three-Lane Primary	Two-Lane Secondary	INSTRUCTIONS
30°F and above	Wet	Snow	300 salt	300 salt	300 salt	- wait at least 0.5 hour before plowing
		Sleet or Freezing Rain	200 salt	200 salt	200 salt	- reapply as necessary
25-30°F	Wet	Snow or Sleet	initial at 400 salt repeat at 200 salt	initial at 400 salt repeat at 200 salt	initial at 400 salt repeat at 200 salt	- wait at least 0.5 hour before plowing; repeat
		Freezing Rain	initial at 300 salt repeat at 200 salt	initial at 300 salt repeat at 200 salt	initial at 300 salt repeat at 200 salt	- repeat as necessary
20-25°F	Wet	Snow or Sleet	initial at 500 salt repeat at 250 salt	initial at 500 salt repeat at 250 salt	1200 of 5:1 Sand/Salt; repeat same	- wait about 0.75 hour before plowing; repeat
		Freezing Rain	initial at 400 salt repeat at 300 salt	initial at 400 salt repeat at 300 salt		- repeat as necessary
15-20°F	Dry	Dry Snow	plow	plow	plow	- treat hazardous areas with 1200 of 20:1 Sand/Salt
	Wet	Wet Snow or Sleet	500 of 3:1 Salt/ Calcium Chloride	500 of 3:1 Salt/ Calcium Chloride	1200 of 5:1 Sand	- wait about one hour before plowing; continue plowing until storm ends; then repeat application
below 15°F	Dry	Dry Snow	plow	plow	plow	- treat hazardous area with 1200 of 20:1 Sand/Salt

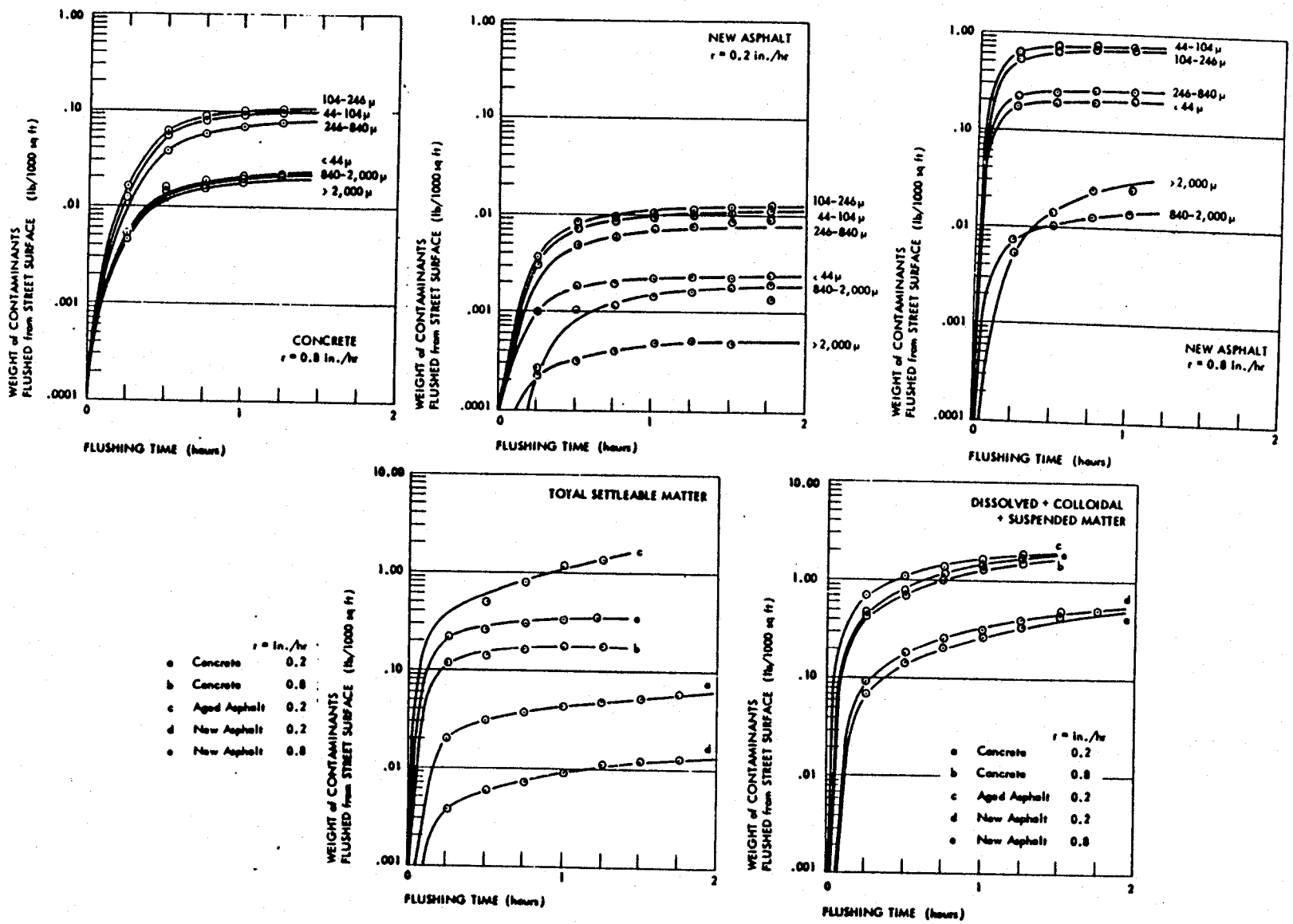


Figure 4-30. Washoff of Street Solids by Flushing with a Sprinkler System. (After Sartor and Boyd, 1972, pp. 86-87.)

$$PSHED(t) = PSHED_o e^{-kt} \quad (4\text{-}33)$$

where PSHED(t) = quantity remaining on surface at time, t,
$PSHED_o$ = initial amount of quantity, and
k = coefficient.

It is clear that the coefficient, k, is a function of both particle size and runoff rate. An analysis of the Sartor and Boyd (1972) data by Ammon (1979) indicates that k increases with runoff rate, as would be expected, and decreases with particle size.

The Sartor and Boyd data lend credibility to the washoff assumption included in the original SWMM release (and all versions to date) that the rate of washoff (e.g., mg/sec) at any time is proportional to the remaining quantity:

$$dPSHED/dt = -k \cdot PSHED \quad (4\text{-}34)$$

The solution of equation 4-34 is equation 4-33. This was first proposed by Mr. Allen J. Burdoin, a consultant to Metcalf and Eddy, during the original SWMM development. The coefficient k may be evaluated by assuming it is proportional to runoff rate, r:

$$k = RCOEF \cdot r \quad (4\text{-}35)$$

where RCOEF = washoff coefficient, $in.^{-1}$, and
r = runoff rate over subcatchment, in./hr.

Burdoin <u>assumed</u> that one-half inch of total runoff in one hour would wash off 90 percent of the initial surface load, leading to the now familiar value of RCOEF of 4.6 $in.^{-1}$. (The actual time distribution of intensity does not affect the calculation of RCOEF.)

Sonnen (1980) estimated values for RCOEF from sediment transport theory ranging from 0.052 to 6.6 $in.^{-1}$, increasing as particle diameter decreases, rainfall intensity decreases, and as catchment area decreases. He pointed out that 4.6 $in.^{-1}$ is relatively large compared to most of his calculated values. Although the exponential washoff formulation of equations 4-34 and 4-35 is not completely satisfactory as explained below, it has been verified experimentally by Nakamura (1984a, 1984b), who also showed the dependence of the coefficient k on slope, runoff rate and cumulative runoff volume.

Even in the original SWMM release, this exponential formulation did not adequately fit some data, and as a "correction," availability factors of the form

$$AV = a + br^c \quad (4\text{-}36)$$

where AV = availability factor, and
a,b,c = coefficients,

were multiplied by equation 4-32 in order to match measured suspended solids concentrations in Cincinnati and San Francisco (Metcalf and Eddy et al., 1971a, Section 11). The primary difficulty is that use of equations 4-34 and 4-35 will always produce decreasing concentrations as a function of time regardless of the time distribution of runoff. This is counter-intuitive, since it is expected that high rates during the middle of a storm might indeed produce higher concentrations than those preceding. This may be explained by observing that concentrations are calculated by dividing the load rate (e.g., mg/sec) to obtain the quantity per volume (e.g., mg/l). Thus,

$$C = \frac{1}{Q}\frac{dPSHED}{dt} = const \cdot \frac{RCOEF \cdot r \cdot PSHED}{A \cdot r} \qquad (4\text{-}37)$$

where C = concentration, quantity/volume,
Q = A · r = flow rate, cfs,
A = subcatchment area, ac, and
r = runoff rate, in./hr.,

and the constant incorporates conversion factors. Clearly, the concentration will always decrease with time since the runoff rate, r, divides out of the equation and the quantity remaining, PSHED, continues to decrease. This problem is overcome in SWMM by making washoff at each time step, POFF, proportional to runoff rate to a power, WASHPO:

$$-POFF(t) = dPSHED/dt = -RCOEFX \cdot r^{WASHPO} \cdot PSHED \qquad (4\text{-}38)$$

where POFF = constituent load washed off at time, t, quantity/sec (e.g., mg/sec),
PSHED = quantity of constituent available for washoff at time, t, (e.g., mg),
RCOEFX = washoff coefficient = RCOEF/3600, $(in/hr)^{-WASHPO} \cdot sec^{-1}$, and
r = runoff rate, in./hr.

It may be seen that if equation 4-38 is divided by runoff rate to obtain concentration, then concentration is now proportional to $r^{WASHPO-1}$. Hence, if the increase in runoff rate is sufficient, concentrations can increase during the middle of a storm even if PSHED is diminished. (Equation 4-38 was first suggested in a 1974 report to the Boston District Corps of Engineers, authorship unknown).

There are two parameters to be determined, RCOEF and WASHPO. Availability factors of the form of equation 4-36 are no longer used since there is sufficient flexibility for calibration using only equation 4-38. Of course, the original SWMM methodology can be recovered by using WASHPO = 1.0.

Effects of Parameters —

The effect of different values for RCOEF and WASHPO on PSHED and concentration is shown for four temporal distributions of runoff (Figure 4-31) in Figures 4-32 to 4-35. The basis for the calculations and plotted values is given in Table 4-21. It may be seen that concentrations may be made to in-

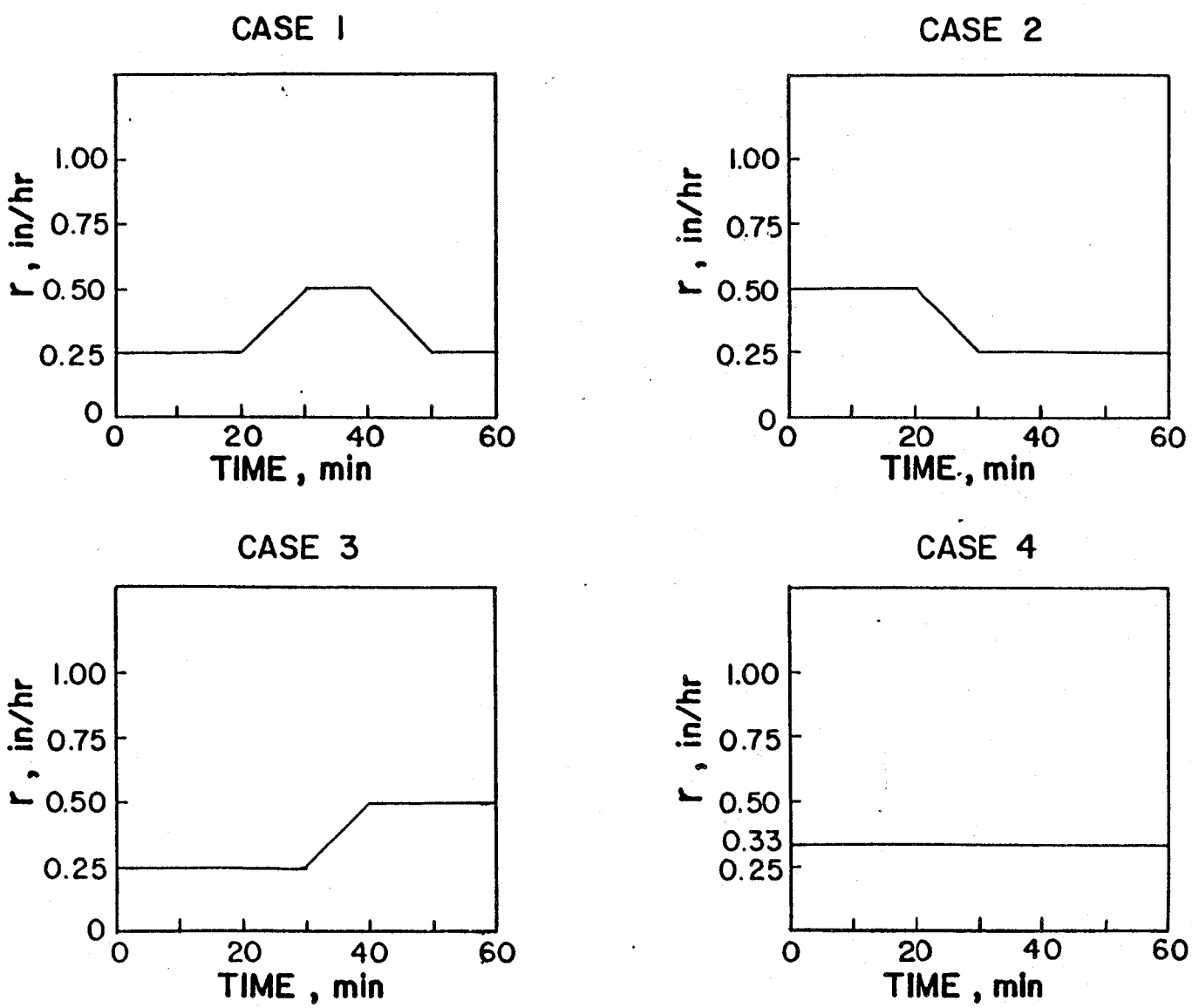


Figure 4-31. Time Variation of Runoff Rate Used in Example of Table 4-21 and Figures 4-32 to 4-35

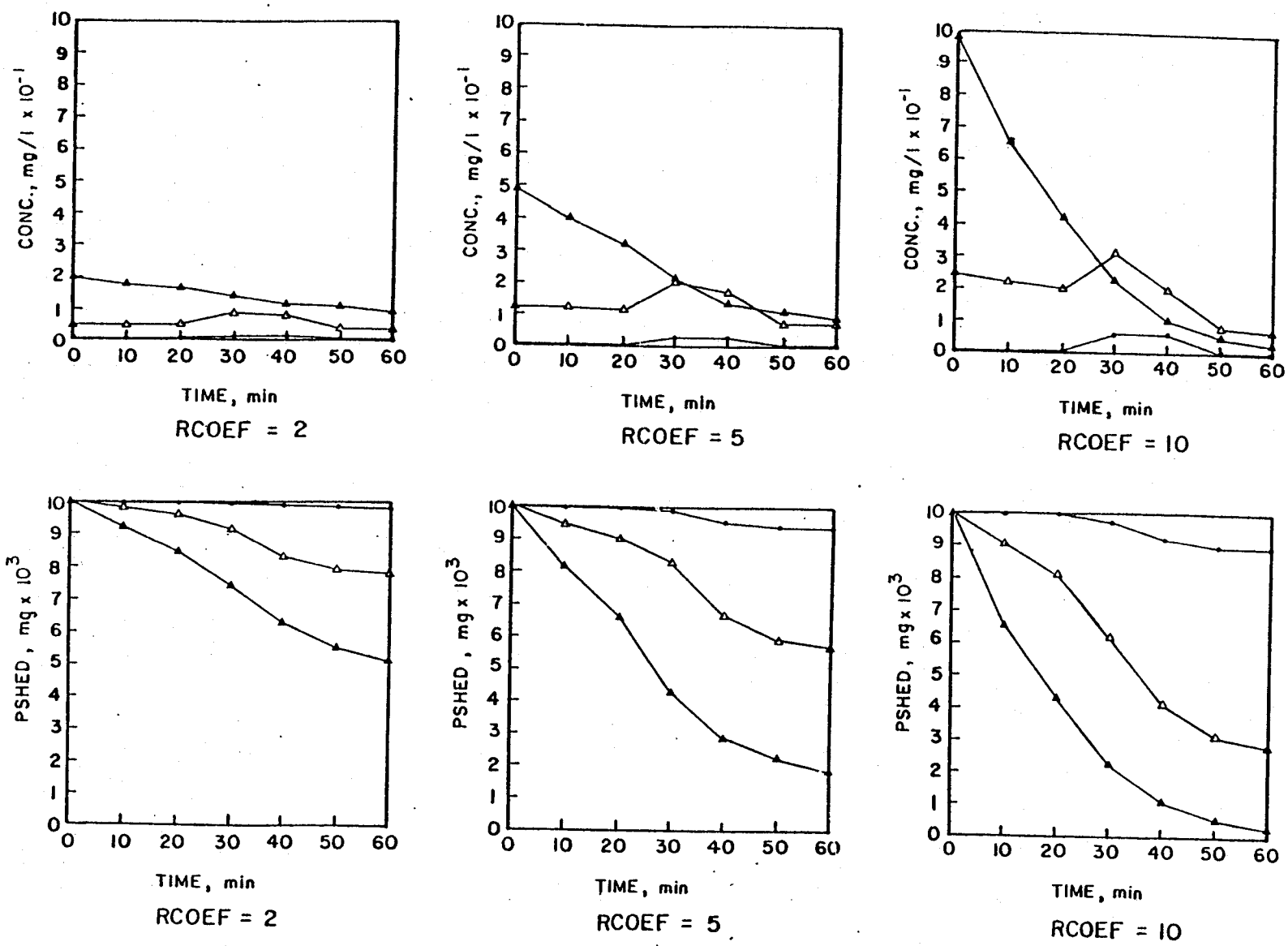


Figure 4-32. Time History of Concentration and Subcatchment Load (PSHED) for Case 1 Runoff (Figure 4-31).

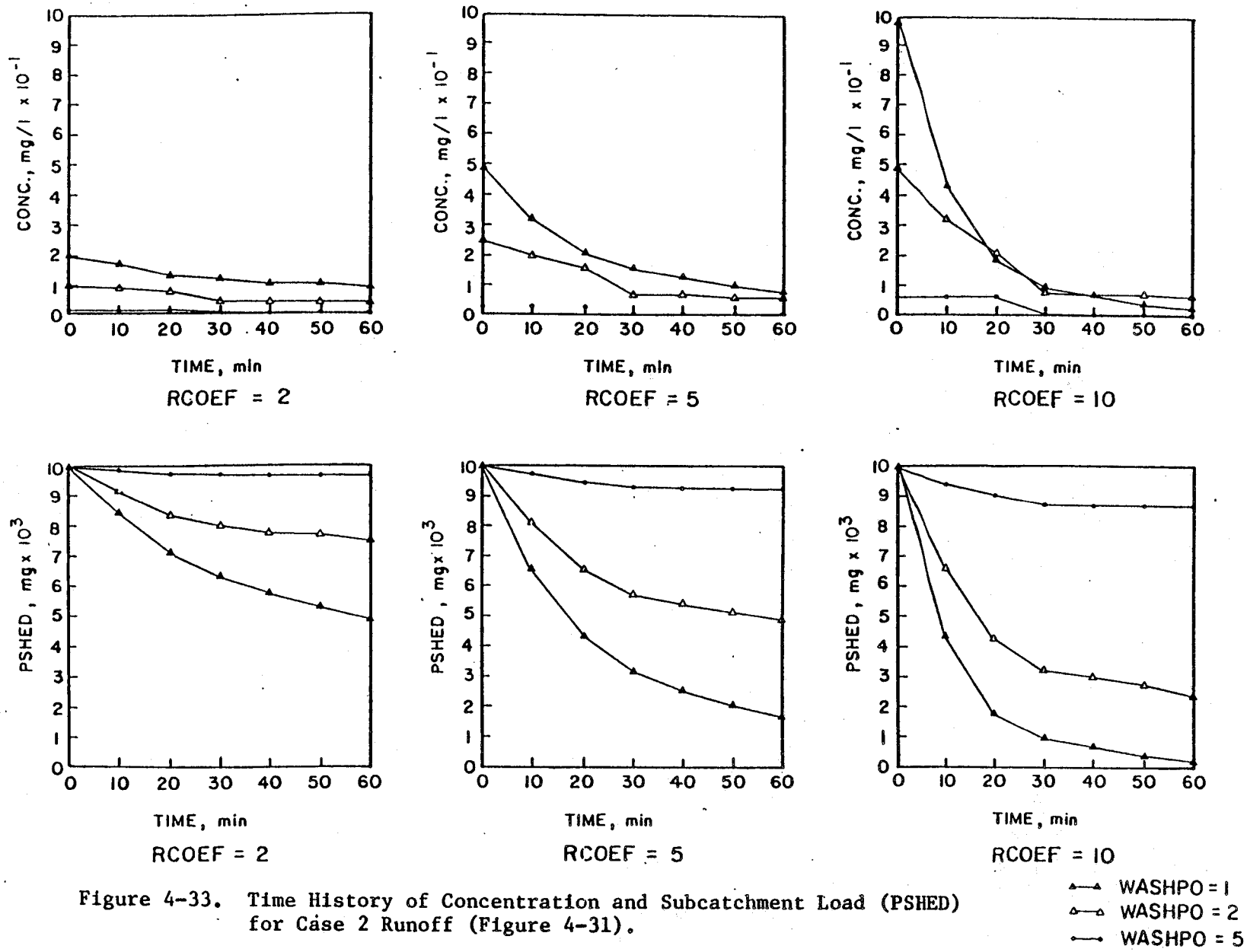


Figure 4-33. Time History of Concentration and Subcatchment Load (PSHED) for Case 2 Runoff (Figure 4-31).

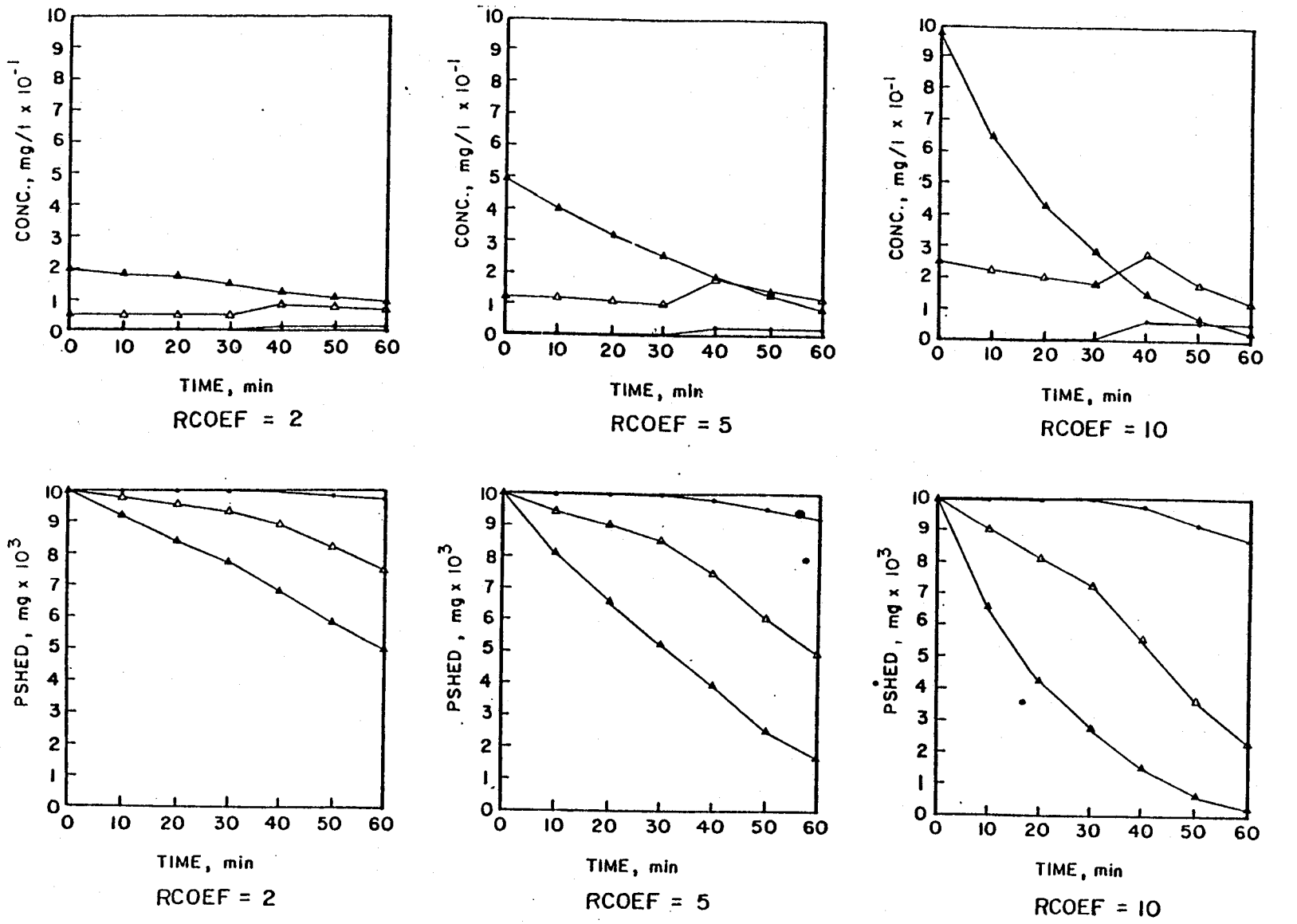


Figure 4-34. Time History of Concentration and Subcatchment Load (PSHED) for Case 3 Runoff (Figure 4-31).

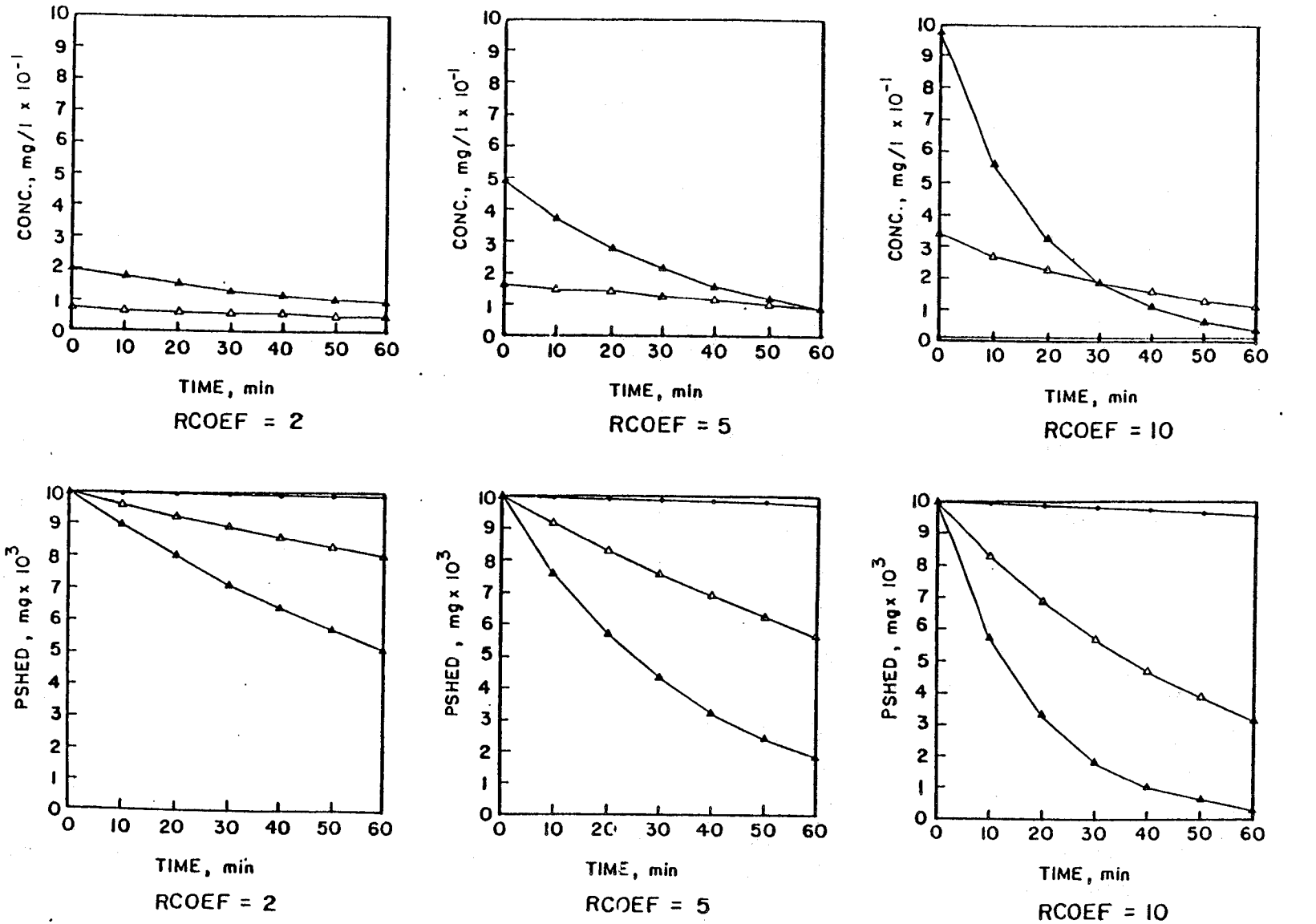


Figure 4-35. Time History of Concentration and Subcatchment Load (PSHED) for Case 4 Runoff (Figure 4-31).

crease with increasing runoff rate during the middle of a storm by increasing the value of WASHPO. However, perhaps counter intuitively, a larger value of WASHPO generally yields lower concentrations and higher values of PSHED. This is because the runoff rates used for the example are all less than 1.0 in./hr. (25.4 mm/hr) and decrease in magnitude when raised to a power. The reverse will be true for values of $r > 1.0$. But most storms will have $r < 1.0$ throughout their durations. Increasing the value of RCOEF always increases concentrations. (See also the subsequent discussion under "Overall Sensitivity to Quality Parameters".)

In subroutine QSHED of the Runoff Block, washoff load rates (e.g., mg/sec) are computed instantaneously at the end of a time step using equation 4-35. They are subsequently combined with other possible inflow loads to a gutter/pipe or inlet before dividing by the total inflow rate to obtain a concentration. The remaining constituent load on the subcatchment at the end of a time step is determined by using the average power of the runoff rate over the time step,

$$PSHED(t+\Delta t) = PSHED(t) \cdot e^{-RCOEF \cdot \frac{r(t)^{WASHPO} + r(t+\Delta t)^{WASHPO}}{2} \cdot \Delta t} \qquad (4\text{-}39)$$

Table 4-21. Parameters Used for Washoff Equation Example

Equations Used:

Equation 4-39 and

$$C(t+\Delta t) = \frac{Const.\ \ RCOEFX}{A} \cdot r(t+\Delta t)^{WASHPO-1} \cdot PSHED(t+\Delta t)$$

where PSHED(t) = mg on catchment,
PSHED(0) = 1000 mg,
C(t) = concentration, mg/l,
RCOEFX = RCOEF/3600,
Const. = 0.0353 ft^3/l, (utilizing 1 ac-in/hr = 1 cfs approx.),
A = 1 ac,
Δt = 0.16667 hr. (10 min),
r(t) = runoff rate in in./hr. (Figure 4-31).

Evaluate for the 36 combinations of four runoff rate distributions (Figure 4-31), three values of RCOEF and three values of WASHPO given below:

RCOEF, $(in/hr)^{-WASHPO} \cdot hr^{-1}$	WASHPO
2	1
5	2
10	5

This calculation is done prior to application of equation 4-38. The average (trapezoidal rule) approximates the integral of r^{WASHPO} over the time step.

That the load rate of sediment is proportional to flow rate as in equation 4-38 is supported by both theory and data. For instance, sediment data from streams can usually be described by a sediment rating curve of the form

$$G = aQ^b \tag{4-40}$$

where G = sediment load rate, mg/sec,
Q = flow rate, cfs, and
a,b = coefficients.

Due to a hysteresis effect, such relationships may vary during the passing of a flood wave, but the functional form is evident in many rivers, e.g., Vanoni (1975), pp. 220-225, Graf (1971), pp.234-241, and Simons and Senturk (1977), p. 602. Of particular relevance to overland flow washoff is the appearance of similar relationships describing sediment yield from a catchment e.g., Vanoni (1975), pp. 472-481. The exponent b in equation 4-40 corresponds to the exponent WASHPO in equation 4-38, and the presence of the quantity PSHED in equations 4-38 reflects the fact that the total quantity of sediment washed off a largely impervious urban area is likely to be limited to the amount built up during dry weather. Natural catchments and rivers from which equation 4-40 is derived generally have no source limitation.

The use of rating curves in their own right is an option in the Runoff Block which will be discussed subsequently. At this point, however, results from sediment transport theory can be used to provide guidance for the magnitude of parameters WASHPO and RCOEF in equation 4-38. Values of the exponent b in equation 4-40 range between 1.1 and 2.6 for rivers and sediment yield from catchments, with most values near 2.0. Typically, the exponent tends to decrease (approach 1.0) at high flow rates (Vanoni, 1975, p. 476). In the Runoff Block, constituent concentrations will follow runoff rates better if WASHPO is higher (see Figures 4-32 to 4-35). A reasonable first guess for WASHPO would appear to be in the range of 1.5-2.5.

Values of RCOEF are much harder to infer from the sediment rating curve data since they vary in nature by almost five orders of magnitude. The issue is further complicated by the fact that equation 4-38 includes the quantity remaining to be washed off, PSHED, which decreases steadily during an event. At this point it will suffice to say that values of RCOEF between 1.0 and 10 appear to give concentrations in the range of most observed values in urban runoff. Both RCOEF and WASHPO may be varied in order to calibrate the model to observed data.

The preceding discussion assumes that urban runoff quality constituents will behave in some manner similar to "sediment" of sediment transport theory. Since many constituents are in particulate form the assumption may not be too bad. If the concentration of a dissolved constituent is observed to decrease strongly with increasing flow rate, a value of WASHPO < 1.0 could be used.

Although the development has ignored the physics of rainfall energy in eroding particles, the runoff rate, r, in equation 4-38 closely follows rainfall intensity. Hence to some degree at least, greater washoff will be experienced with greater rainfall rates. As an option, soil erosion literature could be surveyed to infer a value of WASHPO if erosion is proportional to rainfall intensity to a power.

An idea of the relative effect of parameters RCOEF and WASHPO has been shown in Figures 4-32 to 4-35. Another view is presented in Figure 4-36 in which the time history of washoff is presented as a function of flow for various parameter values and for a more realistic runoff hydrograph. By variation of WASHPO especially, the shape of the curve may be varied to match local data. A plot using such data (Figure 4-37) is illustrated under the discussion of rating curves, and several such plots are given later on.

Related Buildup-Washoff Studies

Several studies are directly related to the preceding discussions of the SWMM Runoff Block water quality routines. Some of these have been mentioned previously in the text, but it is worthwhile pointing out those that are particularly relevant to SWMM modeling as opposed to data collection and analysis (although most of the studies do, of course, utilize data as well). The following discussion is by no means exhaustive but does include several studies that have simulated water quality using buildup-washoff mechanisms, rating curves or both.

The U.S. Geological Survey (USGS) has performed comprehensive urban hydrologic studies from both a data collection and modeling point of view. For example, their South Florida urban runoff data are described and referenced in the EPA Urban Rainfall-Runoff Quality Data Base (Huber et al., 1981a). Urban rainfall-runoff quantity may be simulated with the USGS distributed Routing Rainfall-Runoff Model (Dawdy et al., 1978; Alley et al., 1980a) which includes simulation of water quality. This is accomplished using a separate program that uses the quantity model results as input. These efforts are described by Alley (1980) and Alley et al. (1980b). Alley (1981) also provides a method for optimal estimation of washoff parameters using measured data. The USGS procedures are based in part upon earlier work of Ellis and Sutherland (1979). These four references all discuss the use of the original SWMM buildup-washoff equations. An application of SWMM Runoff and Transport Blocks to two Denver catchments during which buildup-washoff parameters were calibrated is described by Ellis (1978) and Alley and Ellis (1979).

Work at the University of Massachusetts has developed procedures for calibration of SWMM Runoff Block quality (Jewell et al., 1978a) and for determination of appropriate washoff relationships (Jewell et al., 1978b). Jewell et al. (1980) and Jewell and Adrian (1981) reviewed the supporting data base for buildup-washoff relationships and advocate using local data to develop site specific equations for buildup and washoff. Most of their suggested forms could be simulated using the available functional forms in SWMM.

Since several other models use quality formulations similar to those of SWMM, their documentation provides insight into choosing proper SWMM parame-

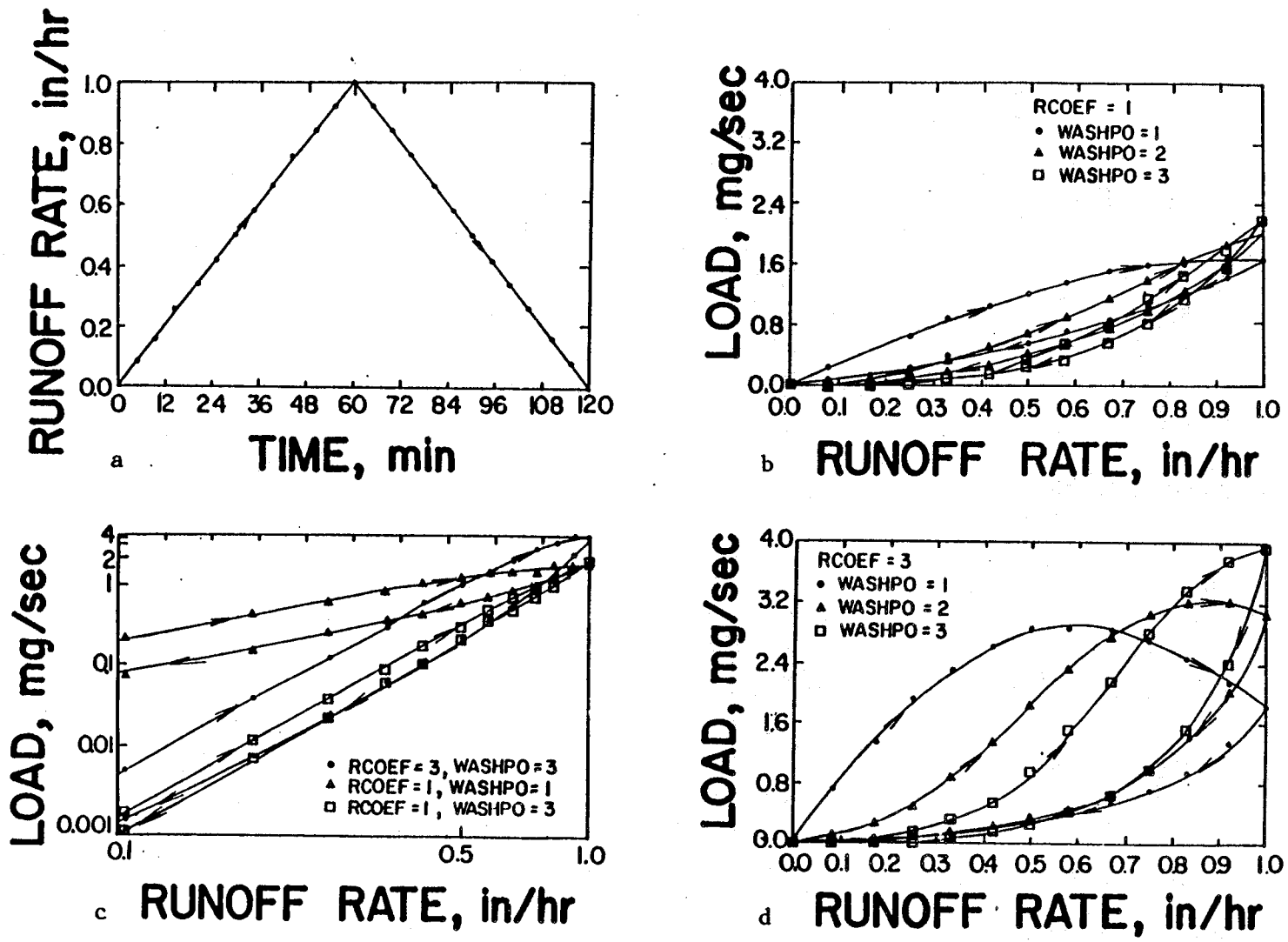


Figure 4-36. Simulated Load Variations within a Storm as a Function of Runoff Rate. The initial surface load is 1000 mg on a 1 ac catchment, and the time step is 5 min. The loop effect is exagerated as RCOEF is increased (Figures b vs. d). The loops are flattened when using a log-log scale (Figure c).

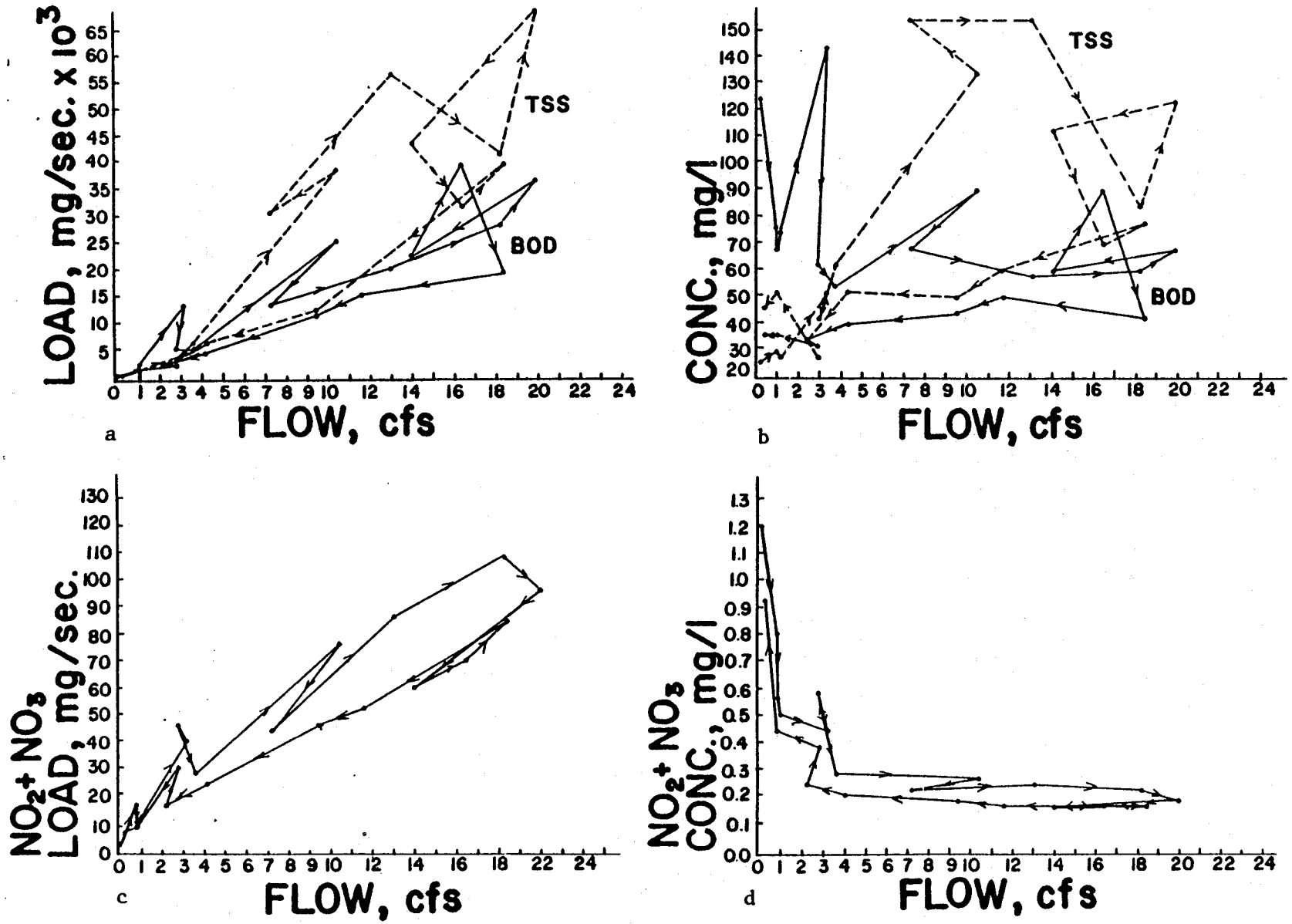
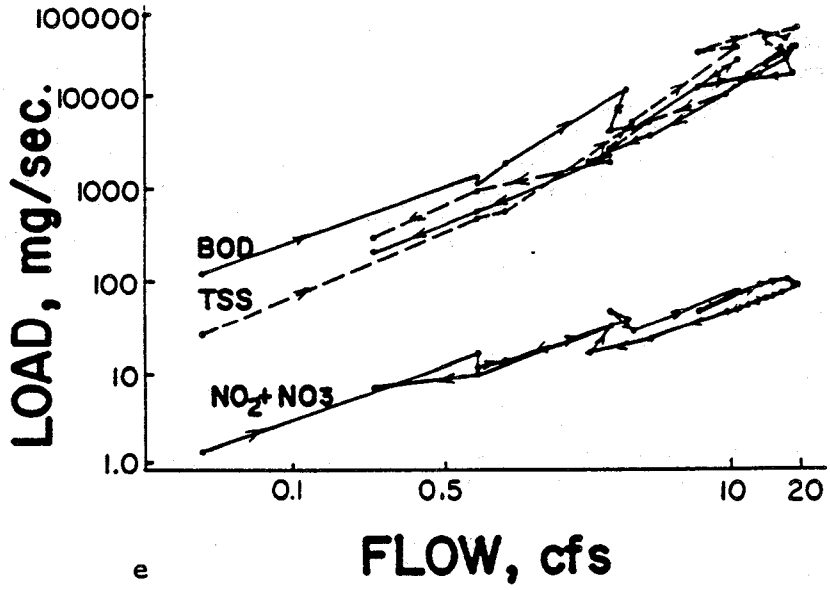


Figure 4-37. Variation of BOD_5, TSS and NO_2+NO_3-N Load and Concentration for Storm of 11/17/74 for View Ridge 1 Catchment, Seattle (from Huber et al., 1979). Connected points trace time history. (Figure continued, next page.)



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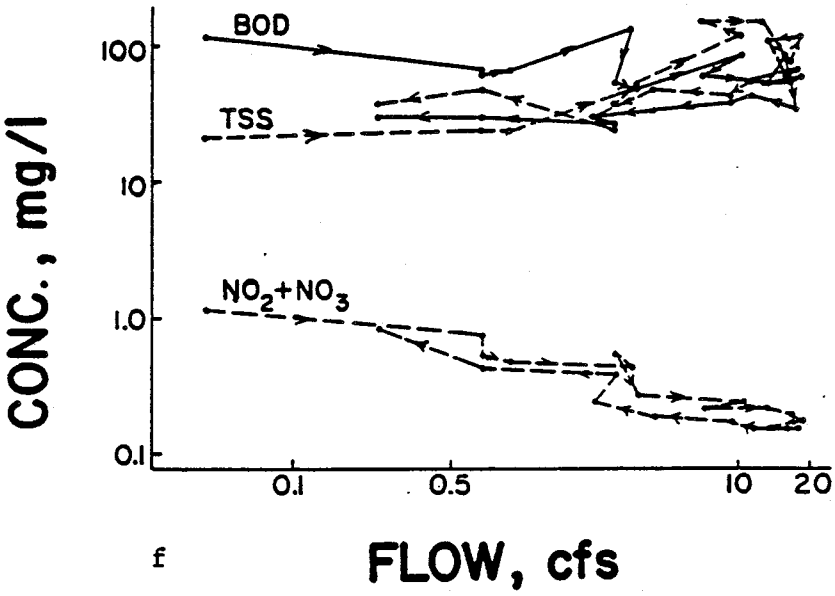

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Figure 4-37(Continued). The log-log plots could form the basis for rating curves, although the loop effect may only be simulated using a washoff calculation. Compare with Figure 4-36 b and d. Several more plots are shown in Appendix VII.

ters. In particular, most of the STORM calibration procedures (Roesner et al., 1974, HEC, 1977a,b) can be applied also to SWMM (with WASHPO = 1). Inclusion of water quality simulation in ILLUDAS (Terstriep et al., 1978; Han and Delleur, 1979) also is based on SWMM procedures. Finally, modified SWMM routines have been used to simulate water quality in Houston (Diniz, 1978; Bedient et al., 1978).

Rating Curve

As discussed above, the washoff calculations may be avoided and load rates computed for each subcatchment at each time step by a rating curve method, analogous to equation 4-37,

$$POFF = RCOEF \cdot WFLOW^{WASHPO} \tag{4-41}$$

where WFLOW = subcatchment runoff, cfs, (or m^3/sec for metric input),
POFF = constituent load washed off at time, t, quantity/sec (e.g., mg/sec),
RCOEF = coefficient that includes correct units conversion, and
WASHPO = exponent.

Parameters RCOEF and WASHPO are entered for a particular constituent in group J3. That these parameters apply to a rating curve is indicated by parameter KWASH in group J3. Although used on a time step basis, the parameters for equation 4-41 are customarily determined on a storm event basis, by plotting total load versus total flow (Huber, 1980; Wallace, 1980).

Two differences are apparent between equations 4-38 and 4-41. First, the former includes the quantity remaining on the surface, PSHED, in the right-hand side of the equation, leading to an exponential-type decay of the quantity in addition to being a function of runoff rate.

Second, the form of the runoff rate is different in the equations. The power-exponential washoff, equation 4-38, uses a normalized runoff rate, r, in in./hr over the total subcatchment surface (not just the impervious part). The rating curve, equation 4-41, also uses the total runoff, but in an unnormalized form, WFLOW, in cfs. Since data for a particular catchment are often analyzed as a log-log plot of load versus flow, equation 4-41 facilitates use of the best fit line. For example, data for Seattle are plotted in Figure 4-37. In addition, Appendix VII contains several other similar plots for three Seattle catchments and for Lancaster, Pennsylvania.

Clearly, the rating curve will work better for some storms and parameters than for others. If the data plot primarily as a loop (Figure 4-37), the power-exponential washoff formulation will work better since it tends to produce lower loads at the end of storm events. But if the load versus flow data tend to plot as a straight line on log-log paper, the rating curve method should work better. On the basis of the previous discussion of rating curves based on sediment data, it is expected that the exponent, WASHPO, would be in the range of 1.5 - 3.0 for constituents that behave like particulates. For dissolved constituents, the exponent will tend to be less than 1.0 since concentration often decreases as flow increases, and concentration is propor-

tional to flow to the power WASHPO-1. (Constant concentration would use WASHPO = 1.0.) Much more variability is expected for RCOEF.

The rating curve approach may be combined with constituent buildup if desired. If KWASH = 1 in group J3, constituents are generated according to the rating curve with no upper limit. There is no buildup between storms during continuous simulation, nor will measures like street sweeping have any effect. Constituents will be generated solely on the basis of flow rate.

Alternatively, with KWASH = 2, the rating curve is still used, but the maximum amount that can be removed is the amount built up prior to the storm. It will have an effect only if this limit is reached, at which time loads and concentrations will suddenly drop to zero. They will not assume non-zero values again until dry-weather time steps occur to allow buildup (during continuous simulation). Street sweeping will have an effect if the buildup limit is reached.

The rating curve method is generally easiest to use when only total runoff volumes and pollutant loads are available for calibration. In this case a pure regression approach should suffice to determine parameters RCOEF and WASHPO in equation 4-41.

Street Cleaning

Street cleaning is performed in most urban areas for control of solids and trash deposited along street gutters. Although it has long been assumed that street cleaning has a beneficial effect upon the quality of urban runoff, until recently, few data have been available to quantify this effect. Unless performed on a daily basis, EPA Nationwide Urban Runoff Program (NURP) studies generally found little improvement of runoff quality by street sweeping (EPA, 1983b).

The most elaborate studies are probably those of Pitt (1979, 1985) in which street surface loadings were carefully monitored along with runoff quality in order to determine the effectiveness of street cleaning. In San Jose, California (Pitt, 1979) frequent street cleaning on smooth asphalt surfaces (once or twice per day) can remove up to 50 percent of the total solids and heavy metal yields of urban runoff. Under more typical cleaning programs (once or twice a month), less than 5 percent of the total solids and heavy metals in the runoff are removed. Organics and nutrients in the runoff cannot be effectively controlled by intensive street cleaning -- typically much less than 10 percent removal, even for daily cleaning. This is because the latter originate primarily in runoff and erosion from off-street areas during storms. In Bellevue, Washington (Pitt, 1985) similar conclusions were reached, with a maximum projected effectiveness for pollutant removal from runoff of about 10 percent.

The removal effectiveness of street cleaning depends upon many factors such as the type of sweeper, whether flushing is included, the presence of parked cars, the quantity of total solids, the constituent being considered, and the relative frequency of rainfall events. Obviously, if street sweeping is performed infrequently in relation to rainfall events, it will not be ef-

fective. Removal efficiencies for several constituents are shown in Table 4-21 (Pitt, 1979). Clearly, efficiencies are greater for constituents that behave as particulates.

Within the Runoff Block, street cleaning (usually assumed to be sweeping) is performed (if desired) prior to the beginning of the first storm event and in between storm events (for continuous simulation). Unless initial constituent loads are input in group L1 (or unless a rating curve is used) a "mini-simulation" is performed for each constituent during the dry days prior to a storm during which buildup and sweeping are modeled. Starting with zero initial load, buildup occurs according to the method chosen in groups J2 and J3. Street sweeping occurs at intervals of CLFREQ days (group J2). (During continuous simulation, sweeping occurs between storms based on intervals calculated using dry time steps only. A dry time step does not have runoff greater than 0.0005 in./hr (0.013 mm/hr), nor is snow present on the impervious area of the catchment.) Removal occurs such that the fraction of constituent surface load, PSHED, remaining on the surface is

$$REMAIN = 1.0 - AVSWP(J) \cdot REFF(K) \qquad (4\text{-}42)$$

where REMAIN = fraction of constituent (or dust and dirt) load remaining on catchment surface,
AVSWP = availability factor (fraction) for land use J, and
REFF = removal efficiency (fraction) for constituent K.

The removal efficiency differs for each constituent as seen in Table 4-22, from which estimates of REFF may be obtained. The effect of multiple passes must be included in the value of REFF. During the mini-simulation that occurs prior to the initial storm or start of simulation "dust and dirt" is also removed during sweeping using an efficiency REFFDD (group J2). It is probably reasonable to assume that dust and dirt is removed similarly to the total solids of Table 4-22. A non-linear effect is exhibited in Table 4-22, in which efficiencies tend to increase as the total solids on the street surface increase. The Runoff Block algorithm does not duplicate this effect. Rather, the same fraction is removed during each sweeping.

The availability factor, AVSWP, is intended to account for the fraction of the catchment area that is actually sweepable. For instance, Heaney and Nix (1977) demonstrate that total imperviousness increases faster as a function of population density than does imperviousness due to streets only. Thus, the ratio of street surface to total imperviousness is one measure of the availability factor, and their relationship is

$$AVSWP = 0.6 \cdot PD_d^{-0.2}, \quad P_d > 0.1 \qquad (4\text{-}43)$$

where AVSWP = availability factor, fraction, and
PD_d = population density over developed area, persons/ac.

Such a relationship is reasonably a function of land use. Although a value of AVSWP must be entered for each land use (group J2), the equation of Heaney and Nix (1977) was developed only for an overall urban area. Thus, extrapolation to specific land uses should be done only with caution, but equation 4-43 is

Table 4-22. Removal Efficiencies from Street Cleaner Path for Various Street Cleaning Programs.* (Pitt, 1979)

Sreet Cleaning Program and Street Surface Loading Conditions	Total Solids	BOD_5	COD	KN	PO_4	Pesti-cides	Cd	Sr	Cu	Ni	Cr	Zn	Mn	Pb	Fe
Vacuum Street Cleaner 1 pass; 20 → 200 lb/curb mile total solids	31	24	16	26	8	33	23	27	30	37	34	34	37	40	40
2 passes	45	35	22	37	12	50	34	35	45	54	53	52	56	59	59
3 passes	53	41	27	45	14	59	40	48	52	63	60	59	65	70	68
Vacuum Street Cleaner 1 pass; 200 → 1,000 lb/curb mile total solids	37	29	21	31	12	40	30	34	36	43	42	41	45	49	59
2 passes	51	42	29	46	17	59	43	48	49	59	60	59	63	68	68
3 passes	58	47	35	51	20	67	50	53	59	68	66	67	70	76	75
Vacuum Street Cleaner 1 pass; 1000 → 10,000 lb/curb mile total solids	48	38	33	43	20	57	45	44	49	55	53	55	58	62	63
2 passes	60	50	42	54	25	72	57	55	63	70	68	69	72	79	77
3 passes	63	52	44	57	26	75	60	58	66	73	72	73	76	83	82
Mechanical Street Cleaner 1 pass; 180 → 1800 lb/curb mile total solids	54	40	31	40	20	40	28	40	38	45	44	43	47	44	49
2 passes	75	58	48	58	35	60	45	59	58	65	64	64	64	65	71
3 passes	85	69	59	69	46	72	57	70	69	76	75	75	79	77	82
Flusher	30	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Mechanical Street Cleaner followed by a flusher	80	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

(a) 15 → 40 percent estimated
(b) 35 → 100 percent estimated

*These removal values assume all the pollutants would lie within the cleaner path (0 to 8 ft. from the curb)

probably suitable for use on a large, aggregated catchment, such as might be used for continuous simulation.

An alternative approach may be found in Pitt (1979) in which the issue of parked cars is dealt with directly. Pitt shows that the percentage of curb left uncleaned is essentially equal to the percentage of curb occupied by parked cars. Thus, if typically 40 percent of the curb (length) is occupied by parked cars, the availability factor would be about 0.60. In many cities, parking restrictions on street cleaning days limit the length of curb occupied during sweeping.

Parameter DSLCL (group J2) merely establishes the proper time sequence for the "mini-simulation" prior to the start of the storm (or continuous simulation). A hypothetical sequence of linear buildup and street sweeping prior to a storm is sketched in Figure 4-38. Eventually an equilibrium between buildup and sweeping will occur. For the example shown in Figure 4-38, this is when the removal, $0.32 \cdot PSHED$, equals the weekly buildup, $0.3 \times 10^6 \cdot 7$, or $PSHED = 6.56 \times 10^6$ mg. If sweeping is scheduled for the day of the start of the storm (DSCL = CLFREQ) it does <u>not</u> occur. (An exception would be when the first day of a continuous simulation is a dry day. Sweeping would then occur during the first time step.)

The SWMM user should bear in mind that although the model assumes constituents to build up over the entire subcatchment surface, the surface load, PSHED, is simply a lumped total in, say, mg (for NDIM = 0), and there are no spatial effects on buildup or washoff. Hence, if it is assumed that a particular constituent originates only on the impervious portion of the catchment, loading rates and parameters can be scaled accordingly. Likewise, AVSWP can be determined based on the characterization of only the impervious areas described above. However, if a constituent originates over both the pervious and impervious area of the subcatchment (e.g., nutrients and organics) the removal efficiency, REFF, should be reduced by the average ratio of impervious to total area since it is independent of land type. The availability factor, AVSWP, differs for individual land uses but has the same effect on all constituents.

<u>Catchbasins</u>

Background --

Catchbasins are found in a large number of cities. They were originally installed at stormwater inlets to combined sewers to prevent sewer clogging by trapping coarse debris and solids and to prevent emanation of odors from the sewer by providing a water seal. There is no standard design for catchbasins; representative designs are shown in Figure 4-39. The purpose of the deep well or sump is to trap solids by sedimentation prior to stormwater entry into the sewer, which distinguishes catchbasins from stormwater inlets. The volume of the sump varies considerably with design, ranging from 2.8 to 78 ft^3 (0.08 - 2.21 m^3). The volume is typically reduced by a large quantity of solids trapped in the sump, often by more than 50 percent.

A comprehensive examination of catchbasins and their effectiveness for

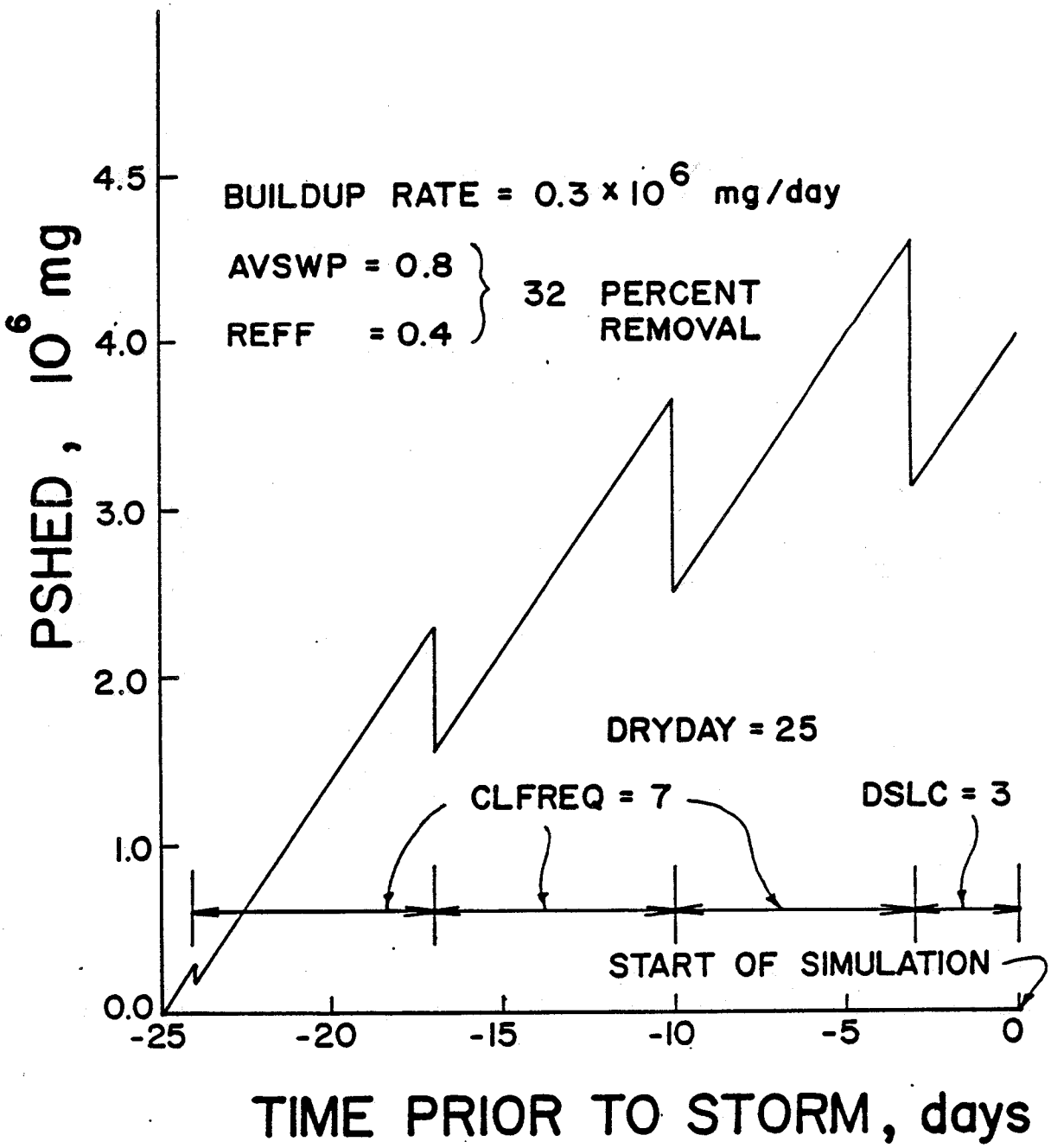

Figure 4-38. Hypothetical Time Sequence of Linear Buildup and Street Sweeping.

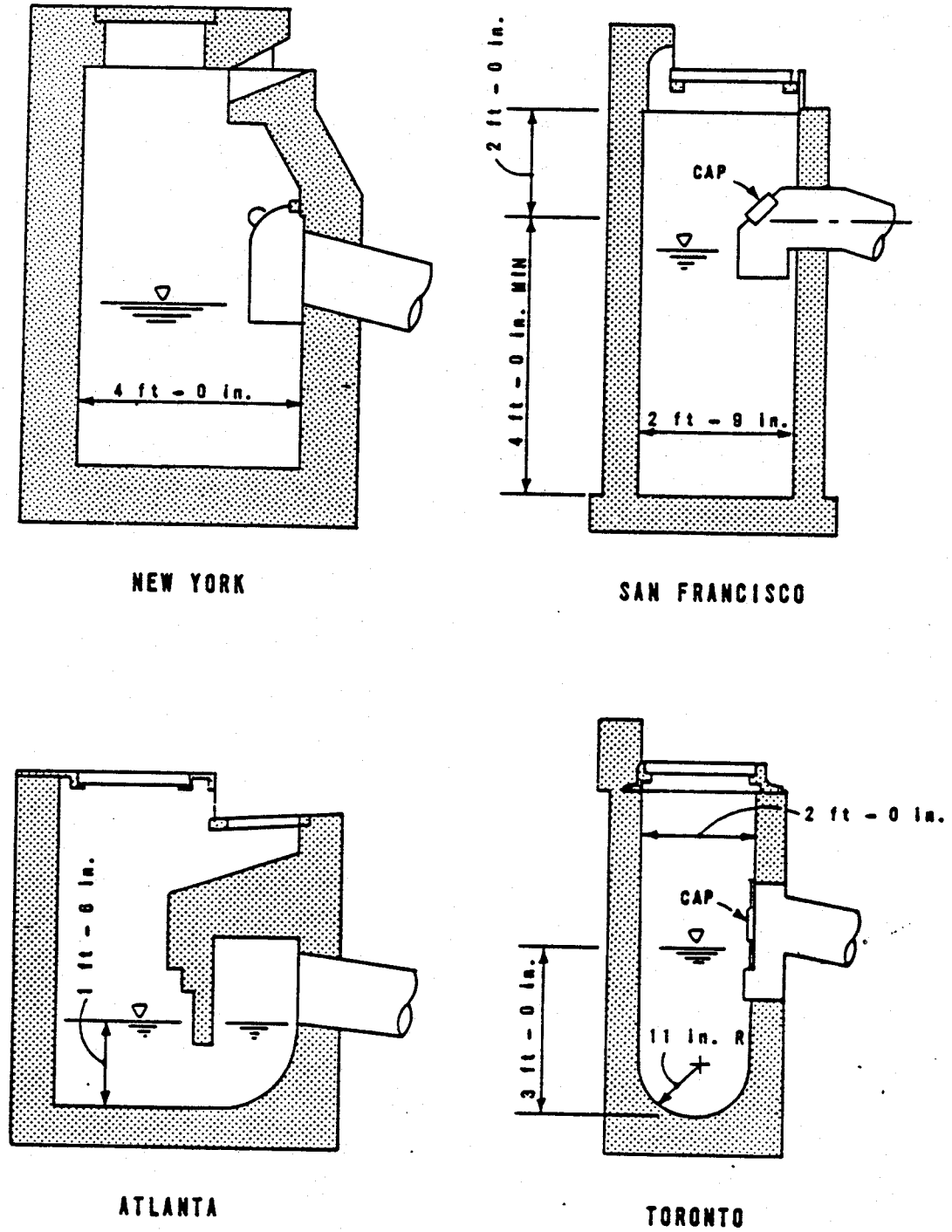

Figure 4-39. Representative Catchbasin Designs. (After Lager et al., 1977b, p. 12.)

pollutant control is presented by Lager et al. (1977b). They conclude that:

> "Existing catchbasins exhibit mixed performance with respect to pollutant control. The trapped liquid purged from catchbasins to the sewers during each storm generally has a high pollution content that contributes to the intensification of first-flush loadings. Countering this negative impact is the removal of pollutants associated with the solids retained in, and subsequently cleaned from, the basin."

In fact according to their data, there is unlikely to be much removal (treatment) at all in most cities because of infrequent maintenance; the median cleaning frequency in 1973 was once per year. Without such maintenance, solids accumulate in the sump until there is little removal effectiveness, even for large particles. Lager et al. (1977b) conclude that, with the possible exception of total solids and heavy metals, catchbasins are of limited usefulness for pollution abatement, both because of their ineffectiveness and because of their high maintenance costs. More recently, Pitt (1985) found that semi-annual catchbasin cleaning could reduce solids loads by up to 25 percent. However, their treatment potential is not modeled in SWMM. (If it is significant in a given city, surface loadings could be correspondingly reduced.)

Modeling Approach --

The potential for a first flush of catchbasin material is simulated by assuming that the sump contains at the beginning of a storm a constituent load (e.g., mass, in mg, for NDIM = 0) given by:

$$PBASIN = CBVOL \cdot BASINS \cdot CBFACT \cdot FACT3 \qquad (4\text{-}44)$$

where PBASIN = subcatchment constituent load in catchbasins at beginning of storm, mg for NDIM = 0,
CBVOL = individual catchbasin volume of sump, reduced by quantity of stored solids, if known, ft^3,
BASINS = number of basins in subcatchment,
CBFACT = constituent concentration in basin at beginning of storm, mg/l for NDIM = 0, and
FACT3 = conversion factor, equals 28.3 l/ft^3 for NDIM = 0.

Parameter CBVOL is entered in group J1 as an average for the entire catchment. The number of basins in each subcatchment, BASINS, is entered in group L1. Numbers can be obtained knowing the general basin density for the catchment in lieu of the more tedious method of counting every one. Constituent concentrations, CBFACT, are entered in group J3 and should, of course, be measured in the catchment under study. Literature values are few. Samples from 12 San Francisco catchbasins (Sartor and Boyd, 1972) were characterized by Lager et al. (1977b) by "casting out the extremes and averaging," resulting in the values shown in Table 4-23. Concentrations from ten catchbasins in a residential catchment in Bellevue, Washington are also shown (Pitt, 1985). The values for COD and Total-N are consistent with a few samples reported by Sartor and Boyd (1972) for Baltimore and Milwaukee, although the "phosphates" concentration in those two cities was somewhat higher, 1.1 - 2.2 mg/l. The concentration of BOD5 in seven Chicago catchbasins was measured by APWA

(1969). The average concentration for five commercial area basins was 126 mg/l, ranging from 35 to 225 mg/l. Two residential area basins yielded BOD5 concentrations of 50 and 85 mg/l.

Table 4-23. Constituent Concentrations in Catchbasins

City	Constituent	Concentration, mg/l Average	Range
San Francisco (Sartor and Boyd, 1972)	COD	6,400	153 - 143,000
	BOD5	110	5 - 1,500
	Total-N	8	0.5 - 33
	Total-P	0.2	< 0.2 - 0.3
Bellevue (Pitt, 1985)	COD	59	20 - 244
	Total Solids	67	34 - 272
	TKN	2.1	< 0.5 - 5.6
	Total-P	0.95	0.078 - 6.9
	Pb	0.14	0.05 - 0.45
	Zn	0.19	0.033 - 1.19

Suspended solids (SS) concentrations can be expected to be high for particle sizes less than about 0.25 mm, on the basis of flushing tests (Sartor and Boyd, 1972; Lager et al., 1977b). Initial suspended and total solids concentrations of several thousand mg/l are probably justified, although measurements by Waller (1971) during storms in four residential catchbasins in Halifax indicate SS concentrations in a range of 42 to 305 mg/l. Pitt (1985) provides a particle size distribution for the constituents listed in Table 4-23.

Flushing of stored constituents from catchbasin sumps is based on tests conducted by APWA (1969) in which salt was used as a tracer and its rate of flushing observed. Data and fitted equations are shown in Figure 4-40. The basin behaves approximately as a completely mixed tank in which

$$dPBASIN/dt = - \frac{WFLOW}{k \quad BASINS} \cdot PBASIN \qquad (4\text{-}45)$$

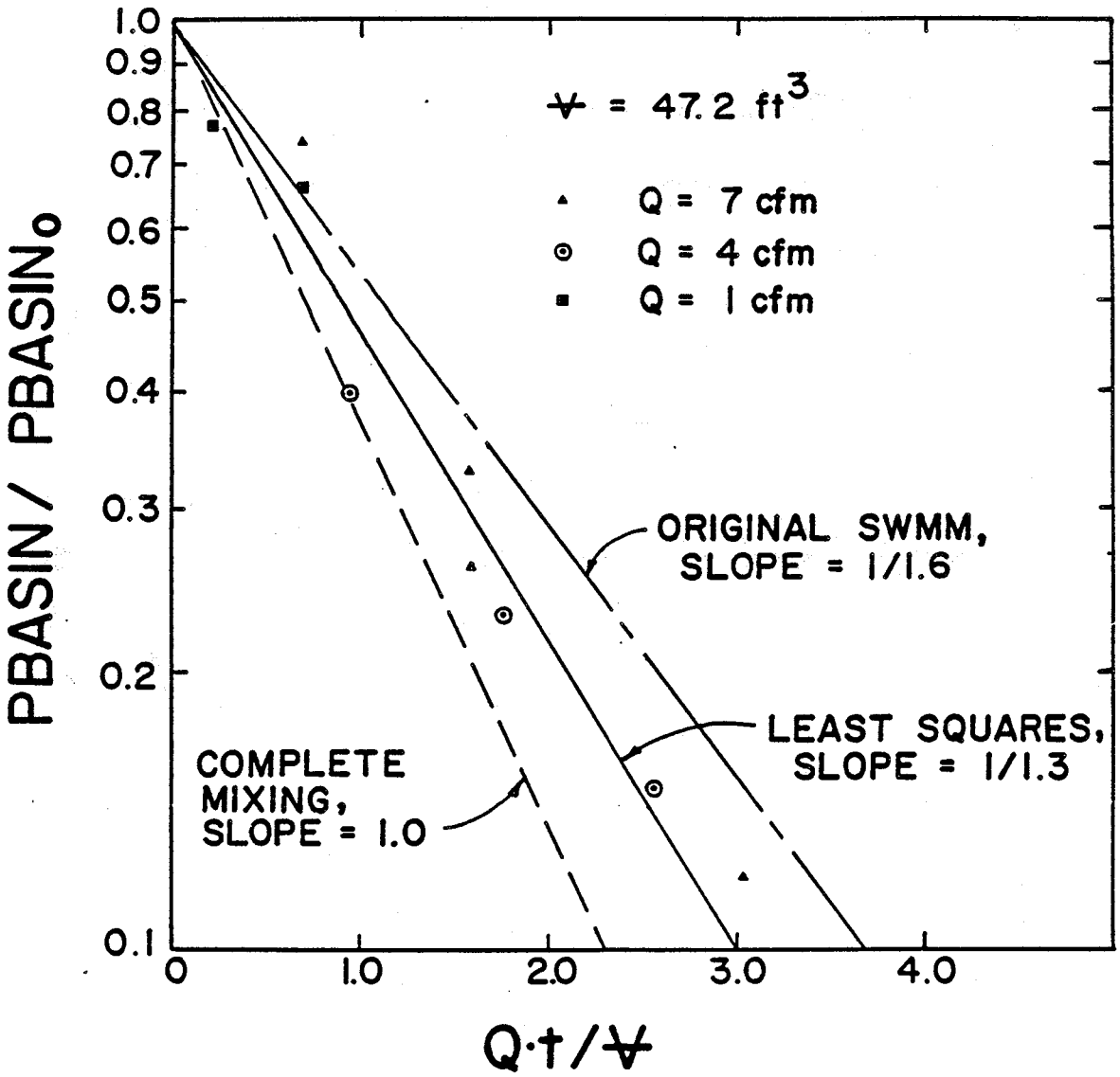

Figure 4-40. Catchbasin Flushing Characteristics. Data are from APWA (1969).

where PBASIN = constituent load remaining in the catchbasin as a function of time, e.g., mg for NDIM = 0,
WFLOW = flow through the basin (runoff from the subcatchment), cfs,
BASINS = volume of catchbasin sump, ft^3, and
k = constant to be determined from flushing tests.

When the flow rate is constant, equation 4-45 integrates to

$$PBASIN = PBASIN_o \cdot e^{-\frac{WFLOW}{k\ BASINS} \cdot t} \qquad (4\text{-}46)$$

where $PBASIN_o$ = initial catchbasin load.

If complete mixing occurs, k = 1. For the Chicago tests this did not quite occur, as seen in Figure 4-40. The original SWMM version (Metcalf and Eddy et al., 19761a) used k = 1.6, but this does not give the best-fit line. Rather, a k value of 1.3 is consistent with a least squares fit through the data points and is used in this version of SWMM. (However, the difference is probably undetectable in a simulation.)

During a runoff event, equation 4-45 is used to calculate the load rate, dPBASIN/dt, at each time step. (Parameter BASINS represents the total catchbasin volume for the subcatchment.) The remaining catchbasin load is then computed by multiplying the load rate by DELT and subtracting from PBASIN. This crude Euler integrations is justified because of 1) the weakness of field data and mixing assumptions, 2) the necessity for an additional array and computation time for a more sophisticated approximation, and 3) insensitivity of most simulations to catchbasin flushing. The latter point will be discussed further subsequently.

Regeneration of Catchbasin Loads --

During continuous simulation, catchbasin loads are regenerated to their original values, $PBASIN_o$, at a rate $PBASIN_o$/DRYBSN (e.g., mg/day) where DRYBSN is entered in group J1 and is the time required for complete regeneration from a zero load. No data are available herein to establish a value for DRYBSN, but it is likely that catchbasins are at "full strength" after only a few days of dry weather.

Effect on Simulation --

It is the experience of the authors of this report that catchbasins have a negligible effect on most simulation results. Typical drainage areas served by catchbasins range from 2.15 to 5.05 ac/basin (0.85 to 2.05 ha/basin) in the U.S. (Lager et al., 1977b). Unless the area served is low, surface loadings tend to overwhelm those from catchbasins. Although they do contribute to a first flush effect, the most important task in most simulations is to obtain a proper total storm load, to which catchbasins are seldom strong contributors. Hence, excessive effort to pin down catchbasin simulation parameters is seldom justified.

Constituent Fractions

Background --

As previously discussed, the original SWMM Runoff Block quality routines were based on the 1969 APWA study in Chicago (APWA, 1969). A particular aspect of that study that led to modifications to the first buildup-washoff formulation was that the Chicago quality data (e.g., Table 4-15) were reported for the soluble fraction only, i.e., the samples were filtered prior to chemical analysis. Hence, they could not represent the total content of, say, BOD5 in the stormwater. In calibration of SWMM in San Francisco and Cincinnati, 5 percent of predicted suspended solids was added to BOD5 to account for the insoluble fraction. This provided a reasonable BOD5 calibration in both cities.

The Version II release of SWMM (Huber et al., 1975) followed the STORM model (Roesner et al., 1974) and added to BOD5, N and PO_4 fractions of both suspended solids and settleable solids. Adding a fraction from settleable solids is double counting, however, since it is no more than a fraction of suspended solids itself. Furthermore, all the fractions in SWMM and STORM were basically just assumed from calibration exercises as opposed to being measured from field samples.

Agricultural models, such as NPS (Donigian and Crawford, 1976), ARM (Donigian et al., 1977) and HSPF (Johanson et al., 1980) also relate other constituent mass load rates and concentrations to that of "solids," usually "sediment" predicted by an erosion equation. The ratio of constituent to "solids" is then called a "potency factor" and for some constituents is the only means by which their concentrations are predicted. The approach works well when constituents are transported in solid form, either as particulates or by adsorption onto soil particles. this approach can also be used in SWMM. For instance, one constituent could represent "solids" and be predicted by any of the means available (i.e., buildup-washoff, rating curve, Universal Soil Loss Equation). Other constituents could then be treated simply as a fraction, F1, of "solids." The fractions (potency factors) are entered in data group J4. As a refinement, two or more constituents could represent "solids" in different particle size ranges, and fractions of each summed to predict other constituents. Again, this approach will not work well for constituents that are transported primarily in a dissolved state, e.g., NO_3.

Available Information --

In an effort to evaluate potency factors for various constituents in both urban and agricultural runoff, Zison (1980) examined available data and developed regression relationships as a function of suspended solids and other parameters. His only urban catchments were three from Seattle, taken from the Urban Rainfall-Runoff-Quality Data Base (Huber et al., 1981a), for which several water quality and storm event parameters were available. Unfortunately, statistically meaningful results could only be obtained using log-transformed data, and simple fractions of the type required for input in group J4 are seldom reported. Zison (1980) acknowledged this and suggested that model modifications might be made or piecewise-linear approximations made to the

power function relationship. In any event, Zison related the total constituent concentration (not just the nonsoluble portion) to other parameters. Hence, for their use in SWMM< the buildup-washoff portion would need to be "zeroed out," (easily accomplished), as suggested earlier.

Other reports also provide some insight as to potential values for the constituent fractions. For instance, Sartor and Boyd (1972), Shaheen (1975) and Manning et al. (1977) report particle size distributions for several constituents. However, the distributions refer principally to fractions of constituents appearing as "dust and dirt," not to fractions of total concentration, soluble plus nonsoluble. Finally, Pitt and Amy (1973) give fractions (and surface loadings) for heavy metals.

If constituent fractions are used in SWMM, local samples should identify the soluble (filterable) and nonsoluble fractions for the constituents of interest. Alternatively, the fractions may be avoided altogether by treating the buildup-washoff or rating curve approach as one for the total concentration, thus eliminating the need to break constituents into more than one form.

Effect in Runoff Block --

The fractions entered in group J4 act only in "one direction." That is, nothing is subtracted from, say, suspended solids if it is a constituent that contributes to others. When the fractions are used, they can contribute significantly to the concentration of a constituent. For instance, if 5 percent of suspended solids is added to BOD5, high SS concentrations will insure somewhat high BOD5 concentrations, event if BOD5 loadings are small.

Units conversions must be accounted for in the fractions. For instance, if a fraction of SS is added to total coliforms, units for F1 would be MPN per mg of SS. In general, F1 has units of the "quantity" of KTO (e.g., MPN) per "quantity" of constituent KFROM (e.g., mg).

The contributions from other constituents are the penultimate step in subroutine QSHED. The occur after the Universal Soil Loss Equation calculation, and the the to-from constituents can include the contribution from erosion if desired. Only the contribution from precipitation comes later and thus cannot be included in the constituent fractions. Rather it is added to the constituent load at the end of the chain of calculations, as described below.

<u>Precipitation Contributions</u>

Precipitation Chemistry --

There is now considerable public awareness of the fact that precipitation is by no means "pure" and does not have characteristics of distilled water. Low pH (acid rain) is the best known parameter but many substances can also be found in precipitation, including organics, solids, nutrients, metals and pesticides. Compared to surface sources, rainfall is probably an important contributor mainly of some nutrients, although it may contribute substantially

to other constituents as well. In particular, Kluesener and Lee (1974) found ammonia levels in rainfall higher than in runoff in a residential catchment in Madison, Wisconsin; rainfall nitrate accounted for 20 to 90 percent of the nitrate in stormwater runoff to Lake Wingra. Mattraw and Sherwood (1977) report similar findings for nitrate and total nitrogen for a residential area near Fort Lauderdale, Florida. Data from the latter study are presented in Table 4-24 in which rainfall may be seen to be an important contributor to all nitrogen forms, plus COD, although the instance of a higher COD value in rainfall than in runoff is probably anomalous.

In addition to the two references first cited, Weibel et al. (1964, 1966) report concentrations of constituents in Cincinnati rainfall (Table 4-25), and a summary is also given by Manning et al. (1977). Other data on rainfall chemistry and loadings is given by Betson (1977), Hendry and Brezonik (1980), Novotny and Kincaid (1981) and Randall et al. (1981). A comprehensive summary is presented by Brezonik (1975) from which it may be seen in Table 4-25 that there is a wide range of concentrations observed in rainfall. Again, the most important parameters relative to urban runoff are probably the various nitrogen forms.

Uttormark et al. (1974) provide annual nitrogen (and phosphorus) precipitation loading values (kg/ha-yr) for many cities regionally for the U.S. and Canada. Their nitrogen loadings are shown in Figure 4-41 although it should be remembered that considerable seasonal variability may exist. These may be easily converted to precipitation <u>concentrations</u> required for SWMM input if the local rainfall is known, since 10 x kg/ha-yr / cm/yr = mg/l. For instance, annual NH_3-N + NO_3-N loadings at Miami are almost 2 kg/ha-yr from Figure 4-41, and annual rainfall is 60 in. (152 cm). From the above, the inorganic nitrogen concentration is 10 x 2/152 = 0.13 mg/l which compares quite favorably with the sum of NH_3-N and NO_3-N concentrations for two of the three Ft. Lauderdale storms given in Table 4-24. For a better breakdown of nitrogen forms, see Table 17 of Uttormark et al. (1974).

Effect in Runoff Block --

Constituent concentrations in precipitation are entered in group J3. <u>All</u> runoff, including snowmelt, is assumed to have at least this concentration, and the precipitation load is calculated by multiplying this concentration by the runoff rate and adding to the load already generated by other mechanisms. It may be inappropriate to add a precipitation load to loads generated by a calibration of buildup-washoff or rating curve parameters against measured runoff concentrations, since the latter already reflect the sum of all contributions, land surface and otherwise. But precipitation loads might well be included if starting with buildup-washoff data from other sources. They also provide a simple means for imposing a constant concentration on any Runoff Block constituent.

For single event simulation, use of precipitation concentrations is a simple way in which to account for the high concentrations of several constituents found in snowpacks (Proctor and Redfern and James F. MacLaren, 1976b). It would be inappropriate for continuous simulation, however, since such high concentrations in runoff would not be expected to persist over the whole year.

Table 4-24. Rainfall and Runoff Concentrations For a Residential Area Near Fort Lauderdale, Florida (After Mattraw and Sherwood, 1977)

	Storm		
	8/23/75	9/17/75	9/26/75
Rainfall, in.	1.01	0.55	0.77
Runoff, in.	0.060	0.012	0.072
Concentration (mg/l):			
Total N, rainfall	0.30	0.84	0.29
Total N, runoff	0.52	0.74	1.50
NO3-N, rainfall	0.14	0.73	0.12
NO3-N, runoff	0.16	0.19	0.26
Org.-N, rainfall	0.15	0.09	0.12
Org.-N, runoff	0.34	0.49	1.10
NH3-N, rainfall	0.01	0.01	0.04
NH3-N, runoff	0.02	0.04	0.13
Total P, rainfall	0.01	0.02	0.05
Total P, runoff	0.12	0.20	0.30
COD, rainfall	22	12	4
COD, runoff	16	21	17

If this is the only method used to simulate melt quality, however, a constant predicted concentration will result. Also, caution should be used if simulating particulates (e.g., suspended solids) or heavy metals since high concentrations in a snowpack do not necessarily mean high concentrations in runoff, since the material may rapidly settle during overland flow. For instance, the very high lead concentrations (2 - 100 mg/l) found in snow windrows in urban areas are greatly reduced in the melt runoff (0.05 - 0.95 mg/l), (Proctor and Redfern and James F. Maclaren, 1976b).

Table 4-25. Representative Concentrations in Rainfall.

Parameter	Ft. Lauderdale[a] (Mattraw and Sherwood, 1977)	Cincinnati[b] (Weibel et al., 1966)	"Typical Range" (Brezonik, 1975)
Acidity (pH)			3-6
Organics			
BOD_5, mg/l			1-13
COD, mg/l	4-22	16	9-16
TOC, mg/l	1-3		Few
Inorg. C, mg/l	0-2		
Color, PCU	5-10		
Solids			
Total Solids, mg/l	18-24		
Suspended Solids, mg/l	2-10	13	
Turbidity, JTU	4-7		
Nutrients			
Org. N, mg/l	0.09-0.15	0.58	0.05-1.0
NH_3-N, mg/l	0.01-0.04		
NO_2-N, mg/l	0.00-0.01		
NO_3-N, mg/l	0.12-0.73	1.27[c]	0.05-1.0
Total N, mg/l	0.29-0.84		0.2 -1.5
Orthophosphorus, mg/l	0.01-0.03	0.08	0.0 -0.05
Total P, mg/l	0.01-0.05		0.02-0.15
Pesticides, μg/l		3-600	Few
Heavy metals, μg/l			Few
Lead, μg/l			30-70

[a]Range for three storms [b]Average of 35 storms [c]Sum of NH_3-N, NO_2-N, NO_3-N

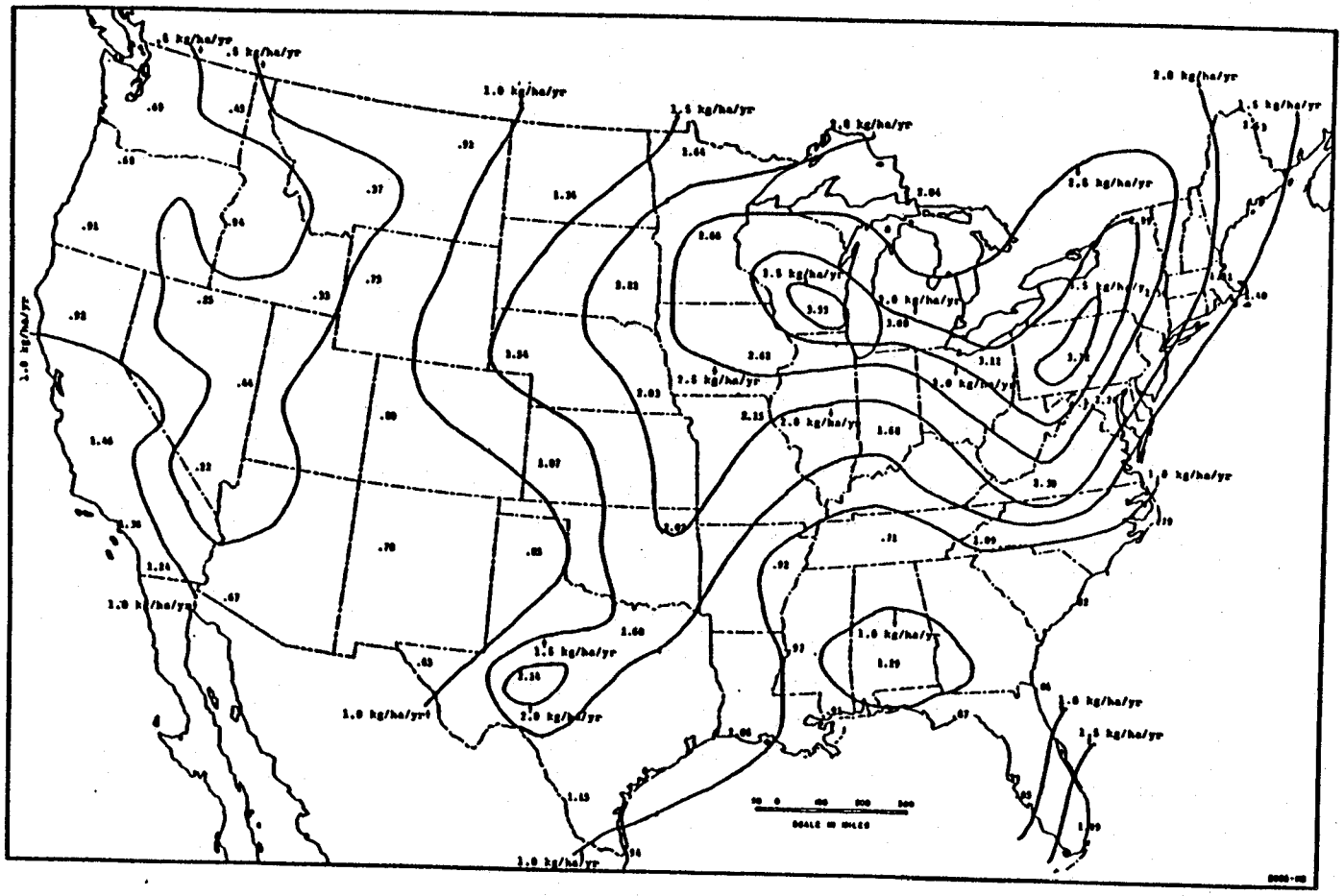

Figure 4-41. Nationwide Annual Loadings of NH_4^+-N + NO_3-N in Precipitation (after Uttormark et al., 1974, p. 87). Dry fallout is not included.

Urban Erosion

Background --

Erosion and sedimentation are often cited as a major problem related to urban runoff. They not only contribute to degradation of land surfaces and soil loss but also to adverse receiving water quality and sedimentation in channels and sewer networks. Several ways exist to analyze erosion from the land surface (e.g., Vanoni, 1975), the most sophisticated of which include calculations of the shear stress exerted on soil particles by overland flow and/or the influence of rainfall energy in dislodging them. In keeping with the simplified quality procedures included in the rest of the Runoff Block, a widely-used empirical approach, the Universal Soil Loss Equation (USLE), has been adapted for use in SWMM. Full details and further information on the USLE are given by Heaney et al. (1975).

Universal Soil Loss Equation --

The USLE was derived from statistical analyses of soil loss and associated data obtained in 40 years of research by the Agricultural Research Service (ARS) and assembled at the ARS runoff and soil loss data center at Purdue University. The data include more that 250,000 runoff events at 48 research stations in 26 states, representing about 10,000 plot-years of erosion studies under natural rain. It was developed by Wischmeier and Smith (1958) as an estimate of the average annual soil erosion from rainstorms for a given upland area, L, expressed as the average annual soil loss per unit area, (tons per acre per year):

$$L = R \cdot K \cdot LS \cdot C \cdot P \qquad (4\text{-}47)$$

where R = the rainfall factor,
K = the soil erodibility factor,
LS = the slope length gradient ratio,
C = the cropping management factor or cover index factor, and
P = the erosion control practice factor.

This equation represents a comprehensive attempt at relating the major factors in soil erosion. It is used in SWMM to predict the average soil loss for a given storm or time period. It is recognized that the USLE was not developed for making predictions based on specific rainfall events. There are many random variables which tend to cancel out when predicting individual storm yields. For example, the initial soil moisture condition, or antecedent moisture condition, is a parameter which cannot routinely be determined directly and used reliably. It should be understood by the SWMM user that equation 4-44 enables land management planners to estimate gross erosion rates for a wide range of rainfall, soil, slope, crop, and management conditions.

Input Parameters --

Erosion Simulation--If erosion is to be simulated, it is so indicated by parameter IROS in group J1. Note that at least one other (arbitrary) quality constituent must be simulated along with "erosion." No particular soil char-

acteristics (e.g., particle size distribution) are assigned to the erosion parameter, and its title is "EROSION," with units of mg/l, in the output. Erosion may be added to another constituent, e.g., suspended solids, if desired using parameter IROSAD in group J1. However, the erosion parameter will also always be maintained as an individual parameter throughout the Runoff Block.

Other input parameters are:

1) the maximum 30-minute rainfall intensity of the storm (single-event) or of the simulation period (continuous), RAINIT, (group J1),

2) the area of each subcatchment subject to erosion, ERODAR, (group K1),

3) the flow distance in feet from the point of origin of overland flow over the erodible area to the point at which runoff enters the gutter or inlet, ERLEN, (group K1),

4) the soil factor K, SOILF, (group K1),

5) the cropping management factor C, CROPMF, (group K1), and

6) the control practice factor P, CONTPF, (group K1).

The source and use of these parameters is described below.

Rainfall Factor and Maximum Thirty Minute Intensity--The rainfall factor, R, of the equation 4-47 is the product of the maximum thirty minute intensity and the sum of the rainfall energy for the time of simulation. Rainfall energy, E, is given by an empirical expression by Wischmeier and Smith (1958):

$$E = \sum [9.16 + 3.31 \cdot \log_{10}(RNINHR_j)] \cdot RNINHR_j \cdot DELT \qquad (4\text{-}48)$$

where E = total rainfall energy for time period of summation, 100-ft-ton/ac,
$RNINHR_j$ = rainfall intensity at time interval j, in./hr, and
DELT = time interval, hr, such that the product RNINHR x DELT equals the rainfall depth during the time interval.

The summation was performed over all time intervals with rainfall for a year for the original USLE development; contours of R over the U.S. are given by Wischmeier and Smith (1965). However, it can also be performed for an individual storm. In SWMM this is performed on a time step basis; that is, E is evaluated at each time step using the rainfall intensity at that time step (no summation). The rainfall factor, R, is then

$$R = E \cdot RAINIT \qquad (4\text{-}49)$$

where RAINIT = maximum average 30 minute rainfall intensity for the storm (single event) or the period of simulation (continuous) in./hr.

RAINIT must be found from an inspection of the input hyetograph prior to simulation. Computed in this manner, the rainfall factor does not account for soil losses due to snowmelt or wind erosion. The units of R (100-ft-ton-in/ac-hr) are generally meaningless since the soil factor, K, is designed to cancel them. But the indicated units for RAINIT and RNINHR (in/hr) must be used.

Erosion Area--Parameter ERODAR (group K1) represents the acres of the subcatchment subject to erosion. This would ordinarily be less than or equal to the pervious area of the subcatchment and could indicate land that is barren or under construction.

Soil Factor--The soil factor, K, is a measure of the potential erodibility of a soil and has units of tons per unit of rainfall factor, R. The soil erodibility nomograph shown in Figure 4-42 (Wischmeier et al., 1971) may be used to find the value of the soil factor once five soil parameters have been estimated. These parameters are: percent silt plus very fine sand (0.05 - 0.10 mm), percent sand greater than 0.10 mm, organic matter (O.M.) content, structure, and permeability. To use the nomograph, enter on the left vertical scale with the appropriate percent silt plus very fine sand. Proceed horizontally to the correct percent sand curve, then move vertically to correct organic matter curve. Moving horizontally to the right from this point, the first approximation of K is given on the vertical scale. For soils of fine granular structure and moderate permeability, this first approximation value corresponds to the final K value and the procedure is terminated. If the soil structure and permeability is different than this, it is necessary to continue the horizontal path to intersect the correct structure curve, proceed vertically downward to the correct permeability curve, and move left to the soil erodibility scale to find K. This procedure is illustrated by the dotted line on the nomograph. For a more complete discussion of this topic, see Wischmeier et al. (1971).

A preferable and often simpler alternative to the use of the nomograph of Figure 4-42 is to refer directly to the soil survey interpretation sheet for the soil in question, on which may be found the value of the soil factor. This is illustrated in Figure 4-19 for Conestoga Silt Loam whereupon the K value is given as 0.43. Since this is site-specific local information, it is highly recommended. Local Agricultural Research Service and Soil Conservation Service offices are available to obtain the soil survey interpretation sheets and to provide much other useful information.

Slope Length Gradient Ratio--This parameter is an empirical function of runoff length and slope and is given by

$$LS = ERLEN^{0.5} \cdot (0.0076 + 0.53 \cdot WSLOPE + 7.6 \cdot WSLOPE^2) \qquad (4\text{-}50)$$

where LS = slope length gradient ratio,
ERLEN = the length in feet from the point of origin of overland flow to the point where the slope decreases to the extent that deposition begins or to the point at which runoff enters a defined channel, e.g., channel/pipe or

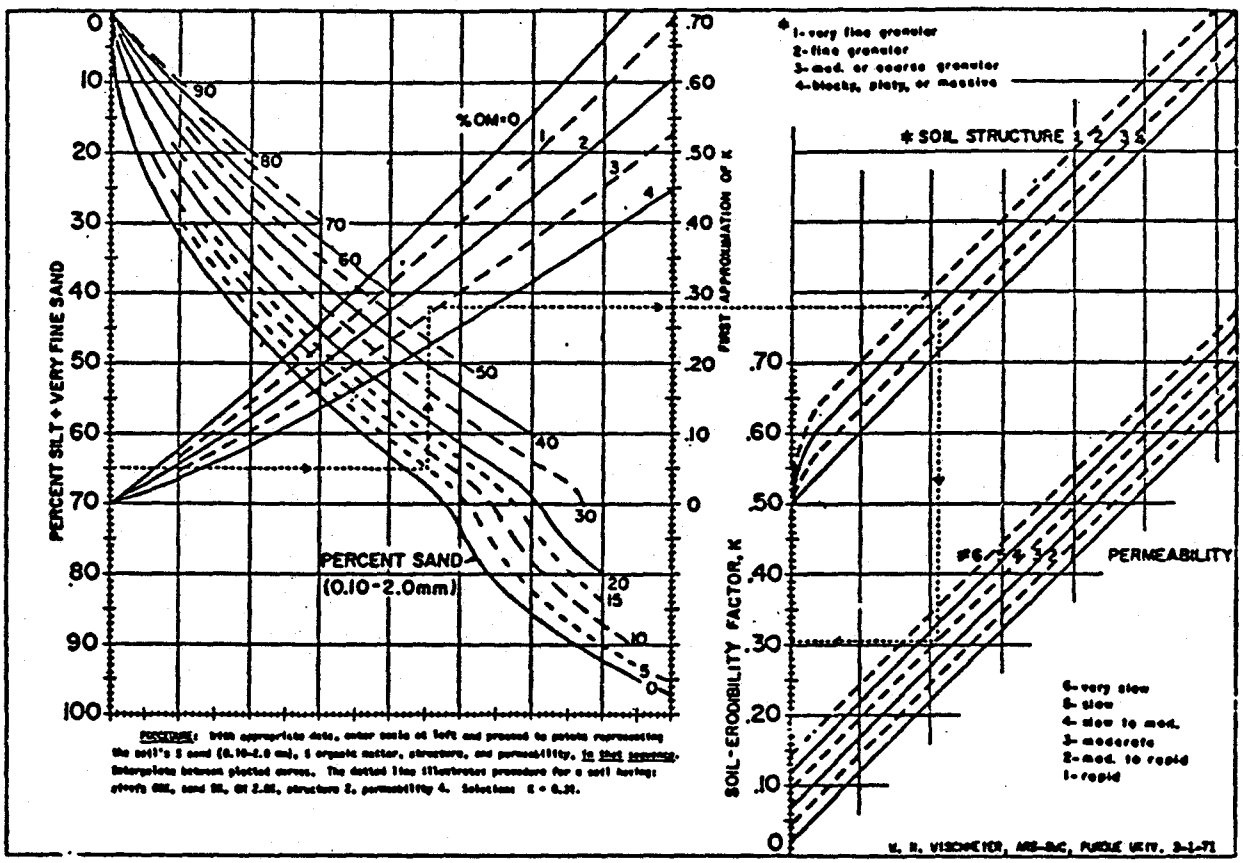

Figure 4-42. Nomograph for Calculation of Soil Erodability Factor, K. (After Wischmeier et al., 1971.)

inlet, and

WSLOPE = the average slope over the given runoff length, ft/ft.

Parameter ERLEN is entered with the erosion parameters in group K1. The slope, WSLOPE, is the same as for runoff calculations and will already have been entered in group H1.

In using the average slope in calculating the LS factor, the predicted erosion will be different from the actual erosion when the slope is not uniform. Meyer and Kramer (1969) show that when the actual slope is convex, the average slope prediction will underestimate the total erosion whereas for a concave slope, the prediction equation will overestimate the actual erosion. If possible, to minimize these errors, large eroding sites should be broken up into areas of fairly uniform slope.

Cropping Management Factor--This factor is dependent upon the type of ground cover, the general management practice and the condition of the soil over the area of concern. The C factor (CROPMF in group K1) is set equal to 1.0 for continuous fallow ground which is defined as land that has been tilled and kept free of vegetation and surface crusting. Values for the cropping management factor are given in Table 4-26 (Maryland Dept. of Natural Resources, 1973). Again consultation with local soils experts is recommended.

Control Practice Factor--This is similar to the C factor except that P (CONTPF in group K1) accounts for the erosion-control effectiveness of superimposed practices such as contouring, terracing, compacting, sediment basins and control structures. Values for the control practice factor for construction sites are given in Table 4-27 (Ports, 1973). Agricultural land use P factor values are given by Wischmeier and Smith (1965).

The C and P factors are the subject of much controversy among erosion and sedimentation experts of the U.S. Department of Agriculture (USDA) and the Soil Conservation Service (SCS). These factors are estimates and many have no theoretical or experimental justification. It has been suggested that upper and lower limits be placed on these factors by local experts to increase the flexibility of the USLE for local conditions.

The P factors in the upper portion of Table 4-27 were designated as estimates when they were originally published. SCS scientists have found no theoretical or experimental justification for factors significantly greater than 1.0. Surface conditions 4, 6, 7 and 8 ($P \leq 1.0$) of Table 4-26 also are estimates with no experimental verification.

Subcatchment Quality Data (Group L1)

Introduction --

As discussed earlier while describing buildup and washoff mechanisms, certain quality parameters are unique to each subcatchment and are entered in this data group. These parameters are independent of the quantity parameter entered in group H1 (except for subcatchment number, of course) and are not required if no quality simulation is performed.

Table 4-26. Cropping Management Factor, C

(Maryland Dept. of Natural Resources, 1973)

Type of cover	C Value	Mulch	Rate of Application (tons/acre)	C Value	Maximum Allowable Slope Length
None (fallow)	1.00	Hay or straw	0.5	0.35	20 feet
			1.0	0.20	30
Temporary seedings:			1.5	0.10	40
First sixty days	0.40		2.0	0.05	50
After sixty days	0.05				
		Stone or gravel	15.0	0.80	15
Permanent seedings:			60.0	0.20	80
First sixty days	0.40		135.0	0.10	175
After sixty days	0.05		240.0	0.05	200
		Chemical mulches			
Sod (laid immediately)	0.01	First ninety days	a	0.50	50
		After ninety days	a	1.00	50
		Woodchips	2.0	0.80	25
			4.0	0.30	50
			12.0	0.10	100
			20.0	0.06	150
			25.0	0.05	200

[a]As recommended by manufacturer

Table 4-27. Erosion Control Practice Factor, P, for Construction Sites (Ports, 1973).

Surface Condition With no Cover	Factor P
1. Compact, smooth, scraped with bulldozer or scraper up and down hill	1.30
2. Same as above, except raked with bulldozer root, raked up and down hill	1.20
3. Compact, smooth, scraped with bulldozer or scraper across the slope	1.20
4. Same as above, except raked with bulldozer root, raked across the slope	0.90
5. Loose, as in a disked plow layer	1.00
6. Rough irregular surface, equipment tracks in all directions	0.90
7. Loose with rough surface greater than 12 in. depth	0.80
8. Loose with smooth surface greater than 12 in. depth	0.90
Structures	
1. Small sediment basins:	
0.04 basin/acre	0.50
0.06 basin/acre	0.30
2. Downstream sediment basins	
with chemical flocculants	0.10
without chemical flocculants	0.20
3. Erosion control structures	
normal rate usage	0.50
high rate usage	0.40
4. Strip building	0.75

Land Use --

Each subcatchment is assigned one of up to five land uses defined in group J2. Parameters entered for an individual land use will then be used on the corresponding subcatchments.

Catchbasins --

The total number is entered for parameter BASINS. (See earlier discussion of catchbasins.) In lieu of counting every one, BASINS may be computed if the general catchbasin density is known, e.g., 0.2 - 0.5 per ac (0.5 - 1.2 per ha) for most cities (Lager et al., 1977b). When BASINS = 0, no catchbasin computations are performed for the subcatchment.

Gutter Length --

Gutter or curb length, GQLEN, is used <u>only</u> for <u>quality</u> calculations for which buildup parameters are normalized as lb/100-ft curb, etc. (i.e., only when parameters JACGUT or KACGUT equal zero in groups J2 and J3). This parameter may be measured directly by scaling the total length of streets off of maps and multiplying by two. As for other parameters, estimation of GQLEN is most economically achieved by measurements in a few representative areas and extrapolation to others.

Curb length has been measured in several cities as a function of land use. Results for Tulsa and for ten Ontario cities are shown in Table 4-28. The Ontario results were compiled from aerial photographs. On a broad, totally urbanized area basis, curb length has been related to population density, e.g., Graham et al. (1974) for the Washington, D.C. area. Manning et al. (1977) augmented the Washington, D.C. data with data from six other U.S. cities to develop the equation:

$$GD = 413 - 353 \cdot 0.839^{PD} \qquad (4\text{-}51)$$

where GD = curb length density, ft/ac, and
PD = population density, persons/ac.

Subcatchment gutter length may then be obtained simply by

$$GQLEN = GD \cdot WAREA/100 \qquad (4\text{-}52)$$

where GQLEN = gutter (curb) length, 100-ft, and
WAREA = subcatchment area, ac.

Equation 4-51 should be used for large areas, such as an aggregated subcatchment used for continuous simulation. Site specific data are always preferred in any event.

Constituent Loadings --

As an alternative to the several buildup options available in groups J2 and J3, <u>initial</u> desired constituent loads may be entered on a per acre basis for each subcatchment. Total initial loads are then computed simply by multiplication by the subcatchment area,

$$PSHED = pshed \cdot WAREA \cdot FACT1 \qquad (4\text{-}53)$$

where PSHED = initial surface constituent load, e.g., mg for NDIM = 0,
pshed = loading entered on data group L1, e.g., lb/ac for NDIM = 0,
WAREA = subcatchment area, ac, and
FACT1 = conversion factor, e.g., 453600 mg/lb for NDIM = 0.

Loadings may be entered for any number of constituents. A loading entered for one subcatchment does not affect buildup calculations on another for which a zero loading is used.

Table 4-28. Measured Curb Length Density for Various Land Uses (Heaney et al., 1977; Sullivan et al., 1978)

Location:	Tulsa, Oklahoma			10 Ontario Cities		
Land Use	mi/ac	km/ha	100-ft/ac	mi/ac	km/ha	100-ft/ac
Residential	0.076	0.30	4.0	0.042	0.17	2.2
Commercial	0.081	0.32	4.3	0.057	0.23	3.0
Industrial	0.042	0.17	2.2	0.025	0.099	1.3
Park	0.042	0.17	2.2	-	-	-
Open	0.016	0.063	0.85	0.015	0.059	0.79
Institutional	-	-	-	0.030	0.12	1.6

For continuous simulation, constituents will buildup between storms, (unless the rating curve option is used). These buildup parameters must be entered in groups J2 and J3. The initial loading will have no effect after the first storm has ended except for a possible residual load (PSHED) remaining on the surface. The loading parameters on group L1 are thus most easily adapted to single event simulation. They also provide one method of avoiding computation of an equivalent gutter length for land uses such as parking lots (if that type of normalized loading rate is being used).

Overall Sensitivity to Quality Parameters

One of the advantages of computer simulation is that it permits examination of the interactions between the complex precipitation time series and the various quantity and quality process of the catchment. It should be borne in mind that quality buildup processes in the model occur only during storms (or during runoff due to snow melt). For the moment it will be assumed that the rating curve approach is not being used.

As a general rule, predicted concentrations and total loads are most sensitive to buildup rates. Twice the initial surface load usually means that

about twice the load in the runoff will occur. (An obvious qualification is if washoff parameters are such that not all the material is washed from the surface during most storm events.) For instance, if linear buildup is used for dust and dirt, parameter DDFACT in group J2 is a very important parameter. But the upper limit to buildup also enters the picture.

Consider the sketch in Figure 4-43. If the limiting buildup quantity is reached before a storm occurs, the results will be sensitive to the buildup limit (i.e., DDLIM or QFACT(1)) but not the rate. On the other hand, if the limit is not reached before a storm occurs, the results will be sensitive to the buildup rate (i.e., DDFACT or QFACT(3)) but not the limit. During continuous simulation the interevent time between storms varies, typically with an exponential probability density function. But examination of the average interevent time should permit a sensitivity analysis of the type sketched in Figure 4-43. A similar argument could be made using power, exponential or Michaelis-Menton buildup functions.

The effect of street cleaning is also obviously related to average interevent time. Clearly if the interval, CLFREQ, exceeds the storm interevent time, cleaning will have a decreasing effect. For example, for a continuous simulation of Des Moines, Iowa, street cleaning had essentially no effect for intervals greater that 20 days (Heaney et al., 1977). The average interevent time for Des Moines is about 4 days.

Should it be desired to evaluate the average interevent time for precipitation, the computer program SYNOP may be used to process the National Weather Service precipitation tapes. This is described in the EPA Area-wide Assessment Procedures Manual (EPA, 1976). Alternatively, the SWMM Statistics Block may be used.

Total storm loads will be sensitive to washoff parameters as long as they do not already produce 100 percent washoff during most storms. For example, in many past SWMM applications, parameters RCOEF and WASHPO (Equation 4-38) were set to 4.6 in^{-1} and 1.0 respectively. This resulted in 90 percent washoff after 0.5 in (13 mm) of runoff (independent of the time, as discussed earlier). Since most applications of single event SWMM simulated storm events for which runoff was greater than 0.5 in (13 mm), total loads were insensitive to increases in RCOEF and relatively insensitive to decreases.

This may still be true for single event simulations of "large" storms (i.e., depths greater that 0.5 in or 13 mm). But during continuous simulation the median runoff depth is likely to be considerably less than 0.5 in (13mm), more on the order of 0.2 in (5 mm). Hence washoff coefficients will be relatively more important for continuous simulation. As an indication of relative sensitivity, equation 4-38 can be rearranged for constant runoff rate, r, and for 90 percent washoff ($PSHED/PSHED_o = 0.1$) to give

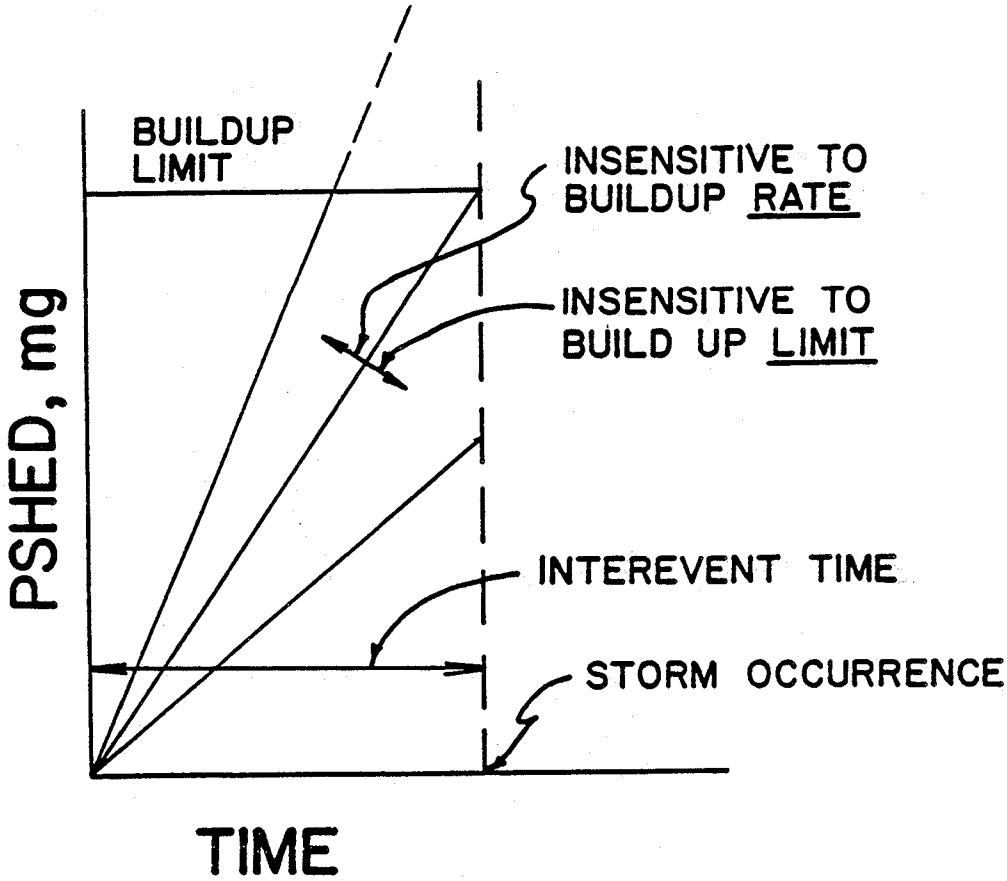

Figure 4-43. Interaction of Buildup Parameters and Storm Interevent Time.

$$RCOEF \cdot r^{WASHPO} \cdot t = RCOEF \cdot r^{WASHPO-1} \cdot d = -\ln 0.1 = 2.303 \qquad (4\text{-}54)$$

where RCOEF = washoff coefficient, $in.^{-WASHPO} \cdot hr^{WASHPO-1}$,
WASHPO = washoff power,
t = time (runoff duration), hr,
r = runoff rate, in/hr, and
d = storm runoff depth = r·t, in.

This relationship between RCOEF and WASHPO (linear on semi-log paper) is shown for d = 0.2 and 0.5 in. (5 and 13 mm) on Figure 4-44 for various values of r. Note that for a half-inch of runoff, the familiar value for RCOEF of 4.6 is found for r = 1.0 in./hr or WASHPO = 1.0. The figure shows that for runoff rates less that 1.0 in./hr (25 mm/hr) RCOEF must be increased as WASHPO is increased to achieve the same percent washoff. (This is because an increase in WASHPO results in a decrease in washoff for r < 1.0 in./hr.) The relationship is reversed for r > 1.0 in./hr, but runoff rates this high occur only over brief intervals during a year. In fact, average hourly rainfall intensities greater than 1.0 in./hr are rarely found in precipitation records. Hence, during continuous simulation, if RCOEF or WASHPO is changed, the other parameter should be increased if the same percentage total washoff is desired. Manipulations similar to equation 4-54 may be performed if a different percentage washoff is being considered.

During single event simulation it may occasionally be important to match the pollutograph (concentration versus time) shape to measured data, as well as the total storm load. The effect of RCOEF and WASHPO on pollutographs has already been discussed and illustrated in Figures 4-32 to 4-36. Generally, if the data show that concentrations tend to increase with flow rate, especially late in the storm, then WASHPO should be greater than one.

If a rating curve approach is being used, buildup parameters will have no effect (KWASH = 1) or little effect (KWASH=2). In general, as WASHPO increases beyond 1.0, the predicted loads and concentrations will closely follow flow variations. If WASHPO is less than 1.0, concentration will be inversely proportional to flow.

As has been discussed, catchbasins have only a small effect on total storm load and affect pollutographs only during the first several time steps of a storm. Their main effect is to enhance the first flush, if there is one.

The constituent fractions (group J4) are capable of having a large effect on a few constituents if those constituents are added to a large loading. Thus, if suspended solids (SS) are high and 5 percent of SS is added to BOD, BOD can also be high without any surface loading. Since the fractions interrelate the constituents, it is often easier to calibrate the model without them, although it may be more physically realistic to include them.

PRINT CONTROL (GROUPS M1-M3)

Runoff Output

The output tables and graphs generated by the Runoff Block are briefly

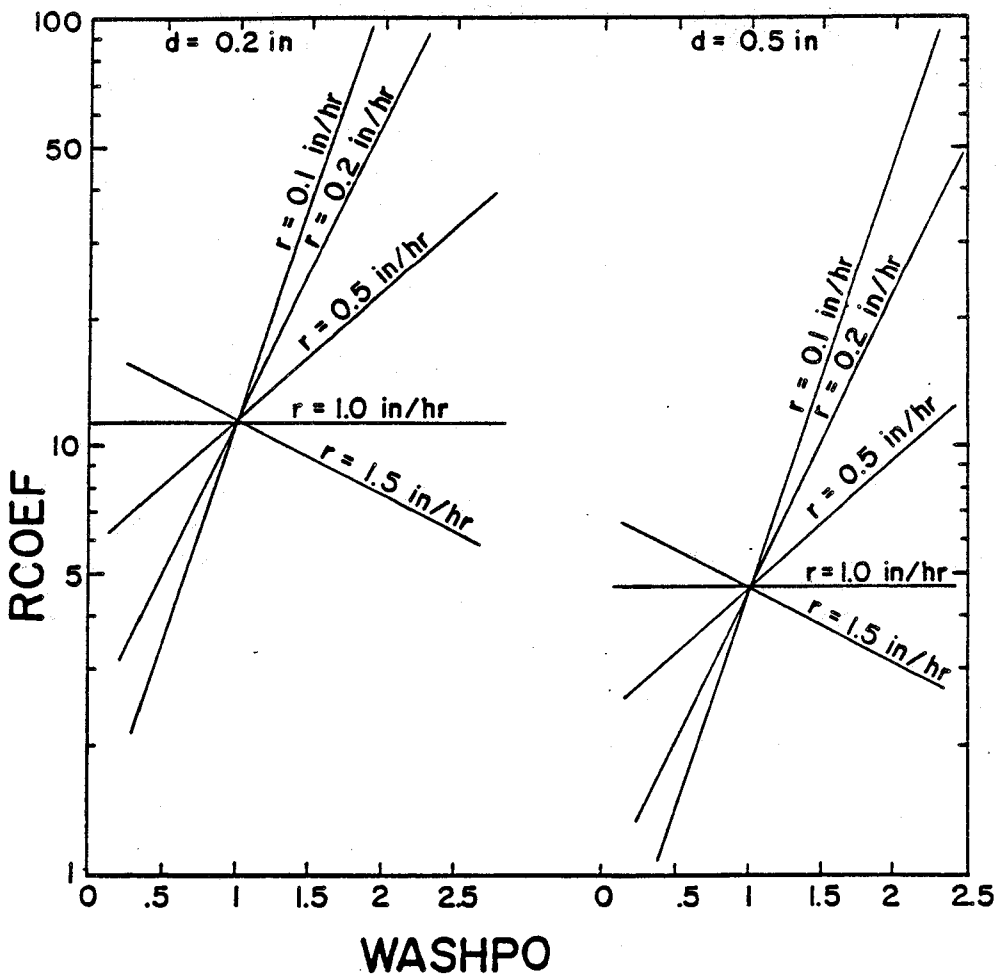

Figure 4-44. Relationship Between RCOEF and WASHPO for 90 Percent Washoff During a Storm Event of Runoff Depth d. The runoff rate is r.

described in Table 4-29. Possible outputs include: continuity checks for quantity and quality; daily, monthly, annual and simulation summaries of surface water flow; groundwater soil moisture, stage, and flow; hyetographs; inlet hydrographs; and graphs of soil moisture content and groundwater stage and flow.

Subroutine HYDRO prints a continuity check for quantity. The error will ordinarily be less than 1 percent due to round-off and the method of summing (numerically integrating) instantaneous flow rates. Should non-convergence messages be encountered, the continuity error could be somewhat higher.

Subroutine PRINTR generates a summary quality table that concisely summarizes the sources, concentrations, and losses of surface water quality simulation. Groundwater output by subcatchment is controlled by parameters ISFPF and ISFGF on the individual H2 data lines.

Print Options

Data groups M1-M3 control two types of printed output from subroutine PRINTR of the Runoff Block: (1) summary flows and concentrations, and (2) detailed time step printouts. The channels/inlets to be printed are selected using data groups M1 and M3. Summary tables listing total flow volumes and quality loads for each selected channel/inlet are always printed.

The first possible output is summary output for daily, monthly, or annual periods. For any simulation, options exist for the frequency of summaries (daily, monthly and annual) as indicated by parameter IPRN(3) on data group B1. Caution should be used in order not to produce excessive lines and pages of output.

The second type of output available is on a time step basis. Single event SWMM will print output for desired locations for the total event duration. Since there is no limit on time steps, it is possible for this output to be lengthy. However, the number of time steps between printing may be varied using parameter INTERV in group M1.

For longer (continuous) simulation, time step print out is available for up to ten specified time periods. The parameters are entered on data group M2. The choice of these time periods must be made in advance and can be most reasonably accomplished by examination of the precipitation record prior to running the total continuous simulation, using the Rain Block.

All time step flows and concentrations are instantaneous values at the indicated time. In addition to the time step values, the total load, and flow-weighted averages and standard deviations are printed for flow and each quality parameter.

The SWMM user can use IPRN(3) on data group B2, INTERV on data group M1, and NDET on data group M2 to control the amount of printout. At a minimum for each selected channel/inlet a simulation summary will be generated. At the most a detailed time step printout for every time step, plus daily, monthly, annual, and simulation summaries will be generated. Judicious usage of the

print controls is strongly recommended.

The print control groups mark the end of Runoff Block input. The sequence of all required input data is given in Table 4-30, followed by detailed instructions for data entry in Table 4-31. Control is now returned to the Executive Block. For review of hydrographs and pollutographs and for ease of calibration, use of the Graph Block is highly recommended. Finally, continuous SWMM output may most conveniently be summarized using the Statistics Block.

Table 4-29. Output from the Runoff Block

Description	Comments
Continuity Check	Quantity check from HYDRO that is always printed.
Continuity Check	Quality continuity check from PRINTR that is printed only if quality is simulated.
Daily, Monthly, and Annual Summaries	Select channel/inlet with M1 and M3 data groups. Control printout with parameter IPRN(3) on data group B2. Printed by Subroutine PRINTR.
Detailed time step printout every INTERV times.	Select channel/inlet with M1 and M3 data groups. Control printout with INTERV parameter on data group M1. INTERV=0 prints only simulation summary.
Detailed time step printout of groundwater	Select using parameter ISFPF on data group H2. The stage, soil moisture, and flow are printed by Subroutine PRINTR.
Graph of stage, flow and soil moisture from groundwater storage.	Select using parameter ISFGF on data group H2. The stage, flow and soil moisture are graphed by Subroutine HCURVE, called from the Runoff Block.
Graph of the inlet hydrograph, hyetograph, and infiltration.	Control graph using parameter IPRN(2) on data group B2.

Table 4-30. Input Data Sequence for the Runoff Block.

Data Group	Description
$Runoff	Read in Executive Block - Starts Runoff Simulation
A1	Descriptive titles - 2 lines
B1-B4	Control Parameters
C1-C5	Snowmelt Parameters
D1	Precipitation Control
E1-E3	Precipitation Data
F1	Evaporation Data
G1	Channel/pipe Data
G2	Weir, Orifice Data
H1	Subcatchment Surface Data
H2-H4	Subcatchment Soil Moisture and Groundwater Data
I1-I3	Subcatchment Snowmelt Data
J1-J4	Quality Data
K1	Erosion Data
L1	Subcatchment Quality Data
M1-M3	Print Control Input
M4	Channel/Pipe Depths

Table 4-31. Runoff Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Two Title Lines	
A1	Group identifier	None
TITLE	Title lines: two lines with heading to be printed on output. Each line has format A76.	Blank
	First Control Data Group	
B1	Group identifier	None
METRIC	Metric input-output. =0, Use U.S. customary units =1, Use metric units. Metric input indicated in brackets [] in remainder of this table.	0
ISNOW	Snowmelt parameter[1] =0, Snowmelt not simulated. =1, Single event snowmelt simulation. =2, Continuous snowmelt simulation.	0
NRGAG	Number of hyetographs (rain gages), maximum of 10 hyetographs.	1
INFILM	Choice of infiltration equation =0, Horton equation used =1, Green-Ampt equation used.	0
KWALTY	Quality (or erosion) simulated? =0, No. =1, Yes.	0
IVAP	Evaporation parameter[2] =0, Evaporation data not read in, default rate used of 0.1 in/day [3 mm/day]. =1, Read monthly evaporation data in Group F1. =2, Read evaporation data from NSCRAT(3). Created by the Temp Block.	0
NHR	Hour of day of start of storm (24 hour clock, midnight = 0.0).	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
NMN	Minute of hour of start of storm.	0
NDAY	Day of month of start of simulation[3].	2
MONTH	Month of start of simulation[4].	8
IYRSTR	Year of start of simulation	41
	Second Control Data Group	
B2	Group identifier	None
IPRN(1)	Print control for SWMM input. = 0, Print all input data. = 1, Do not print channel/pipe, snowmelt, subcatchment, or quality data, only control information is printed. = K, where K equals possible combinations of channel/pipe(2), snowmelt(3), subcatchment(4), or water quality(5). Channel/pipe + subcatchment would be 24. Channel/pipe + subcatchment + quality would be 245, etc.	0
IPRN(2)	Print control for Runoff Block graphs. = 0, Plot all graphs. = 1, Do not plot hyetograph(s) (for each gage), or inlet hydrograph (sum of all inlets).	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
IPRN(3)	Print control for output of SWMM. 'Totals' below refer to precipitation, runoff and all quality parameters. Done for each inlet. Daily, monthly, and yearly printouts only function if simulation is long enough. =0, Do not print daily, monthly, or yearly totals. =1, Monthly and annual totals only, one year per page. =2, Daily, monthly and annual totals, two months per page. Daily totals are printed whenever there is non-zero precipitation and/or runoff.	0
	Third Control Data Group	
B3	Group identifier	None
WET	Wet time step (seconds). WET must be $\geq$ 1 second.	3600.0
WETDRY	Transition between wet and dry time step in seconds. WETDRY should be greater than WET and less than DRY.	7200.0
DRY	Dry time step (seconds). DRY must be greater than or equal to WET.	86400.0
LUNIT	Units of LONG (simulation length) = 0, seconds. = 1, minutes. = 2, hours. = 3, days. = 4, ending date, a six figure number (yr/mo/dy), e.g. 870730	0
LONG	Simulation length (units from LUNIT)	1.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Optional data group. The B4 data group is used only if the user desires to modify one of SWMM's subcatchment default parameters.	
B4	Group identifier	None
PCTZER	Percent of impervious area with zero detention (immediate runoff)[5]	25.0
REGEN	For continuous SWMM, infiltration capacity is regenerated using Horton type exponential rate constant equal to REGEN·DECAY, where DECAY is the Horton rate constant read in for each subcatchment in Group H1. N.R. (not required) if using Green-Ampt infiltration.	0.01

General Snow Input Data

*** IF ISNOW = 0 IN GROUP B1, SKIP TO GROUP D1 ***

C1	Group identifier	None
ELEV	Average watershed elevation, ft, msl [m, msl]	0.0
FWFRAC(1)	Ratio of free water holding capacity to snow depth (in. or mm w.e.)[6] on snow covered impervious area.	0.0
FWFRAC(2)	Ratio of free water holding capacity to snow depth (in. or mm w.e.) on snow covered pervious area.	0.0

*** The following parameters are required only for ISNOW=2. ***

FWFRAC(3)	Ratio of free water holding capacity to snow depth (in. or mm w.e.) for snow on normally bare impervious area.	0.0
SNOTMP	Dividing temperature between snow and rain, °F [°C]. Precipitation occurring at air temperatures above this value will be rain, at or below will be snow.	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
SCF	Snow gage catch correction factor. Snow depths computed from NWS precipitation tape will be multiplied by this value[7].	1.0
TIPM	Weight used to compute antecedent temperature index, $0 \leq TIPM \leq 1.0$. Low values (e.g., 0.1) give more weight to past temperatures. Values ≥ 0.5 essentially give weight to temperatures only during the past day.	0.0
RNM	Ratio of negative melt coefficient to melt coefficient. "Negative melt coefficient" is used when snow is warming or cooling below the base melt temperature without producing liquid melt. RNM is usually ≤ 1.0 with a typical value of 0.6.	0.6
ANGLAT	Average latitude of watershed, degrees north.	0.0
DTLONG	Longitude correction, standard time minus mean solar time, minutes (of time)[8].	0.0

Monthly Wind Speeds

Enter values only for months with potential snow melt. Enter values for months in any order.

C2	Group identifier	None
NUMB	Enter number of months with wind speed data.	0
MONTH	Integer number of first month.	1
WIND(MONTH)	Average wind speed for first month, mi/hr [km/hr].	0.0
⋮	⋮	
MONTH	Integer number of last month.	12
WIND(MONTH)	Average wind speed for last month, mi/hr [km/hr].	0.0

Table 4-31 (continued). Runoff Block Input Data.

VARIABLE	DESCRIPTION	DEFAULT
	Areal Depletion Curve for Impervious Area[9]	
	IF ISNOW=1 IN GROUP B1, SKIP TO DATA GROUP C5	
C3	Group identifier	None
ADCI(1)	Fraction of area covered by snow (ASC) at "zero+"[10] ratio of snow depth to depth at 100 percent cover (AWESI)[11].	0.0
ADCI(2)	Value of ASC for AWESI=0.1.	0.0
ADCI(3)	Value of ASC for AWESI=0.2.	0.0
.	.	
.	.	
.	.	
ADCI(9)	Value of ASC for AWESI=0.8.	0.0
ADCI(10)	Value of ASC for AWESI=0.9.	0.0
Note: Program automatically assigns value of ADCI=1.0 when AWESI=1.0.		
	Areal Depletion Curve for Pervious Area[9]	
C4	Group identifier	None
ADCP(1)	Fraction of area covered by snow (ASC) at "zero+"[10] ratio of snow depth to depth at 100 percent cover (AWESI).[11]	0.0
ADCP(2)	Value of ASC for AWESI=0.1.	0.0
ADCP(3)	Value of ASC for AWESI=0.2.	0.0
.	.	
.	.	
.	.	
ADCP(9)	Value of ASC for AWESI=0.8.	0.0
ADCP(10)	Value of ASC for AWESI=0.9.	0.0
Note: Program automatically assigns value of ADCP=1.0 when AWESI = 1.0.		

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Air Temperatures	
	READ GROUP C5 ONLY IF ISNOW = 1. SKIP TO GROUP D1 IF ISNOW = 2.	
	For ISNOW = 2 (continuous SWMM), air temperatures are entered in the Temp Block. For ISNOW = 1, read an air temperature for each time interval DTAIR, for a total of NAIRT values. (Maximum number of values = 200. If more are needed, use ISNOW = 2 option.) DTAIR, the time step of air temperatures, is not necessarily equal to the time steps entered on data group B1. Air temperatures are considered constant over the air time step.	
C5	Group identifier	None
DTAIR	Time interval for input of air temperatures, hours. First line only.	0.0
NAIRT	Number of air temperatures read. First line only.	0
TAIR(1)	Air temperature during time interval 1, °F [°C].	0.0
. . .	. . .	
TAIR(NAIRT)	Air temperature during time interval NAIRT, °F [°C].	0.0
	First Rainfall Control Card	
D1	Group identifier	None
ROPT	Precipitation input option. = 0, Read NRGAG hyetographs on E1, E2 and E3 data groups. (Rain data can be saved permanently on NSCRAT(1) using the @ function.) = 1, Read processed precipitation file on JIN file. This file is either from the Rain Block (earlier saved JOUT file) or from a previous run of the Runoff Block (earlier saved NSCRAT(1) file). Unless blocks are run as part of a single overall SWMM run, access to earlier saved files is through the @ function described in Section 2.	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Second Rainfall Control Card	
E1	Group identifier	None
KTYPE	Type of precipitation input. Precipitation is in units of in./hr [mm/hr] for THISTO minutes or hours. Use variable KTIME to select units of time. = 0, Read KINC precipitation values per line. = 1, Read KINC time and precipitation pairs per line. = 2, Read time and NRGAG precipitation values per line.	0
KINC	Number of precipitation or time/precipitation pairs per line. Enter any number if KTYPE=2.	0
KPRINT	Print control for precipitation input. = 0, Print all precipitation input. = 1, Suppress all but summary of precipitation input.	0
KTHIS	Variable THISTO option. Data input on E2 lines. = 0, rainfall interval (THISTO) is constant. = K, where K is the number of variable rainfall intervals entered on the E2 data group lines. Precipitation values outside the time frame of any variable rainfall interval uses THISTO as the rainfall interval.	0
KTIME	Precipitation time units. = 0, time in minutes. = 1, time in hours.	0
KPREP	Precipitation unit type. =0, intensity, in./hr [mm/hr]. =1, total precipitation volume over the interval, in. [mm]	0
NHISTO	Number of data points for each hyetograph.	None
THISTO	Time interval between values, units of KTIME.	None
TZRAIN	Initial time of day of rainfall input, units of KTIME. Added to times entered in groups E2 and E3. (If first time entered in groups E2 and/or E3 is 0.0, TZRAIN will ordinarily correspond to time of start of storm entered on group B1.)	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Variable Rainfall Interval Information.	
Required only if KTHIS > 0. Enter variable precipitation intervals, 10 per line for a total of KTHIS intervals. This data group is used to collate rainfall records of differing intervals, for example, a period of 5 minute rainfall between periods of 15 minute rainfall. See text.		
E2	Group identifier	None
WTHIS(1,1)	Start time for first variable precipitation interval. Units of KTIME.	0.0
WTHIS(1,2)	End time for first variable precipitation interval. Units of KTIME.	0.0
WTHIS(1,3)	Length of THISTO for the first precipitation interval. Units of KTIME.	1.0
.	.	
.	.	
.	.	
WTHIS(KTHIS,1)	Start time for last variable precipitation interval. Units of KTIME.	0.0
WTHIS(KTHIS,2)	End time for last variable precipitation interval. Units of KTIME.	0.0
WTHIS(KTHIS,3)	Length of THISTO for the last precipitation interval. Units of KTIME.	1.0

Rainfall input if KTYPE = 0.

Rainfall hyetograph lines: read KINC intervals per line, up to NHISTO values. Repeat group E3 for each hyetograph, up to NRGAG times.

E3	Group identifier	None
RAIN(1)	Rainfall intensity, first interval, in./hr [mm/hr].	0.0
.	.	
.	.	
.	.	
RAIN(KINC)	Rainfall intensity, last interval per line, in./hr [mm/hr].	0.0

Note: If ISNOW=1, snowfall during a time step may be entered as a negative value. Units are in. [mm] water equivalent/hr.

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Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Rainfall input if KTYPE = 1.	
Rainfall hyetograph lines: read KINC pairs per line, up to NHISTO values. Repeat group E3 for each hyetograph, up to NRGAG times.		
E3	Group identifier	None
REIN(1)	Time of first precipitation. Units of KTIME.	0.0
REIN(2)	Precipitation in./hr [mm/hr], for first interval.	0.0
.	.	
.	.	
.	.	
REIN(2*KINC-1)	Time of last precipitation. Units of KTIME.	0.0
REIN(2*KINC)	Precipitation for last interval, in./hr [mm/hr].	0.0
Note: If ISNOW=1, snowfall during a time step may be entered as a negative value. Units are in. [mm] water equivalent/hr.		
	Rainfall input if KTYPE = 2.	
Rainfall hyetograph lines: read NRGAG precipitation values per line. Repeat NHISTO times.		
E3	Group identifier	None
REIN(1)	Time of precipitation. Units of KTIME.	0.0
REIN(2)	Precipitation, first raingage, in./hr [mm/hr].	0.0
.	.	
.	.	
.	.	
REIN(NRGAG+1)	Precipitation, last raingage, in./hr [mm/hr].	0.0
Note: If ISNOW=1, snowfall during a time step may be entered as a negative value. Units are in. [mm] water equivalent/hr.		

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	* * * INCLUDE THIS GROUP ONLY IF IVAP=1 ON GROUP B1 * * *	
	Evaporation data[12]	
F1	Group identifier	None
VAP(1)	Evaporation rate for month 1 (January) in./day [mm/day].	0.0
.	.	
.	.	
.	.	
VAP(12)	Evaporation rate for month 12 (December) in./day [mm/day].	0.0

Channel/Pipe Data

Channel/pipe data: one line per channel/pipe (if none, leave out). Maximum number of channels or pipes plus inlets is 200. An inlet is any location identified by NGTO (groups G1 and H1) that is not listed in group G1 as a channel or pipe. All inlets are saved on interface file, if JOUT ≠ 0.

Variables with asterisks can be modified using the Default/Ratio option[13,14].

G1	Group identifier	None
NAMEG[15]	Channel/pipe number.	None
NGTO[15,16]	Channel/pipe or inlet number for drainage.	None
NPG=NP	Type of channel or pipe. = 1 for channel (trapezoidal channel), = 2 for circular pipe, = 3 for dummy channel/pipe, inflow=outflow,[17] = 4 for parabolic channel, = 5 for trapezoidal channel with weir or orifice (follow with G2 data group), = 6 for circular pipe with weir or orifice (follow with G2 data group), and = 7 for parabolic channel with weir or orifice (follow with G2 data group).	None

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** The following parameters are N.R. if NP=3 ***	
GWIDTH=G1*	Bottom width of trapezoidal channel[18], diameter of pipe, or top width of parabolic channel, ft [m].	0.0
GLEN=G2*	Length of channel/pipe, ft [m].	0.0
G3*	Invert slope, ft/ft.	None
GS1=G4	Left-hand side slope, ft/ft.[19] (Slope = horiz./vert.)	None
GS2=G5	Right-hand side slope, ft/ft.	None
G6*	Manning's roughness coefficient.	None
DFULL=G7*	Depth of channel when full, ft [m]. (N.R. if NP equals 2, 3, or 6)	None
GDEPTH=G8*	Starting depth of pipe/channel, ft [m].	0.0

Control Structure Description

A G2 data group must follow a G1 line if NPG is greater than 4.

G2	Group identifier	None
WTYPE	Type of weir/orifice, = 0, Broad or narrow crested weir, = 1, V-notched weir, or = 2, Orifice.	0
WELEV	Elevation of weir (bottom of notch for V-notch) or of orifice centerline, referenced to bottom of channel/pipe, ft [m].	0.0
WDIS	Discharge coefficient of the weir or orifice (parameter C in equations 4-5, 4-6, 4-7). Units for equations 4-5 or 4-6: $ft^{1/2}/sec$ [$m^{1/2}/sec$]. Parameter C_d in equation 4-7 is dimensionless.	3.3
SPILL	Weir length (e.g., width of spillway) for a broad or narrow crested weir, ft [m]. The angle (degrees) of the notch for a V-notch weir. The cross sectional area of the outflow orifice, ft^2 [m^2].	1.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Subcatchment Data	
	REPEAT GROUP H1 FOR EACH SUBCATCHMENT (MAXIMUM of 200)	
Maximum of 200 different subcatchments. Variables with asterisks can be modified using the Default/Ratio option[13,14].		
H1	Group identifier	None
JK	Hyetograph number (based on the order in which they are input, in Group E3).	1
NAMEW[20]	Subcatchment number	None
NGTO[15,21]	Channel/pipe or inlet (manhole) number for drainage.	None
WW(1)*	Width of subcatchment, ft. This term actually refers to the physical width of overland flow in the subcatchment and may be estimated as illustrated in the text.[22]	None
WAREA=WW(2)*	Area of subcatchment, acres [ha].	None
WW(3)*	Percent imperviousness of subcatchment, (percent hydraulically effective impervious area).	None
WSLOPE=WW(4)*	Ground slope, ft/ft (dimensionless).	None
WW(5)*	Impervious area Manning's roughness.	None
WW(6)*	Pervious area Manning's roughness.	None
WSTORE=WW(7)*	Impervious area depression storage, in. [mm].	None
WSTORE=WW(8)*	Pervious area depression storage, in. [mm].	None

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** Horton equation parameters if INFILM=0 (Group B1) ***	
WLMAX=WW(9)*	Maximum initial infiltration rate, in./hr [mm/hr].	None
WLMIN=WW(10)*	Minimum (asymptotic) infiltration rate, in./hr [mm/hr].	None
DECAY=WW(11)*	Decay rate of infiltration in Horton's equation, 1/sec.	None
	*** Green-Ampt equation parameters if INFILM=1 (Group B1) ***	
SUCT=WW(9)*	Average capillary suction, in. (mm) of water. PSIF	None
HYDCON=WW(10)*	Saturated hydraulic conductivity of soil, in./hr (mm/hr) XKSAT	None
SMDMAX=WW(11)*	Initial moisture deficit for soil, volume air/volume voids (fraction). DTHETA	None

Groundwater Subcatchment Data

Data groups H2, H3, and H4 describe the groundwater portion of the subcatchment. They should follow the correct H1 data group line. There are a maximum of (any) 100 subcatchments with groundwater simulation allowed.

H2	Group identifier	None
NMSUB	Subsurface subcatchment indicator variable, must be same as preceding NAMEW[13,14].	None
NGWGW	Number of inlet, channel or pipe for subsurface drainage. Does not have to be the same as preceding NGTO for surface runoff.	None
ISFPF	Indicator variable for saving soil moisture, water table elevation and outflow for printing out. = 0, do not save subsurface information, or = 1, save subsurface information for printout.	0
ISFGF	Indicator variable for saving soil moisture, water table elvation and outflow for graphing. = 0, do not save subsurface information, or = 1, save subsurface information for graphing.	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** See Figure X-1 for definition of elevation variables. ***	
BELEV	Elevation of bottom of water table aquifer, ft [m].	0.0
GRELEV	Elevation of ground surface, ft [m].	0.0
STG	Elevation of initial water table stage, ft [m].	0.0
BC	Elevation of channel bottom or threshold stage for groundwater flow, ft [m].	0.0
TW	Channel water influence parameter $\geq$ BC, average elevation of water in channel or pipe over run, ft [m] or, < 0, (e.g., -1) channel water influence will be determined by depth in channel or pipe at the end of the previous time step.	0.0

Groundwater Flow Coefficients And Exponents
(Equations X-24 and X-25)

Variables with asterisks can be modified using the Default/Ratio option[13,14]. Indicator is NMSUB on data group H2.

H3	Group identifier	None
A1*	Groundwater flow coefficient, $ft/s\text{-}ft^{B1}$ [$m/s\text{-}m^{B1}$].	0.0
B1*	Groundwater flow exponent, dimensionless.	0.0
A2*	Coefficient for channel water influence $ft/s\text{-}ft^{B2}$ [$m/s\text{-}m^{B2}$].	0.0
B2*	Exponent for channel water influence, dimensionless.	0.0
A3*	Coefficient for the cross product between groundwater flow and channel water, $ft/s\text{-}ft^{B2}$ [$m/s\text{-}m^{B2}$].	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
POR*	Porosity expressed as a fraction.	0.0
WP*	Wilting point expressed as a fraction.	0.0
FC*	Field capacity expressed as a fraction.	0.0
HKSAT*	Saturated hydraulic conductivity, in./hr [cm/hr].	0.0
TH1*	Initial upper zone moisture expressed as a fraction.	0.0

More Groundwater Parameters

Variables with asterisks can be modified using the Default/Ratio option[13,14]. Indicator is NMSUB on data group H2.

H4	Group identifier	None
HCO*	Hydraulic conductivity vs. moisture content curve-fitting parameter (Eqn. X-21), dimensionless.	0.0
PCO*	Average slope of tension versus soil soil moisture curve (see Figs.. X-2, X-3 X-4), ft/fraction [m/fraction].	0.0
CET*	Fraction of maximum ET rate assigned to the upper zone.	0.0
DP*	Coefficient for unquantified losses, (Eqn. X-23), in./hr [cm/hr].	0.0
DET*	Maximum depth over which significant lower zone transpiration occurs, ft [m].	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
IF ISNOW=0, SKIP TO GROUP J1. IF ISNOW=1, READ ONLY GROUP I1. IF ISNOW=2, READ BOTH GROUPS I1 AND I2, IN PAIRS. ORDER OF SUBCATCHMENTS MUST BE SAME AS IN GROUP H1, AND THERE MUST BE SNOW DATA GROUP(S) FOR EACH ONE. NOTE THAT ALL SNOW-DEPTH RELATED PARAMETERS REFER TO DEPTH OF SNOW WATER EQUIVALENT (w.e.)[6]		
	Subcatchment Snow Input Data	
Variables with asterisks can be modified using the Default/Ratio option[13,14].		
I1	Group identifier	None
JK1 (=NAMEW(N))	Subcatchment number.[23,24,25] Must correspond to NAMEW entered in Group H1.	None
SNN1	Fraction of impervious area with 100 percent snow cover (ISNOW=1) or subject to areal depletion curve (ISNOW=2).	0.0
SNN2=SNCP(N)	Fraction of pervious area subject to 100 percent snow cover (ISNOW=1). N.R. if ISNOW=2.	0.0
SNN3=WSNOW(N,1)	Initial snow depth of impervious area that is normally snow covered, in water equivalent (in. or mm w.e.)[6]	0.0
SNN4=WSNOW(N,2)	Initial snow depth on pervious area, in. w.e. [mm w.e.].	0.0
SNN5=FW(N,1)	Initial free water on snow covered impervious area, in. [mm].	0.0
SNN6=FW(N,2)	Initial free water on snow covered pervious area, in. [mm].	0.0
SN(1)*=DHMAX(N,1)	Melt coefficient (ISNOW=1) or maximum melt coefficient, occurring on June 21 (ISNOW=2) for snow covered impervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0
SN(2)*=DHMAX(N,2)	Melt coefficient (ISNOW=1) or maximum melt coefficient, occurring on June 21 (ISNOW=2) for snow covered pervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
SN(3)*=TBASE(N,1)	Snow melt base temperature for snow covered impervious area, °F [°C].	32.0
SN(4)*=TBASE N,2)	Snow melt base temperature for snow covered pervious area, °F [°C].	32.0

Subcatchment Snow Input Data if ISNOW=2.

Variables with asterisks can be modified using the Default/Ratio option[13,14].

I2	Group identifier	None
JK2 (=NAMEW(N))	Subcatchment number.[23,24,25] Must correspond to JK1 (Group I1) and NAMEW (Group H1).	None
SNN7=WSNOW(N,3)	Initial snow depth on impervious area that is normally bare, in. [mm].	0.0
SNN8=FW(N,3)	Initial free water on impervious area that is normally bare, in. [mm].	0.0
SN(5)*=DHMAX(N,3)	Maximum melt coefficient occurring on June 21, for snow on normally bare impervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0
SN(6)*=TBASE(N,3)	Snow melt base temperature for normally bare impervious area, °F [°C].	32.0
SN(7)*=DHMIN(N,1)	Minimum melt coefficient occurring on December 21 for snow covered impervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0
SN(8)*=DHMIN(N,2)	Minimum melt coefficient occurring on December 21 for snow covered pervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
SN(9)*=DHMIN(N,3)	Minimum melt coefficient occurring on December 21 for snow on normally bare impervious area, in. w.e./hr-°F [mm w.e./hr-°C].	0.0
SN(10)*=SI(N,1)	Snow depth above which there is 100 percent cover on snow covered impervious areas, in. [mm] w.e.[6]	0.0
SN(11)*=SI(N,2)	Snow depth above which there is 100 percent cover on snow covered pervious areas, in. [mm] w.e.	0.0
SNN9=WEPLOW(N)	Redistribution (plowing) depth on normally bare impervious area, in. [mm] w.e. Snow above this depth redistributed according to fractions below.	0.0
	Redistribution (plowing) fractions (see Figure 4-25). Snow above WEPLOW in. [mm] w.e. on normally bare[26] impervious area will be transferred to area(s) indicated below. The five fractions should sum to 1.0 .	
SNN10=SFRAC(N,1)	Fraction transferred to snow covered impervious area.	0.0
SNN11=SFRAC(N,2)	Fraction transferred to snow covered pervious area.	0.0
SNN12=SFRAC(N,3)	Fraction transferred to snow covered pervious area in last catchment.[27]	0.0
SNN13=SFRAC(N,4)	Fraction transferred out of watershed.	0.0
SNN14=SFRAC(N,5).	Fraction converted to immediate melt on normally bare impervious area.	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	IF KWALTY ≠ 1 (GROUP B1) SKIP TO GROUP M1	
	General Quality Control Group	
J1	Group identifier	None
NQS	Number of quality constituents maximum = 10. Must have 1 < NQS ≤ 9 if erosion is simulated (IROS=1).[28]	None
JLAND	Number of land uses (Max of 5).	None
IROS	Erosion simulation parameter =0, Erosion not simulated. =1, Erosion of suspended solids simulated using the Universal Soil Loss Equation. Parameters input in Group K1. Output will be last quality constituent (i.e., constituent NQS+1).[28]	0
IROSAD	Option to add erosion constituent to constituent number IROSAD. E.g., if IROSAD=3, erosion will be added to constituent 3 (perhaps suspended solids). No addition if IROSAD=0. N.R. if IROS=0.[29]	0
DRYDAY	Number of dry days prior to start of storm.[30]	0.0
CBVOL	Average individual catchbasin storage volume, ft^3 [m^3].	0.0
DRYBSN	Dry days required to recharge catchbasin concentrations to initial values (CBFACT, Group J3). Must be > 0.	1.0
RAINIT	For erosion, highest average 30-minute rainfall intensity during the year (continuous SWMM) or during the storm (single event), in./hr [mm/hr]. N.R. if IROS = 0.	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** Street Sweeping Parameters ***	
REFFDD	Street sweeping efficiency (removal) fraction) for "dust and dirt."	0.0
	*** The following two variables are required only for simulations longer than one month. ***	
KLNBGN	Day of year on which street sweeping begins (e.g. March 1 = 60).[31]	0
KLNEND	Day of year on which street sweeping stops (e.g. Nov. 30 = 334)[31]	367
	Land Use Groups	
REPEAT FOR EACH LAND USE, TOTAL OF JLAND GROUPS. (MINIMUM = 1, MAXIMUM = 5) LAND USE 1 WILL BE THAT OF FIRST GROUP, LAND USE WILL BE THAT OF SECOND GROUP, ETC.		
J2	Group identifier	None
LNAME(J)	Name of Land use	'Blank'
METHOD(J)	Buildup equation type for 'dust and dirt' (see text).[32] = -2, New default values[14], = -1, New ratios[13], = 0, Power-linear, = 1, Exponential, = 2, Michaelis - Menton.	0
JACGUT(J)	Functional dependence of buildup parameters.[33] = 0, Function of subcatchment gutter length, = 1, Function of subcatchment area, = 2, Constant.	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
*** Following are up to three buildup parameters.[32] (See Table 4-16) ***		
Variables with asterisks can be modified using the Default/Ratio option[13,14].		
DDLIM(J)*	Limiting buildup quantity	10
DDPOW(J)*	Power or exponent	0.0
DDFACT(J)*	Coefficient	0.0
	*** Street Sweeping Parameters[34] ***	
CLFREQ(J)*	Cleaning interval, days	0.0
AVSWP(J)*	Availability factor, fraction	0.0
DSLCL(J)*	Days since last cleaning, DSLCL $\leq$ CLFREQ	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Constituent Groups	
REPEAT FOR EACH CONSTITUENT, TOTAL OF NQS GROUPS. (MAXIMUM = 10) CONSTITUENT 1 WILL BE THAT OF FIRST GROUP, CONSTITUENT 2 THAT OF SECOND GROUP, ETC.		
Variables with asterisks can be modified using the Default/Ratio option[13,14].		
J3	Group identifier	None
PNAME(K)	Constituent name.[35]	'Blank'
PUNIT(K)	Constituent units.	'Blank'
NDIM(K)	Type of units.[36] = 0, mg/l = 1, "Other" per liter, e.g., MPN/l = 2, Other concentration units, e.g., pH, JTU	0
KALC(K)	Type of buildup calculation[37] = 0, Buildup is fraction of "dust and dirt" for each land use = 1, Power-linear constituent buildup = 2, Exponential constituent buildup = 3, Michaelis-Menton constituent buildup = 4, No buildup required (with KWASH=1)	0
KWASH(K)	Type of washoff calculation[37] = 0, Power-exponential = 1, Rating curve, no upper limit = 2, Rating curve, upper limit by buildup equation	0
KACGUT(K)	Functional dependence of buildup parameters[38]. N.R. for KALC = 0 or 4 = 0, Function of subcatchment gutter length = 1, Function of subcatchment area = 2, Constant	0
LINKUP(K)	Linkage to snowmelt. N.R. if ISNOW = 0 or KALC = 4. = 0, No linkage to snow parameters = 1, Constituent buildup during dry weather only when snow is present on impervious surface of subcatchment[39]	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
Following are up to five buildup parameters (see text and Tables 4-16, 4-17). Variables with asterisks can be modified using the Default/Ratio option[13,14].		
QFACT(1,K)*	First buildup parameter, e.g., limit.	0.0
QFACT(2,K)*	Second buildup parameter, e.g., power or exponent.	0.0
QFACT(3,K)*	Third buildup parameter, e.g. coefficient.	0.0
QFACT(4,K)*	Fourth buildup parameter, N.R. if KALC ≠ 0.	0.0
QFACT(5,K)*	Fifth buildup parameter, N.R., if KALC ≠ 0.	0.0
*** Following are two washoff or rating curve parameters. ***		
WASHPO(K)*	Power (exponent) for runoff rate.	0.0
RCOEF(K)*	Coefficient	0.0
*** Miscellaneous parameters ***		
CBFACT(K)*	Initial catchbasin concentration.[40] (units according to NDIM).	0.0
CONCRN(K)*	Concentration in precipitation.[41] (units according to NDIM).	0.0
REFF(K)*	Street sweeping efficiency (removal fraction) for this constituent.	0.0

Fractions for contributions from other constituents[42].

REPEAT UNTIL ALL DESIRED FRACTIONS ARE ENTERED.

J4	Group identifier	None
KTO	Number (from order in Group J3) of constituent <u>to</u> which fraction will be added.	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
KFROM	Number of constituent from which fraction is computed.	0
F1(KTO,KFROM)	Fraction of constituent KFROM to be added to constituent KTO.	0.0

Erosion Data[43]

IF IROS=0 ON GROUP J1, SKIP TO GROUP L1

REPEAT GROUP K1 ONLY FOR EACH SUBCATCHMENT THAT IS SUBJECT TO EROSION COMPUTATIONS. ORDER OF GROUPS IS ARBITRARY, BUT A MATCH MUST BE FOUND OF SUBCATCHMENT NUMBER WITH A VALUE OF NAMEW USED IN GROUP H1.

Variables with asterisks can be modified using the Default/Ratio option[13,14].

K1	Group identifier	None
N=NAMEW	Subcatchment number.	None
ERODAR*	Area of subcatchment subject to erosion, acres [ha].	0.0
ERLEN*	Flow distance in feet [meters] from point of origin of overland flow over erodible area to point at which runoff enters channel/pipe or inlet.	0.0
SOILF*	Soil factor 'K'.	0.0
CROPMF*	Cropping management factor 'C'.	0.0
CONTPF*	Control practice factor 'P'.	0.0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Subcatchment Surface Quality Data	
	IF NQS=0, SKIP TO GROUP M1	
ONE LINE FOR EACH SUBCATCHMENT IS REQUIRED. ORDER IS ARBITRARY, BUT A MATCH MUST BE FOUND FOR EACH SUBCATCHMENT NUMBER (NAMEW) USED EARLIER IN GROUP H1.		
Variables with asterisks can be modified using the Default/Ratio option[13,14].		
L1	Group identifier	None
N=NAMEW	Subcatchment number.	None
KL	Land use classification. $1 \leq KL \leq 5$. Numbers correspond to input sequence of Group J2.	1
BA*=BASINS(N)	Number of catchbasins in subcatchment.	0
GQ*=GQLEN (N)	Total curb length within subcatchment hundreds of feet [km]. May not be required depending on method used to calculate constituent loadings (Groups J2 and J3).[44]	0

The following constituent loading values may be input as an alternative to computation of loadings via methods specified groups J2 and J3 (for initial conditions only). For any non-zero values read in, initial constituent loadings will be calculated simply by multiplication of the value by the subcatchment area. "Load" has units depending on value of NDIM (Group J3), according to the following table:

NDIM	LOAD
0	pounds [kg]
1	10^6 x quantity, e.g. 10^6 MPN
2	10^6 x quantity x ft^3, e.g. 10^6 pH-ft^3.

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
PSHED(1,N)	Initial loading, first constituent, load/acre (load/ha).	0.0
.	.	
.	.	
.	.	
PSHED(10,N)	Initial loading, tenth constituent, load/acre (load/ha).	0.0
	Channel/Inlet Print Control	
M1	Group identifier	None
NPRNT	Total number of channels/pipes/inlets for which non-zero flows[46] (and concentrations) are to be printed (maximum = 200)[45].	0
INTERV	Print Control. = 0, Print statistical summary only. = 1, Print every time step. = K, Print every K time steps.	None
	* * * IF NPRNT=0, SKIP GROUPS M2 and M3 * * *	
	Print Periods	
M2	Group identifier	None
NDET	Number of detailed printout periods. (Maximum of 10 periods.)	0
	** If NDET = 1 and STARTP(1) = 0 and STOPPR(1) = 0 then total simulation period will be printed as default. **	
STARTP(1)	First starting printout date, year, month, day, e.g., October 2, 1949 = 491002.	None
STOPPR(1)	First stopping printout date.	None
.	.	
.	.	
.	.	
STARTP(NDET)	Last starting date.	0
STOPPR(NDET)	Last stopping date.	0

Table 4-31 (continued). Runoff Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Channel/Inlet Print Groups: 16 Values per Line	
M3	Group identifier	None
IPRNT(1)[47]	Channel/inlet numbers for which flows and concentrations are to be printed.	None
.	.	
.	.	
.	.	
IPRNT(NPRNT)		None

***** END OF RUNOFF BLOCK INPUT DATA *****

At this point, program will seek new input data from the Executive Block.

Footnotes to Table 4-31

1. The main difference between single event and continuous snowmelt simulation follow. For single event SWMM, snow covered areas are constant (areal depletion curves are used for continuous SWMM) and input parameters are fewer. In addition, snowfall quantities are not computed on the basis of air temperatures but may only be input, if desired, as negative precipitation intensities on group E2. Melt coefficients are constant and there is no maintenance of the cold content of the snow pack, nor is there redistribution (e.g., plowing) from normally bare areas. For continuous SWMM, melt coefficients vary daily, from a maximum on June 21 to a minimum on December 21. Both modes use the same melt equations and melt routing procedures.

2. Evaporation is used to renew surface depression storage and is also subtracted from rainfall and/or snowmelt at each time step. It has a negligible effect on single event simulation, but is important for continuous simulation. Evaporation is not used to deplete the snow pack, i.e., it does not also act as sublimation, nor does it affect regeneration of infiltration capacity. However, the evaporation input to Runoff acts as an upper bound for ET losses from groundwater and soil moisture. Evaporation now also occurs from trapezoidal and parabolic channels.

3. Used for information only for single event SWMM. This parameter does not affect computations, but it is passed to subsequent blocks.

4. Used as subscript for monthly wind speed and evaporation data (Groups C2 and F1).

5. Immediate runoff occurs from impervious areas without depression storage, whereas runoff from areas with depression storage may be delayed. As PCTZER is increased, the rising limb of the hydrograph begins earlier.

6. All snow depths are in inches (or mm) of water equivalent, "in. [mm] w.e." One inch of snow water equivalent equals a depth of approximately 11 inches of new snow on the ground surface.

7. Values of SCF are usually > 1.0 and increase as a function of wind speed. See Figure 4-2. The value of SCF can also be used to account for snow losses, such as interception and sublimation, not included in program computations.

8. Compute DTLONG as follows: Determine standard meridian (SM) for time zone of catchment (e.g., EST=75°W, CST=90°W, MST=105°W, PST=120°W). Let theta = average longitude of catchment, and delta = theta - SM. Then DTLONG = 4 (min/deg) x delta. Example: Minneapolis at theta = 93 °W has DTLONG = +12 min (of time).

9. See Figures 4-3 and 4-4 for description of areal depletion curve.

10. Value of ADC may = zero, but curve need not pass through (0,0); see Figure 4-3. Thus ADC can take an arbitrary value for a small departure of AWESI from zero.

11. In the program, AWESI is the ratio of actual snow depth (WSNOW) to depth at 100 percent cover (SI, read in Group I2).

12. If this group is read, the default value of 0.1 in./day [3 mm/day] indicated in Group B1 no longer applies, i.e., the default value becomes zero.

13. Input values in this group indicated with asterisks are multiplied by ratios, initially set equal to 1.0. If the ID number = -1, non-zero data entries for parameters with asterisks will replace old values of the ratios. Ratios may be altered or reset to 1.0 any number of times. The intention of the use of ratios is to simplify sensitivity analyses, etc., by allowing easy changes of data values without re-entering data. Ratios may be reset any number of times and alter the indicated ratios to be applied to all following entries in this data group (until another ratio group is encountered).

14. Input parameters in this group indicated with asterisks will take on default values if input values are zero. If the ID number = -2, non-zero data entries for parameters with asterisks will become new default values for all future entries of these parameters. Default values may be altered or reset to their original values (except zero) any number of times. The indicated default values apply to all following entries in this data group (until another default group is encountered).

It is not possible to reset a default value exactly to zero since only non-zero values are changed. However, the value may be made arbitrarily small by using E-format data entries. For example, 10^{-50} may be entered as 10E-50.

15. Numbers may be arbitrarily chosen, such that 1 $\leq$ NAMEG or NGTO $\leq$ 99999. However, if an inlet number is to correspond to an inlet manhole in the Transport Block, it must be $\leq$ 10,000. The maximum total number of inlets must be $\leq$ 200 for input to Transport and $\leq$ 200 for input to Extended Transport. There is no restriction for input to Storage/Treatment except that that block will select only one of the inlets on the interface file for input. Others will be saved but ignored. Channel/pipe numbers and inlet numbers are contained in the same array and thus must be distinct from one another; however, they may duplicate subcatchment numbers if desired. Each inlet is assigned a dummy channel/pipe to receive upstream flows. Hence the total number of channel/pipes plus inlets must be $\leq$ 200. Internal subscripts in the program for channel/pipe data are assigned in the order in which data in group G1 are read in.

Of course, it makes no sense to indicate a channel/pipe with nothing entering it. Thus, each one should have flow entering, either from other channel/pipe(s) or from subcatchment(s).

16. A maximum of five different channel/pipes may feed to a single channel/pipe or to a single inlet. If more are desired, a dummy channel/pipe may be used to provide five additional "feeds." See footnote 17.

17. Dummy channels may be used for two purposes: 1) to provide five additional "feeds" to a given channel/pipe or inlet (see footnote 16) by placing it in series with the channel/pipe or inlet (although, of course, by placing it in series with the original channel/pipe or inlet, it uses one of the original five "feeds"), or 2) to provide a location for print out of data. The latter situation arises because outflows from subcatchments may not be printed directly (using groups M1 - M3), only inflows or outflows to channel/pipes or inflows to inlets. Hence, if a dummy channel/pipe is placed immediately downstream from a subcatchment, the inflow (or outflow) to the dummy channel/pipe is the outflow from the subcatchment, (provided that that is the only subcatchment feeding the dummy channel/pipe).

18. A bottom width of zero for a channel corresponds to a triangular cross section.

19. A side slope of zero indicates a vertical wall, or a rectangular cross section.

20. Numbers may be arbitrarily chosen such that 1 $\leq$ NAMEW $\leq$ 99999. Numbers may duplicate channel/pipe and inlet numbers if desired. Internal subscripts in the program for subcatchment data are assigned in the order in which data in group H1 are read in.

21. A maximum of five different subcatchments may feed to a single inlet, (in addition to channel/pipes feeding the channel/pipe or inlet). If more "feeds" are desired, a dummy channel/pipe may be used to provide additional feeds. See footnote 17.

22. The subcatchment width is a key calibration parameter, one of the few that

can significantly alter the shape of the hydrograph, rather than just the runoff volume. One way to think of the width is the area of the subcatchment divided by the average path length of overland flow (see Figure 4-13). The effect upon output hydrographs is illustrated in Figure 4-15 and is approximately as follows. For rainfall durations less than the time of concentration, (i.e., less than the equilibrium time of an impervious subcatchment at which inflow equal overflow), increasing the width effectively provides a greater cross sectional area for outflow from the subcatchment, thus increasing the magnitude of the peak flow and decreasing the time to peak. Decreasing the width has the opposite effect, and the subcatchment surface acts more as a reservoir, reducing and delaying the peak. For rainfall durations greater than the time of concentration, the magnitude of the peak is affected only minutely. The time to equilibrium conditions, that is the time of concentration, is reduced slightly for larger widths.

The subcatchment width can thus be used to incorporate storage lost when pipes are removed from the simulation. For instance, if only a coarse discretization of the total catchment is desired, only a few or no pipes need be modeled. To account for this lost storage in the system, the overall subcatchment width is correspondingly reduced (see Figure 4-20). Whether for one aggregated catchment, or for a small individual subcatchment, a reasonable first approximation for determining the width is to use twice the length of the main drainage channel in the catchment (see Figure 4-20).

The same subcatchment width entered here is used for the pervious area of the subcatchment and the total impervious area of the subcatchment (see Figure 4-11).

23. Subcatchment number(s) entered in Groups I1 and I2 must correspond exactly to numbers and order of group H1.

24. Numbers JK1 and JK2 must be the same.

25. Subscript N is the internal subcatchment number (subscript) determined from the order in which subcatchment data are entered in group H1.

26. "Normally bare" implies surfaces such as roadways and sidewalks that receive snowfall but are subject to early snow removal.

27. "Last subcatchment" is last one entered in group H1.

28. The 10 or fewer constituents may be arbitrarily chosen (see text). When erosion is simulated it is stored as the last constituent. Hence, no more than 9 other constituents may be simulated while using the erosion routine. Furthermore, at least one constituent must be simulated in addition to erosion in order to proceed correctly through program loops.

29. This addition is performed before constituent fractions are added (group J4).

30. A "dry day" is not well defined, but may be considered as the number of days prior to start of simulation, in which the cumulative rainfall is less

than a specified value, e.g. 0.1 in (3 mm).

31. For year-round sweeping, let KLNBGN=0 and KLNEND=367. Leap years are not treated separately, other than in maintaining the proper number of days in February and in total annual days.

32. See the text for explanation and illustration of the various options for buildup of dust and dirt. Depending on the form of buildup chosen for each constituent (group J3), the land use buildup parameters may not be required.

33. If JACGUT=0, parameters DDLIM and DDFACT will be multiplied by GQLEN (group L1) in 100-ft (or km for metric input). If JACGUT=1, parameters DDLIM and DDFACT will be multiplied by WAREA (group H1) in acres [ha].

34. For continuous simulation street sweeping occurs at intervals of CLFREQ days, computed during the simulation using dry time steps only (no runoff and no unmelted snow on normally bare impervious areas). When cleaning occurs, a fraction of each pollutant REFF*AVSWP is removed from each subcatchment. The availability factor, AVSWP, is intended to account for the relative amount of subcatchment surface that consists of streets, and therefore may be swept. See the text.

At start of single-event and continuous simulations, streets are swept approximately DRYDAY/CLFREQ times, each time removing a fraction REFF*AVSWP. Parameter DSLCL establishes proper backwards time sequence.

35. The constituent names and units established in this group will be carried through to subsequent SWMM blocks. See Figure 4-26 for illustration of how the character-format names and units will appear as headings.

36. Since most constituents are measurable in mass units, NDIM=0 will be the most common. Since concentrations will be printed using an F10.3 format, NDIM=0 should suffice also for constituents whose concentrations are usually given in ug/l. The value of NDIM basically affects conversion factors used in the program.

37. See the text for full explanation of buildup-washoff equation options and interpretation of parameters.

38. If KACGUT = 0, parameters QFACT(1,K) and QFACT(3,K) will be multiplied by GQLEN (group L1) in 100-ft [km]. If KACGUT=1, parameters QFACT(1,K) and QFACT(3,K) will be multiplied by WAREA (group H1) in acres [ha].

39. For instance, if chlorides are simulated, they might only be applied for street salting when snow is present. The rate of buildup will not be a function of the amount of snow, however.

40. For continuous SWMM, concentrations will be regenerated to this value during dry time steps over a period of DRYBSN days, (DRYBSN entered in group J1).

41. This concentration is assumed to be that of the runoff (and snowmelt)

before adding washoff loads. The precipitation load is always added regardless of the washoff mechanism utilized, unless of course, CONCRN = 0.

42. After computing and summing all loads except rainfall, a fraction of any constituent may be added to any other. (No fractions are removed, however). This is intended to account for insoluble BOD etc. if surface loadings are based only on insoluble portions, as is true for instance for 1969 APWA data from Chicago. For example, 5 percent of suspended solids could be added to BOD. Alternatively, different particle size ranges could be simulated as different constituents, and other constituents could consist of fractions of the first group of different particle sizes. When these fractions are used, concentrations can be drastically (and subtly) increased if, for instance, suspended solids are high, soluble BOD is low and a fraction of 0.05 is used. The choice of whether or not any fractions should be entered depends upon how constituent data are being reported (e.g. total BOD or only the soluble fraction) and on how it is desired to simulate each constituent in SWMM.

43. See the text for explanation of method of computation, parameters and typical values. Also, there may be a need to consult with local soils experts (e.g. Soil Conservation Service or Agricultural Research Service or State Agricultural Extension Service experts in the U.S.) for knowledge of parameter values for particular areas.

A value of the "sediment delivery ratio" is sometimes included in the U.S.L.E. computation. Since it is merely another multiplier, if desired it may incorporated into the "K" or "C" or "P" factors.

44. See footnotes 33 and 38. This is the only use of parameter GQLEN.

45. Zero flows are not printed to avoid voluminous output with continuous SWMM. (There are no quality loads when flows are zero). Thus, some care should be taken in examining the output, since if a zero flow occurs in the middle of a single-event simulation, for instance, it will not be listed. This can be determined by inspecting the sequential time of day printed with each set of values.

Care should still be taken when running continuous SWMM, since one line of output will be generated for each hourly value of non-zero flow, for each indicated location, within the indicated time span. Hence, the potential exists for thousands of lines of output.

46. All printed values are instantaneous (flows and concentrations) at the end of the preceding time step.

47. These numbers correspond to numbers NAMEG and NGTO used in groups G1 and H1. They may be either positive or negative. A positive number will cause total inflows to the indicated channel/pipe or inlet to be printed. A negative number will cause the outflow to be printed. (Both a positive and negative value for the same location may be used). Regardless of the sign, only outflow concentrations are printed, however, since it is computationally inconvenient to calculate the average inflow concentration. Of course, for an inlet (or dummy channel/pipe), inflow values equal outflow values.

SECTION 5

EXTENDED TRANSPORT BLOCK

Following development of the original SWMM model, Water Resources Engineers (now, Camp, Dresser and McKee) participated in a study of the proposed master plan for control of combined sewer overflows in San Francisco. In order to analyze the complex hydraulics of that system, they developed the WRE Transport Model (Shubinski and Roesner, 1973), one that solves the coupled complete St. Venant equations and accounts for phenomena such as backwater, looped connections, surcharging and pressure flow that were either not considered or treated in a very simplified manner in the original Transport Model (Section 6). Through subsequent work for EPA in other cities the WRE Transport Model was acquired for the SWMM package and became known as the Extended Transport Model or Extran. This model has few peers in its capacity for simulation of the hydraulics of urban drainage system and is probably the most sophisticated such model that is non-proprietary and available in the public domain. (Similar proprietary models do exist.) Extran capabilities are compared with those of Runoff and Transport in Table 4-3.

Extran has been part of the SWMM package since 1976. Extran originally contained both quantity and quality routines. However, the only (but very extensive) use for the model has been for hydraulic analysis, and the quality routing has been formally removed from the program. The state of the art in urban runoff quality modeling is such that adequate simulation of pollutographs may be performed using the simpler hydraulics of the Runoff and Transport Blocks.

The comprehensive SWMM Version 3 Extran documentation (Roesner et al., 1981) prepared by Camp, Dresser and McKee has been updated for new SWMM Version 4 features and is included as a separate addendum to this User's Manual (Roesner et al., 1987). Full details of the model are available therein. Interfacing between Extran and the remainder of SWMM is performed as described in Section 2.

SECTION 6

TRANSPORT BLOCK

BLOCK DESCRIPTION

Introduction

Routing through the sewer system may be accomplished in the Storm Water Management Model (SWMM) by the Transport Block. This block has the responsibility of coordinating not only routing of sewage quantitites but also such functions as routing of quality parameters (subroutine QUAL), estimating dry-weather flow, DWF (subroutine FILTH), estimating infiltration (subroutine INFIL), and calling internal storage (subroutine TSTRDT). The relationships among the soubroutines which make up the Transport Block are shown in Figure 6-1. The program is about 5,000 lines long, consisiting of 24 subroutines and functions.

This section describes the Transport Block, provides instructions on data preparation, and furnishes examples of program usage. Instructions are provided for tasks requiring input data, namely: transport, internal storage, infiltration, and DWF.

Broad Description of Flow Routing

Differences in flow routing techniques among the Runoff, Transport and Extended Transport Blocks are described in Section 4 (e.g., Table 4-3); the techniques increase in complexity in the order just listed. A brief description of techniques used in the Transport Block follows.

To categorize a sewer system conveniently prior to flow routing, each component of the system is classified as a certain type of "element." All elements in combination form a conceptual representation of the system in a manner similar to that of links and nodes. Elements may be conduits, manholes, lift stations, overflow structures, or any other component of a real system. Conduits themselves may be of different element types depending upon their geometrical cross-section (e.g., circular, rectangular, horseshoe). A sequencing is first performed to order the numbered elements for computations. Flow routing then proceeds downstream through all elements during each increment in time until the storm hydrographs have been passed through the system.

The solution procedure is described in detail in the original SWMM documentation (Metcalf and Eddy et al., 1971a) and basically follows a kinematic wave approach in which disturbances are allowed to propogate only in the down-

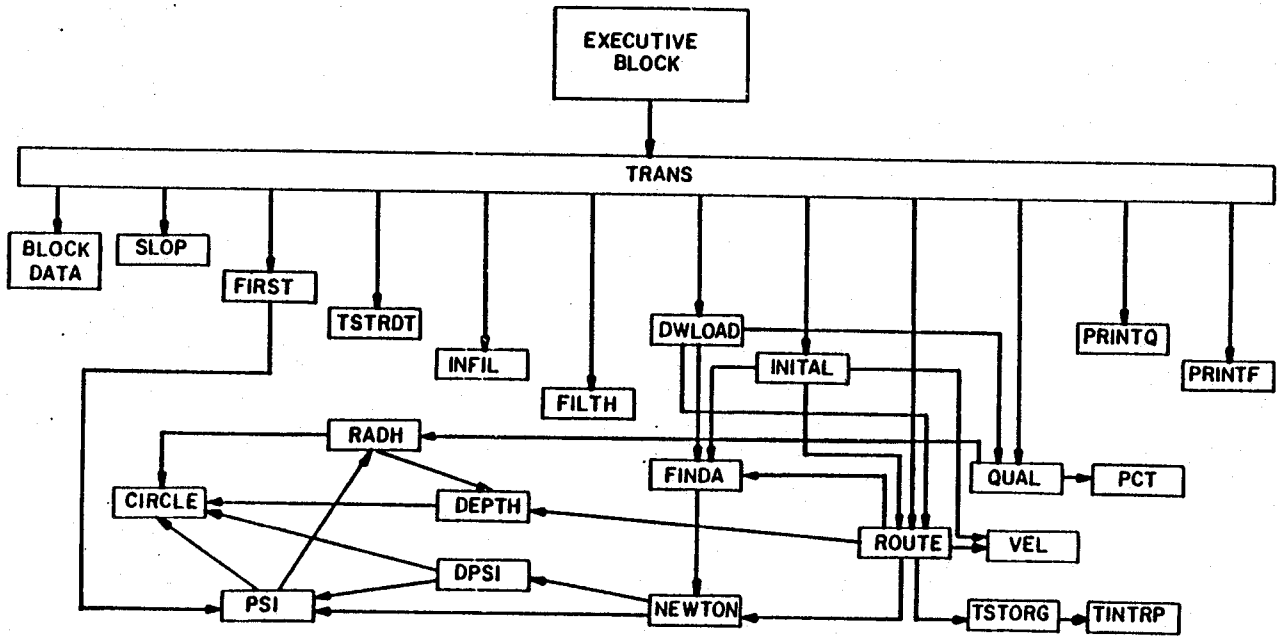

Figure 6-1. Structure of Transport Block Subroutines

stream direction. As a consequence, backwater effects are not modeled beyond the realm of a single conduit, and downstream conditions (e.g., tide gates, diversion structures) are assumed not to affect upstream computations. Systems that branch in the downstream direction can be modelled using "flow divider" elements to the extent that overflows, etc., are not affected by backwater conditions. Surcharging is modeled simply by storing excess flows (over and above the full flow conduit capacity) at the upstream manhole until capacity exists to accept the stored volume. Pressure-flow conditions are not explicitly modeled and no attempt is made to determine if ground surface flooding exists. A message is printed at each time step for each location at which surcharging occurs. The Transport Block has proven its ability to model accurately flows in most sewer systems, within the limitations discussed above, and as such it should be adequate for many applications. However, it will not accurately simulate systems with extensive interconnections or loops, systems that exhibit flow reversals, systems that exhibit significant backwater effects, or systems in which surcharging must be treated as a pressure-flow phenomenon; the Extended Transport Block should be used for these conditions.

An option in the program is the use of the internal storage model which acts as a transport element. It is a scaled down version of the Storage/Treatment Block and provides the possibility of storage routing of the storm (using the Puls method) for up to 30 locations within the sewer or drainage system. The program routes the flow through the storage unit for each time step based on the continuity equation in a manner analogous to flood routing through a reservoir. Extensive backwater conditions may thus be modeled by treating portions of the sewer system as a storage unit with a horizontal water surface.

Broad Description of Quality Routing

Up to four contaminants are handled by the Transport Block. Constituents may be introduced to the sewer system by any combination of four-means:

1) Storm-generated pollutographs computed by an upstream block[a] are transferred on an interface file (for description of the interface file see Section 2) to enter the system at designated inlet manholes.

2) Special storm-generated pollutographs may be entered using data group R1 of this block at designated inlet manholes.

3) Residual bottom sediment in the pipes may be resuspended due to the flushing action of the storm flows (Subroutines DWLOAD and QUAL).

4) For combined systems, constant dry-weather flow pollutographs may be entered at designated inlet manholes or generated by Subroutine FILTH.

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[a] The Transport Block can receive inputs from the Runoff, Storage/Treatment, and Extran Blocks, and from the Transport Block itself.

Routing of the pollutants is then done for each time step by Subroutine QUAL. The maximum number of contaminants that can be routed is four. These may be selected arbitrarily from the input file, except that DWF can only be used to generate suspended solids, BOD_5 and total coliforms. The scour/deposition routines may be used for any constituent.

Program Operation

Most of the input is related to data needed to describe the particular sewer system being modeled (e.g., dimensions, slopes, roughnesses, etc.) and parameters needed to solve the governing flow routing equations.

Following input of these data, the sewer elements are sequenced for computations. Geometric and flow parameters are then initialized. The various program parameters and initialized variables describing the elements are then printed. Parameters relating to the amount of data to be stored and printed out are also read.

If required, infiltration values and quality parameters will be calculated. Alternatively, user-supplied values may simply be input at any manhole location. If desired, Subroutine DWLOAD then initializes constituent depositions, and Subroutine INITAL initializes flows and pollutant concentrations in each element to values corresponding to a condition of dry-weather flow and infiltration only.

The main iterations of the program consist of an outer loop on time steps and an inner loop on element numbers in order to calculate flows and concentrations in all elements at each time step. Inlet hydrographs and pollutograph ordinates are read from the interface file and/or Transport data groups to permit linear interpolation for values at each time step prior to entering the loop of element numbers.

When in the loop on element numbers (with index I), the current sewer element through which flows are to be routed, indicated by the variable M, is determined from the vector JR(I). This array is calculated in subroutine SLOP in a manner to insure that prior to flow routing in a given element, all flows upstream will have been calculated.

When calculating flows in each element, the upstream flows are summed and added to surface runoff, dry-weather flow (DWF), and infiltration entering at that element. These latter three quantities are allowed to enter the system only at non-conduits (e.g., manholes, flow dividers). If the element is a conduit, a check for surcharging is made. If the inflow exceeds the conduit capacity, excess flow is stored at the element just upstream (usually a manhole) and the conduit is assumed to operate at full-flow capacity until the excess flow can be transmitted. A final surcharging summary is printed.

A simple hydraulic design routine is available at this point. If desired (NDESN = 1), when a surcharge condition is encountered, the conduit will be increased in size in standard 6-in. increments (standard for U.S. pipes) for circular pipes or in 6-in. width increments for rectangular conduits until

capacity exists to accept the flow. (Conduits that are neither circular nor rectangular will be converted to circular if they need to be resized.) A message is printed indicating the resizing, and a table of final conduit dimensions is printed at the end of the simulation. This design operation will effectively eliminate surcharging but will also minimize in-system storage within manholes, etc. The net effect is to increase hydrograph peaks at the downstream end of the system. An obvious conflict can thus exist between controls aimed at curing in-system hydraulic problems and controls intended for pollution abatement procedures at the outfall by in-system storage.

Flows are routed through each element in Subroutine ROUTE and quality parameters are routed in Subroutine QUAL. When routing flows in conduits, ROUTE may be entered more than once depending upon the value of ITER, the number of iterations. It is necessary to iterate upon the solution in certain cases because of the implicit nature of calculating the energy grade line in ROUTE.

Upon completion of flow and qualilty routing at all time steps for all elements. TRANS then performs the task of outputting the various data. Hydrograph and pollutograph ordinates for any specified outfall point(s) may be written onto an interface file for further use by the Executive Block, and Subroutine PRINTQ (or PRINTF for flows only) is then called for printing outflows for any of up to 80 desired elements.

Off-Line Files

The Transport Block uses two scratch data sets, NSCRAT(1) and NSCRAT(2), for storage of input and output hydrographs and pollutographs prior to printing. These are specified in the Executive Block. No input data will be sought from the interface file if JIN = 0, and no output will be placed on the file if JOUT = 0.

Organization of Data Input

Instructions for data preparation for the Transport Block have been divided along the lines of the major components for clarity of the presentation. These components are: (1) Transport, (2) Quality, (3) Internal Storage, (4) Infiltration and (5) Dry-Weather Flow. All data enter the Transport Block through one of these components. The typical data deck setup for the complete Transport Block is shown in Table 6-1. Transport data describe the physical characteristics of the conveyance system. Quality data identify pollutants to be routed and their characteristics. Internal storage data describe a particular type of Transport element. Infiltration and DWF data describe the necessary drainage area characteristics to permit the computation of the respective inflow quantities and qualities. Data line preparation and instructions for the complete Transport Block are given at the end of the Section 6 text in Table 6-7.

Table 6-1. Data for the Transport Block

Data Group	Data Type
A1	Title
B1-D3	Executive Data
C1	NKLASS, KPRINT
D1-D9	New Element Data
E1	Element Data
E2-E4	Cross Section Data
F1	Pollutant Data
G1-G5	Storage Element Data
H1-I1	Element I/O Data
J1-J2	Element Print Data
K1-K2	Infiltration Data
L1-Q1	Dry-Weather Flow Data
R1	User-Input Hydrographs and Pollutographs.

TRANSPORT DATA

Categories of Data

Use of the Transport Block involves three primary steps:

1) Preparation of theoretical data for use by subroutines engaged in hydraulic calculations in the block.

2) Preparation of physical data describing the sewer system.

3) Generation of inlet hydrographs and pollutographs required as input to the Transport Block and computational controls.

Data for Step 1 are supplied with the SWMM program for 16 different conduit shapes, and it will only be necessary for the user to generate supplemental data in special instances. These instances will occur only when conduit sections of very unusual geometry are incorporated into the sewer system. Generation of such data is discussed below.

The primary data requirements are for Step 2, the physical description of the sewer system, i.e., the tabulation of shape, dimension, slope, and roughness parameters, which is discussed in detail below.

The data for Step 3 may be generated manually, by an external block and by subroutines INFIL and FILTH.

Theoretical Data

TRANS reads the number and types of new conduit shapes found in the system. Only in the case of a very unusual shape should it become necessary

to generate theoretical data to supplement the data supplied by the program. The required data describe flow-area relationships of conduits, as shown in Figure 6-2 through the parameters ANORM and QNORM. A similar depth-area relationship is also required using the parameter DNORM. Full details are provided by Metcalf and Eddy et al. (1971a).

The flow-area data are generated from Manning's equation, normalized by dividing by the corresponding equation for the conduit flowing full, denoted by the subscript f. Thus,

$$Q/Q_f = \frac{A\ R^{2/3}}{A_f \cdot R_f^{2/3}} = f(A/A_f) \qquad (6\text{-}1)$$

where Q = flow, cfs,
A = flow area, ft^2, and
R = hydraulic radius, ft.

For a given conduit shape (e.g., circular, rectangular, horseshoe), the hydraulic radius is a unique function of the area of flow; hence, Q/Q_f (interpolated between values of QNORM) is a function only of A/A_f (interpolated between values of ANORM). This function is tabulated for circular conduits in Appendix A of Chow (1959), for example, and on page 443 of Davis (1952) for a Boston horseshoe section. It is shown in graphical form for several conduit shapes in Chapter XI of Metcalf and Eddy (1914) from which some data supplied with this program have been generated. Swamee et al. (1987) provide analytical functions for four shapes. A listing of the conduit shapes supplied with the Transport Block as well as all other element types is given in Table 6-2. The conduits are illustrated in Figure 6-3. If y = depth of flow, values of y/y_f corresponding to A/A_f (ANORM) are tabulated as the variable DNORM.

It will often be satisfactory to represent a shape not included in Table 6-2 by one of similar geometry. This use of "equivalent" sewer sections will avoid the problem of generating flow-area and depth-area data. An equivalent section is defined as a conduit shape from Table 6-2 whose dimensions are such that its cross-sectional area and the area of the actual conduit are equal. Only very small errors should result from the flow routing when this is done.

If it is desired to have the exact flow-area and depth-area relationships, then the product $AR^{2/3}$ must be found as a function of area. In general, the mathematical description of the shape will be complex and the task is most easily carried out graphically. Areas may be planimetered, and the wetted perimeter measured to determine R. In addition, the depth may be measured with a scale. The required flow-area relationship of equation 6-1 may then be tabulated as can the depth-area relationship. The number of points on the flow-area and depth-area curves required to describe the curves is an input variable (MM and NN, respectively). Note that the normalized flows (QNORM) and depths (DNORM) must be tabulated at points corresponding to MM-1 and NN-1, respectively, <u>equal</u> divisions of the normalized area axis (ANORM). If desired, the routing parameters stored in the program may be listed by specifying KPRINT = 1 on data line A1. The four pages of output are seldom necessary during the simulations, however.

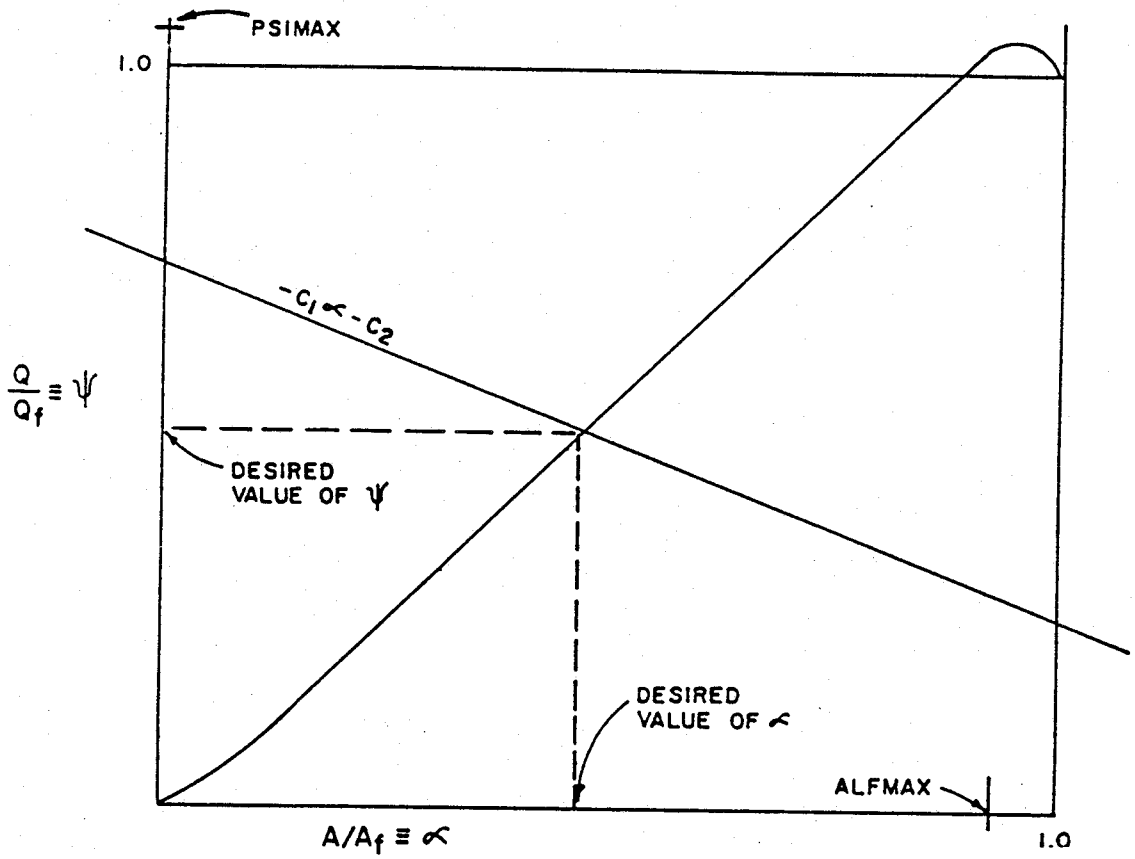
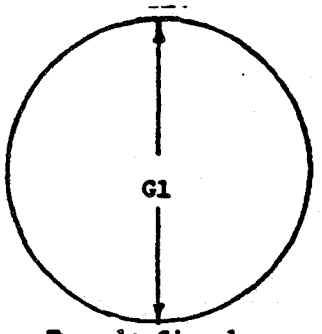
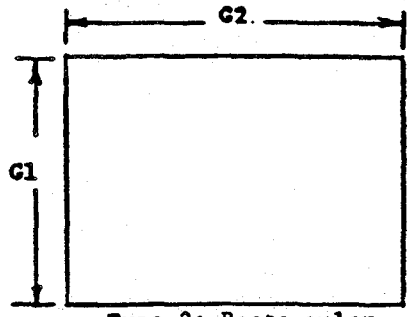


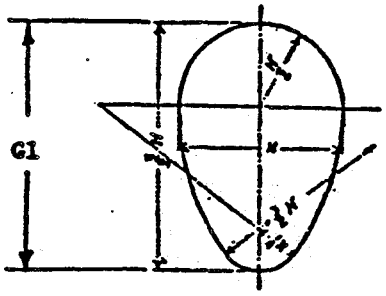
Figure 6-2. The Intersection of the Straight Line and the Normalized Flow-Area Curve as Determined in Route. The ψ-α Curve is Formed by Straight Line Segments Delineated by the Variables ANORM and QNORM, for Conduits with a Tabular Q-A Relationship. Q Denotes Flow, A Denotes Area, and the Subscript f Denotes Values at Full-Flow. The Line $-C_1 \alpha - C_2$ is Formed by the Program from the Continuity Equation.



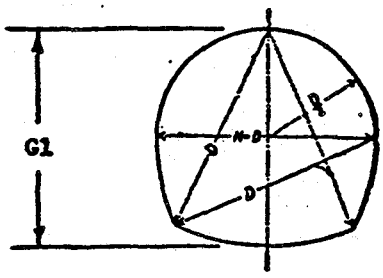
Type 1: Circular



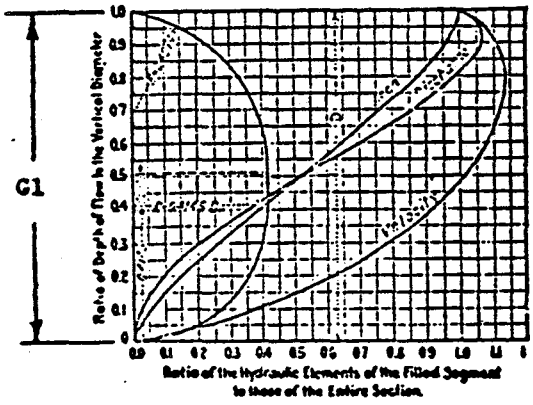
Type 2: Rectangular



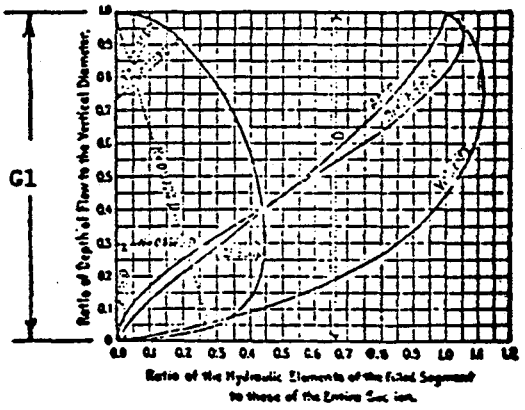
Type 3: Phillips Standard Egg Shape



Type 4: Boston Horseshoe

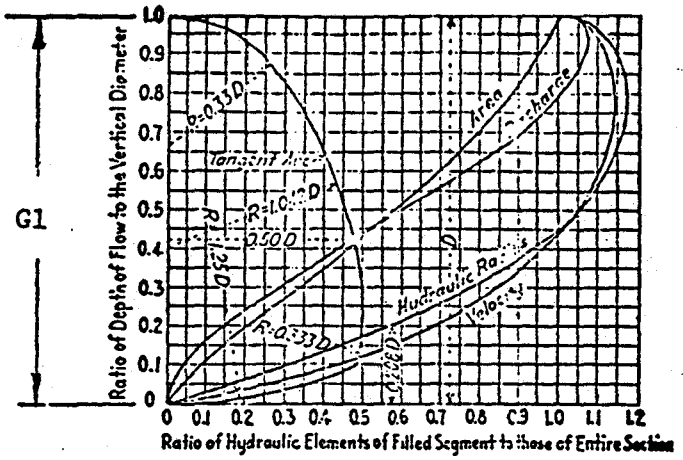


Type 5: Gothic

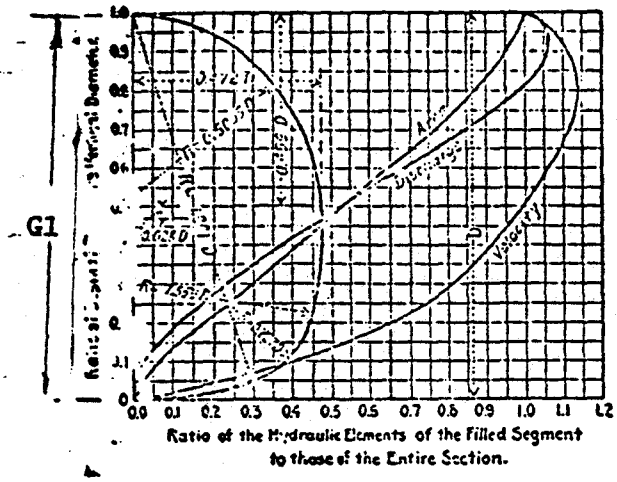


Type 6: Catenary

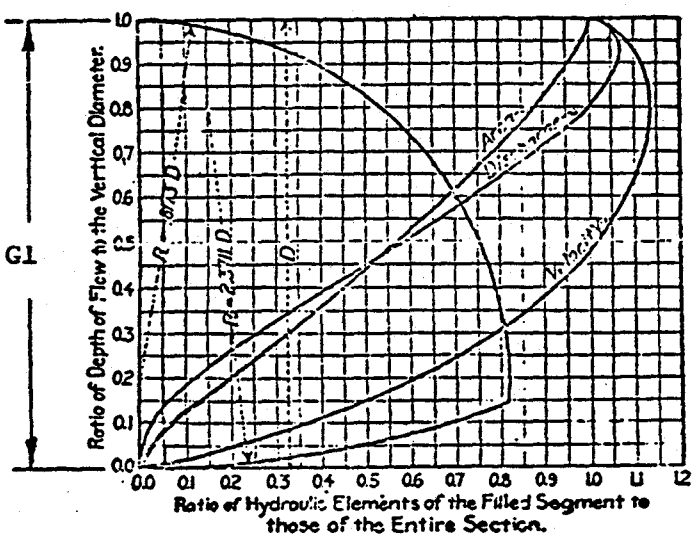
Figure 6-3. Sewer Cross-Sections



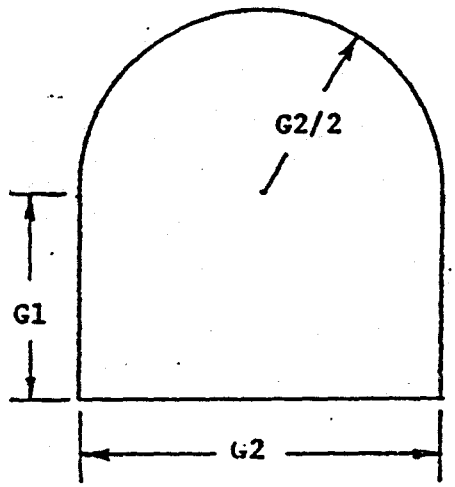
Type 7: Louisville Semielliptic



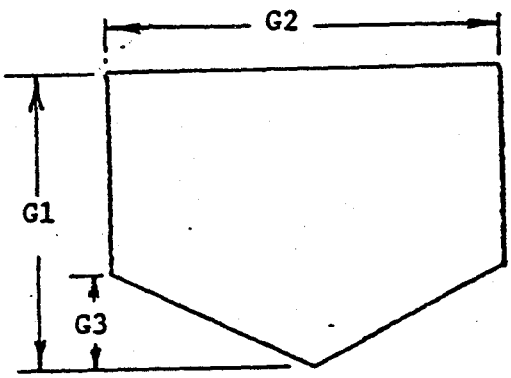
Type 8: Basket-handle



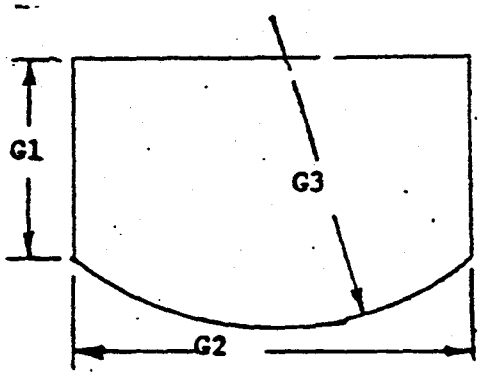
Type 9: Semi-circular



Type 10: Modified Basket-handle

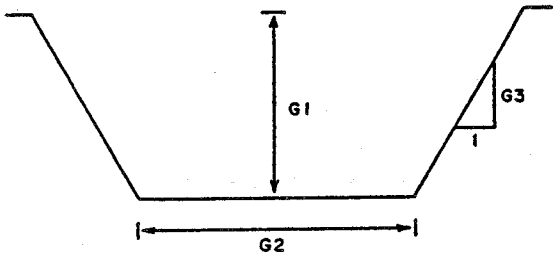


Type 11: Rectangular, Triangular Bottom

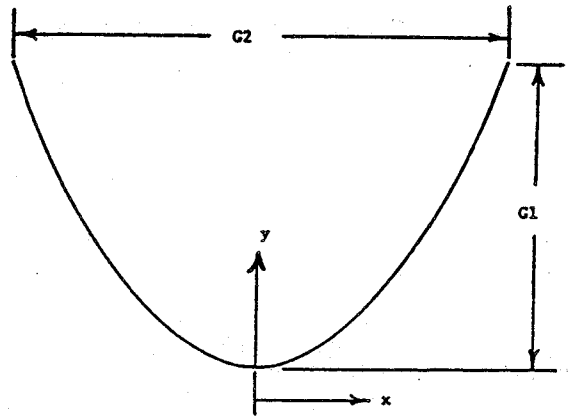


Type 12: Rectangular, Round Bottom

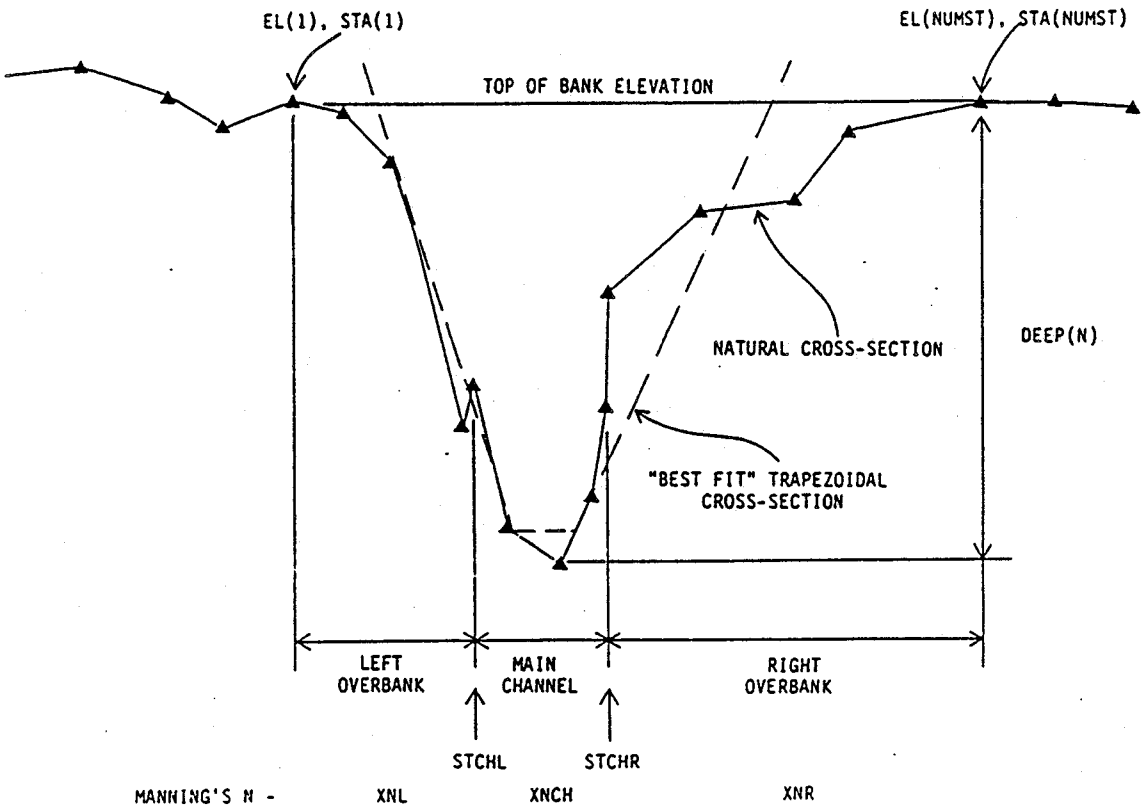
Figure 6-3 (continued). Sewer Cross-Sections



TYPE 13: TRAPEZOID



Type 14: Parabolic, and
Type 15: Power Function



Type 16

Definition Sketch of an Irregular Cross-Section.

Figure 6-3 (continued). Sewer Cross-Sections

Physical Representation of the Sewer System

General --

These data are the different element types of the sewer system and their physical descriptions. The system must first be descritized as a network of conduit lengths, joined at manholes (or other non-conduits). In addition, either real or hypothetical manholes should delineate significant changes in conduit geometry, dimensions, slope, or roughness. Finally, inflows to the system (i.e., stormwater, wastewater, and infiltration) are allowed to enter only at manholes (or other non-conduits). Thus, manholes must be located at points corresponding to inlet points for hydrographs generated by an external block and input points specified in Subroutines FILTH and INFIL. In general, the task of identifying elements of the sewer system will be done most conveniently in conjunction with the preparation of data for these other subroutines, especially the Runoff Block.

Table 6-2. Different Element Types Supplied with the Transport Block

SWMM4.2

	NTYPE	CONDUITS/CHANNELS
	1	Circular
	2	Rectangular
	3	Phillips standard egg shape
	4	Boston horseshoe
	5	Gothic
	6	Catenary
	7	Louisville semielliptic
	8	Basket-handle
	9	Semi-circular
	10	Modified basket-handle
SWMM3.2 same	11	Rectangular, triangular bottom
	12	Rectangular, round bottom
	13	Trapezoid
	14	Parabolic
	15	Power Function
Manhole	16	HEC-2 Format - Natural Channel
	17, 18	User supplied
		Non-conduits
Storage Unit	19	Manhole
17	20	Lift station
18	21	Flow divider
	22	Storage unit
	23	Flow divider - weir
	24	Flow divider
22	25	Backwater element

ent portions with separate Transport runs and combining the results using the Combine Block (see Section 3).

Values of Manning's roughness may be known by engineers familiar with the sewer system. Otherwise, they may be estimated from tables in many engineering references (e.g., Chow, 1959; ASCE-WPCF, 1969) as a function of the construction material and sewer conditions. The value may be adjusted to account for losses not considered in the routing procedure (e.g., head losses in manholes or other structures, roots, obstructions). However, the flow routing is relatively insensitive to small changes in Manning's n.

Description of Non-Conduits --

Types--The sewer system consists of many different structures, each with its own hydraulic properties. Elements types 19 through 25 (denoted by parameter NTYPE on group E1) are designed to simulate such structures. Data requirements for these elements are given in Table 6-4. Brief descriptions of these elements follow.

Manholes (NTYPE = 19)--No physical data are required for manholes except their numbers and upstream element numbers. Note that the number of upstream elements is limited to three. If more than three branches of the system should join at a point, two manholes could be placed in series, allowing a total of five branches to joint at that point, etc. Flow routing is accomplished in manholes by specifying that the outflow equals the sum of the inflows.

As an alternative to the use of the more detailed infiltration (INFIL) and dry-weather flow (FILTH) routines described later, flow and quality constituents may be input at manholes to simulate baseflow conditions. This input is constant over time and is allowed only at manholes and at no other element types.

Lift Stations (NTYPE = 20)--The data requirements for lift stations are given in Table 6-4. It is assumed that the force main will remain full when the pump is not operating, resulting in no time delay in the flow routing (i.e., no time is required to fill the force main when the pump starts, and the force main volume is not accounted for during pollutant routing). When the volume of sewage in the wet well reaches its specified capacity, the pumps begin to operate at a constant rate. This continues until the wet well volume equals zero. (Two-stage pumping may be simulated using a storage element.)

Flow Dividers (NTYPE = 21 and 24)--The routing procedure through these elements is explained in the discussion below. Typical uses are given below.

1) Simple diversion structure - A type 21 flow divider may be used to model a diversion structure in which none of the flow is diverted until it reaches a specified value (GEOM1). When the inflow is above this value, the non-diverted flow (Q01) remains constant at its capacity, GEOM1, and the surplus flow (Q02) is diverted.

2) Cunnette section - A type 24 flow divider may be used to model a

Table 6-4. Parameters Required for Non-Conduits.

NTYPE	Description	DIST	GEOM1	SLOPE	ROUGH	GEOM2	BARREL	GEOM3
19	Manhole	Constant Inflow, cfs, [m^3/sec].	Const. inflow concen. of pollutant 1.[a]	Const. inflow concen. of pollutant 2.[a]	Const. inflow concen. of pollutant 3.[a]	Const. inflow concen. of pollutant 4.[a]	N.R.[b]	N.R.
20	Lift station	Pumping rate, assumed constant, cfs, [m^3/sec].	Volume in wet well at which pumps will start, ft^3, [m^3].	N.R.	N.R.	N.R.	N.R.	N.R.
21	Flow divider	N.R.	Maximum undiverted flow. Inflow in excess of this value is diverted, cfs, [m^3/sec].	N.R.	N.R.	N.R.	N.R.	Number of element into which flows the undiverted flow (include decimal point).
22	Storage unit[c]	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
23	Flow divider	Maximum inflow without flow over the weir, cfs, [m^3/sec].	Weir height, above zero flow depth, ft, [m].	Maximum inflow through whole structure, cfs, [m^3/sec].	Weir constant times weir length, ft, [m].	Depth in structure at time of maximum inflow, ft, [m].	N.R.	Number of element into which flows the undiverted flow (weir flow is the diverted flow).
24	Flow divider	N.R.	N.R. (assigned in program)	N.R.	N.R.	N.R.	N.R.	Number of element into which flows the undiverted flow.
25	Backwater element	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	Element number of downstream storage unit.

[a]Units according to NDIN, Card group F1.

[b]N.R. - Not Required.

[c]Additional parameters are read in subsequently in Card groups G1 - G5.

NOTE: All elements require an element under (NOE), three upstream element numbers (NUE), and type (NTYPE). Parameters for conduits are defined in Table 6-2.

downstream cunnette section. The cunnette section is considered as a separate circular conduit to be placed parallel to the primary conduit as shown in Figure 6-4. In order to model the cunnette as a semi-circle, the separate circular conduit is given a diameter (GEOM1) so that its area will be twice that of the actual total cunnette flow area. (The distance, slope and roughness will be the same as for the primary conduit.) A type 24 flow divider is then the upstream element common to both conduits, as shown in Figure 6-4. (The program assigns a value of GEOM1 of the flow divider equal to half the full flow capacity of the circular pipe simulating the cunnette so that it has the hydraulic characteristics of a semi-circle.) Any flow higher than GEOM1 will be diverted to the primary conduit. Note that the parameter GEOM3 of the flow divider will be the element number assigned to the cunnette section. Note further that the element downstream from the two parallel conduits must list them both as upstream elements.

3) Overbank flow - A type 21 flow divider can be used to simulate flow into a main channel (undiverted flow) and into a parallel overbank channel for simulation of flooded conditions. Parameter GEOM1 would be set equal to the main channel capacity. The channel could be of any shape although two trapezoidal channels might be most appropriate for many natural configurations.

Routing at Flow Dividers (NTYPE = 21 and 24)--Both types will divide the inflow, QI, into two outflows, Q01 and Q02. The divider then acts as follows:

$$\begin{aligned} &\text{For } 0 \le QI \le GEOM1, && Q01 = QI \\ & && Q02 = 0.0 \\ &\text{For } GEOM1 \le QI, && Q01 = GEOM1 \\ & && Q02 = QI - GEOM1 \end{aligned} \qquad (6\text{-}2)$$

The undiverted outflow, Q01, will flow into the downstream element denoted by GEOM3. (The element into which Q02 flows does not need to be specified.)

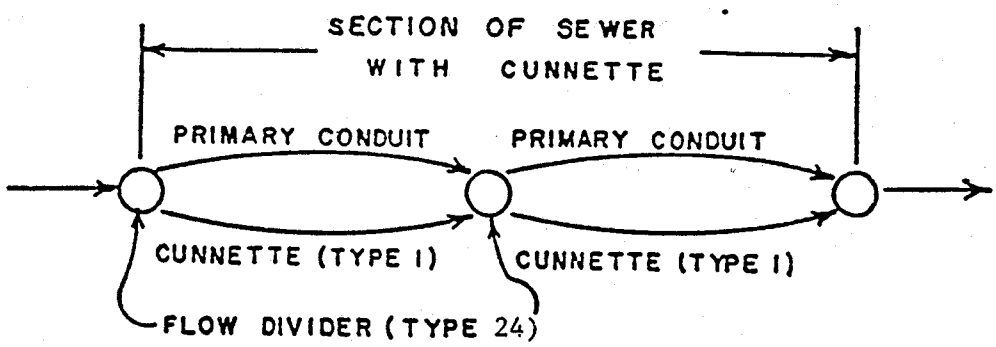
Flow Divider (NTYPE = 23)--This element is used to model a weir-type diversion structure in which a linear relationship can adequately relate the flow rate and the depth of flow into the weir structure. Input parameters are defined in Table 6-4. The weir constant, incorporated into the variable ROUGH, can be varied to account for the type of weir. Typical values of the weir constant are 3.3 for a broad crested weir and 4.1 for a side weir.

The flow divider behaves as a function of the inflow, QI, as follows:

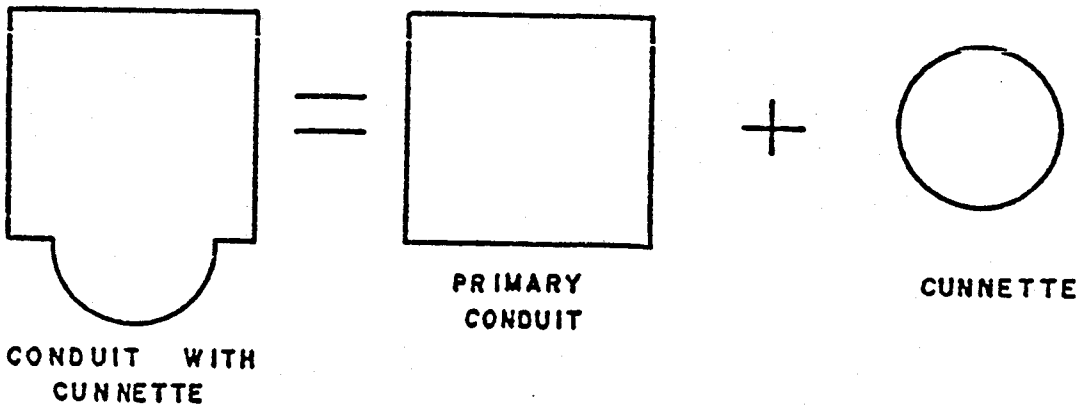
$$\begin{aligned} &\text{For } 0 \le QI \le DIST, && Q01 = QI \\ & && Q02 = 0.0 \end{aligned} \qquad (6\text{-}3)$$

For DIST $\le$ QI, Q01 and Q02 are computed as follows:

1) Compute depth of flow above the weir, DH, assuming a linear flow-depth relationship:



a. SCHEMATIC OF HYPOTHETICAL FLOW DIVISION



b. SPLIT OF CONDUIT INTO PRIMARY CONDUIT AND CUNNETTE

Figure 6-4. Cunnette Section

$$DH = (QI-DIST)\cdot(GEOM2-GEOM1)/(SLOPE-DIST)$$

2) Compute the diverted flow from the weir formula:

$$QO2 = ROUGH \cdot DH^{1.5}$$

3) Compute the undiverted flow:

$$QO1 = QI - QO2$$

Storage Unit (NTYPE 22)--This element is specified only when internal storage computations are required. Internal storage is modeled in a manner similar to a detention unit of the Storage/Treatment Block, using Puls routing for hydrographs and simulating quality processes as a completely mixed reactor. However, unlike a detention unit in the S/T Block, pollutant removal may be simulated only by decay. Data requirements are described on data groups G1 to G5.

Up to 30 storage units may be placed anywhere in the sewer system where appreciable storage may exist, such as at an outflow or diversion structure, or to simulate detention storage in a stormwater management system. It should be noted that the storage area or "reservoir" may consist of a portion of the sewer system itself, and area-depth-discharge relationships developed accordingly.

Backwater Element (NTYPE = 25)--This element may be used to approximate backwater conditions in a series of conduits due to a flow control structure downstream. The situation is modeled in a manner analyogous to reservoir flood routing as follows:

1) A storage element (NTYPE 22) is placed at the location of the control structure. The type of storage element will depend upon the structure (e.g., weir, orifice). One inflow to this storage element is then from the conduit just upstream.

2) If the water surface is extended horizontally upstream from the flow control structure at the time of maximum depth at the structure, it will intersect the invert slope of the sewer at a point corresponding to the assumed maximum length of backwater. The reach between this point and the structure may encompass several conduit lengths. A backwater element (NTYPE 25) is placed at this point of maximum backwater, in place of a manhole, for instance.

3) The backwater element then diverts flow directly into the storage element depending upon the volume of water (and hence, the length of backwater) in the storage element. If the backwater extends all the way to the backwater element, the total flow is diverted to the storage element; none is diverted to the conduits.

4) The amount of diverted flow (QO1) is assumed to be directly proportional to the length of the backwater. The storage area in reality

consists of the conduits. Since most conduits can be assumed to have a constant width, on the average, the backwater length is assumed to be proportional to the square root of the current storage volume, obtained from the storage routine.

5) The parameter GEOM3 of the backwater element must contain the element number of the downstream storage unit.

6) Parameters for the storage element are read in as usual. The depth-area values will correspond to the storage area of the upstream conduits. The storage unit must list the backwater element as one of its upstream elements, as well as the conduit immediately upstream.

7) At each time step, the backwater element computes the ratio of current to maximum storage volume in the downstream storage element. Call this ratio r. Then

$$Q01 = QI \cdot r^{1/2}$$

and (6-4)

$$Q02 = QI - Q01$$

where Q01 = flow directly into storage unit,
Q02 = flow into intermediate conduits, and
QI = inflow to backwater element.

Input Data and Computational Controls

Options --

The basic input data, hydrographs and pollutographs, are generated outside of the Transport Block. However, certain operational controls are available within Transport.

Time Step (DT) --

The size of the time step may be chosen arbitrarily and does not have to correspond to that of the preceding block. If it does not, input hydrograph and pollutograph ordinates will be estimated by linear interpolation of the input time series on the interface file. However, awkward interpolation effects can be avoided if the Transport time step is an integer multiple or integer fraction (e.g., 1/2, 1/3) of the time step of the upstream block. If the upstream block uses a variable time step (e.g., the Runoff Block), the shortest of the variable time steps should be used to compute the integer fraction. Transport uses a constant time step.

In tests of sensitivity (Metcalf and Eddy et al., 1971a), it was found that except for very small values of DT (10 seconds), the output from Transport is insensitive to the length of the time step. Between values of two minutes and 30 minutes, hydrograph ordinates varied by less than one percent. For extremely short time step values, the peak flow moved downstream faster and never attained the maximum value that it had with a DT of two minutes and longer. Within the range commonly needed (two minutes to 30 minutes), the

choice of time step will not significantly affect results. However, continuity errors can occasionally arise if the time step is longer than about two times the travel time through any conduit.

Number of Time Steps (NDT) --

The number of time steps is not restricted. The program will use the number input in Transport (NDT) or the number used by the preceding module, whichever gives the shorter simulation time.

Choice of Number of Iterations (NITER) --

The purpose of iterations in the computations is to eliminate flow oscillations in the output. Flatter pipe slopes (less than 0.001 ft/ft) require iterations of the flow routing portion of the Transport Model to help dampen these oscillations. Four iterations have proven to be sufficient in most cases.

Allowable Convergence Error (EPSIL) --

Convergence of the flow routing procedure should not be any problem, and the default value of EPSIL, 0.0001, may be used. It will provide sufficient accuracy and result in only a very minimal increase in computer time over larger values. The only convergence problems that may exist can occur when flow enters a dry conduit. For instance, this could occur at the beginning of a storm in a sewer with little or no baseflow. Messages to this effect will be printed if parameter NPRINT = 0. These may almost always be ignored since the default options in Subroutine ROUTE will continue program execution and only result in a very small error in continuity (a fraction of a percent).

Alternate Hydrograph and Pollutograph Inputs --

Hydrograph and pollutographs may be entered from an interface file (e.g., as generated in the Runoff Block) and/or entered manually using data groups I1 and R1. Parameters NCNTRL and NINPUT are set accordingly. Note that input from both a Transport input file and interface file may be performed simultaneously. If, for some reason, input from data group R1 will not suffice, an interface file containing the specified input values could be created according to the specifications found in Section 2 and specified as an input file to Transport in place of, say, a file generated by the Runoff Block. The format of such a file is described in the Tables 2-2 and 2-3. In this manner, a user may use an alternative program for generation of the inlet hydrograph, followed by Transport for routing.

QUALITY

Constituents

Up to four pollutants may be arbitrarily chosen for input and routing by the Transport Block. Although these would often be chosen from the group (up to ten) supplied by the Runoff Block (or another preceding block), they do not have to be since data group input may be used in addition to the interface

file. If the same pollutant is entered from both the interface file and from the data group R1, the description (name, name of units, type of units) from the interface file must be used. If the pollutant is entered only from the data group, this description must be supplied on data group F1. Further information on pollutant description, including naming and units, is contained in Section 4.

Decay

Each pollutant may be subjected to a first order decay during the routing process by supplying a first order decay coefficient, DECAY (based on natural logarithms or base e). Although travel time through most sewer systems is short enough so that decay is seldom important, the user could supply, for example, a deoxygenation coefficient, K_1, for BOD if desired. Non-conservative pollutants are not linked. The decay of one has no effect on any other.

Routing

Routing of quality parameters is performed by using the integral solution for the output from a completely mixed conduit volume (Medina et al., 1981). See Appendix IX for a derivation. Although this tends to introduce artificial dispersion of concentration profiles, it is the most convenient way in which to introduce new loadings at manholes along the system, as well as to facilitate scour and deposition calculations. The quality routing procedure is not subject to calibration directly. However, the routing becomes closer to pure advection (plug flow) as the number of elements is increased.

Scour and Deposition

The basis for these procedures is described in Appendix VI. Each pollutant is assigned a specific gravity (SPG) and particle size distribution, assumed to apply throughout the drainage system regardless of the source of the pollutant, e.g., stormwater or dry-weather flow. If the specific gravity is less than or equal to 1.0, the pollutant is considered to be entirely suspended (or dissolved) and not subject to scour and deposition. If all calibration is to be performed using Runoff Block buildup-washoff parameters, for instance, it may be desirable to avoid the complexity of simulating scour, a second real but largely unknown source.

Typical particle size distributions (and interpretation of input parameters PSIZE and PGR) are illustrated in Figure 6-5. Such information should be collected first hand at each catchment; secondary sources such as Sartor and Boyd (1972), Shaheen (1975), Manning et al. (1977) and Pisano et al. (1979) should be used only if local data are not available. During the simulation scour and deposition are simulated using Shield's criterion to determine the critical diameter for incipient motion and deposition (see Appendix VI). The kinematic viscocity of water (GNU on data line B2) is a function of temperature and used to calculate the boundary Reynolds number on Shield's diagram (Graf, 1971; Vanoni, 1975). For each conduit, the critical diameter is determined as a function of velocity, roughness and specific gravity. At the same time, the maximum diameter of the suspended fraction and the minimum diameter of the settled fraction is maintained. If the critical diameter is

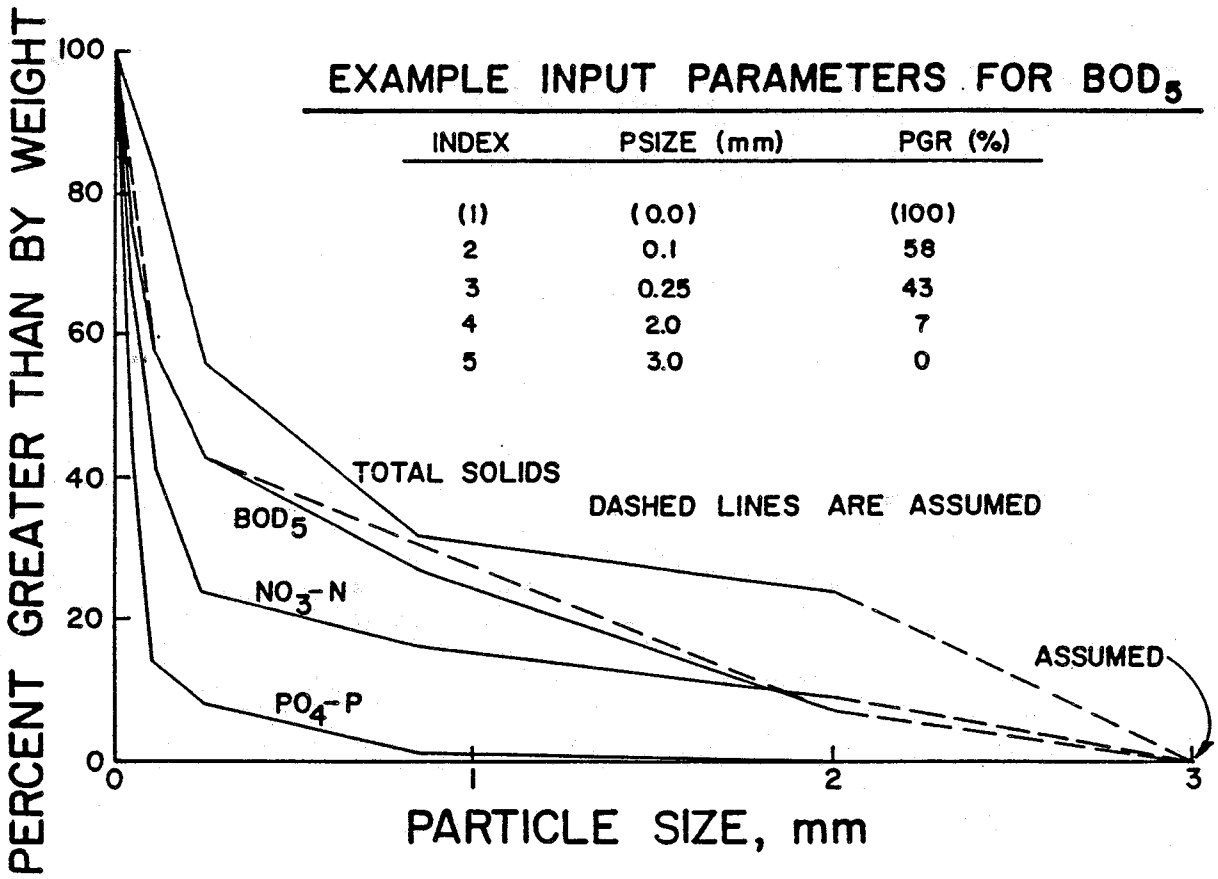


Figure 6-5. Example Particle Size Distributions for Pollutants found on Street Surfaces. (After Sartor and Boyd, 1972, p. 146.)

less than the maximum of the suspended material, more is settled; the settled mass is determined by multiplying by a fraction determined from the particle size distribution (Appendix VI). Similarly, if the critical diameter is greater than the minimum of the settled material, more is suspended. The settled material is thus assumed to have the particle size distribution of the right hand tail of the total distribution (Figure 6-5), and the suspended material has the distribution of the left hand side.

Decreasing the specific gravity (downwards toward 1.0) increases the amount suspended and vice versa. As SPG closely approaches 1.0 the procedure becomes very sensitive to SPG since there is a division by SPG-1.0. Typical values of specific gravities of particulate matter in sewers range from 1.1 for volatile material to 2.7 for sand and grit. The realistic situation in which each particle size range may have its own specific gravity can be handled by the Storage/Treatment Block, but not the Transport Block (except that up to four different pollutants may be simulated). Since it is only one parameter, calibration of the scour-deposition routine may be most easily calibrated using SPG. Alternatively, a greater percentage of large diameter material may be assigned a pollutant using the particle size distribution if, for instance, more deposition were desired.

Continuity of pollutant mass is maintained during scour and deposition. In addition, larger particles can settle upstream in flat conduits and be unavailable for downstream settling. However, no layering within the sediment bed is possible; a uniform distribution with sediment depth is assumed. An initial settled mass in each conduit is computed prior to the start of the simulation by running the routine for DWDAYS days (data line B2) prior to the storm event (or longer) simulation. This initial deposition is assumed to start with a clean bed.

Although this scour-deposition routine is a far cry from the detailed sewer sediment transport program developed by Sonnen (1977), it is reasonably simple, consistent and may be calibrated. And should the user desire, it may be bypassed (using SPG < 1.0), and all quality calibration performed in the Runoff Block.

INTERNAL STORAGE

Steps

Use of the internal storage routine involves four basic steps. A somewhat more detailed data description may be found in the Storage/Treatment Block description in Section 7, and modeling techniques are described in Appendix IV.

Step 1. Call

The internal storage routine is called by subroutine TRANS when element NTYPE 22 is specified. No more than 30 storage locations may be specified in a single run.

Step 2. Storage Description: Part 1

Describe the manner in which the outlet depth-discharge relationship is given (set of data pairs, power equation or pumps). See Appendix IV and Section 7 for a more detailed description of this technique.

Step 3. Storage Description: Part 2

Describe the geometry of the unit with a set of depth-surface area volume data triplets and the depth-discharge relationship with data pairs or a power equation. See Appendix IV and Section 7 for more details.

Step 4. Initial Conditions

Describe the initial conditions of the unit with respect to volume and pollutant concentrations.

INFILTRATION MODEL

Description

The section on infiltration has been developed to help to estimate infiltration into a given sewer system based upon existing information about the sewer, its surrounding soil and groundwater, and precipitation. It should be borne in mind throughout that the accuracy of infiltration prediction is dependent upon the accuracy and extent of data descriptive of infiltration in the system being modeled.

Using these data, Subroutine INFIL is structured to provide estimates of average daily infiltration inflows at discrete locations along the trunk sewers of a given sewer system. A typical urban drainage basin in which infiltration might be estimated is shown in Figure 6-6.

Since the Transport Block's principal use has been mainly to simulate individual storms which cover a time period of less than a day, average daily estimates from INFIL are calculated only once prior to sewer flow routing. INFIL is called from Subroutine TRANS by setting the variable, NINFIL equal to 1, thus signaling the computer to estimate infiltration. In fact, however, the user has most of the responsibility for infiltration estimation, optionally using techniques described below. The program does little more than apportion it properly.

For the purposes of analysis, infiltration is classified into four categories, i.e., miscellaneous sources causing a base dry weather inflow, frozen residual moisture, antecedent precipitation, and high groundwater. The cumulative effects of the first three sources can be seen in Figure 6-7 which excludes surface runoff. Figure 6-7 shows total infiltration QINF as the sum of dry weather infiltration DINFIL, wet weather infiltration RINFIL, and melting residual ice and frost infiltration SINFIL. However, in cases where the groundwater table rises about the sewer invert, it is assumed that groundwater inflow GINFIL alone will be the dominant source of infiltration. Thus, infiltration is defined as:

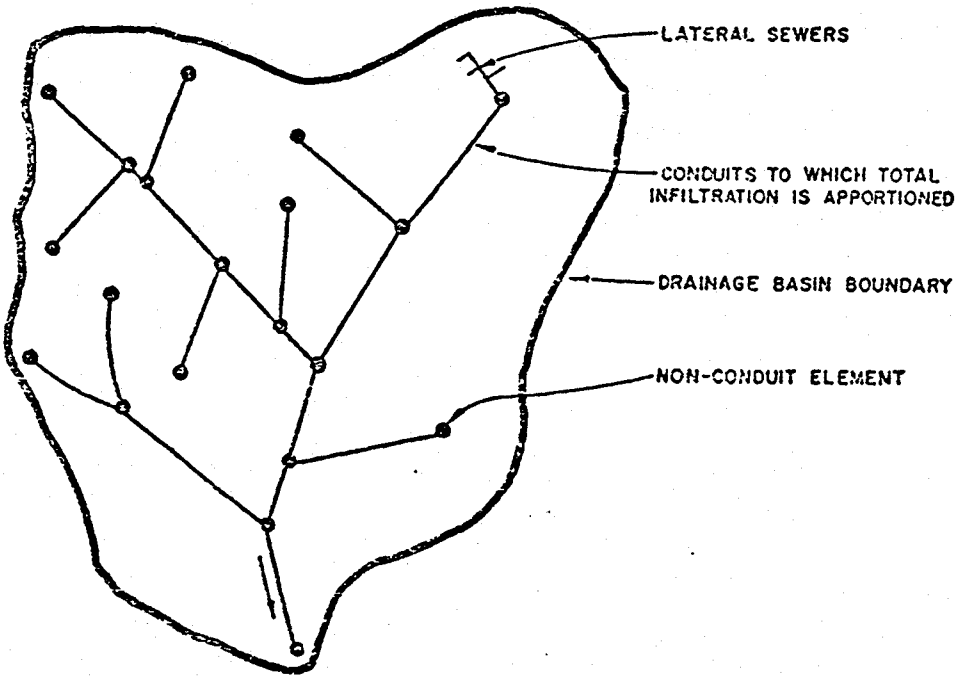
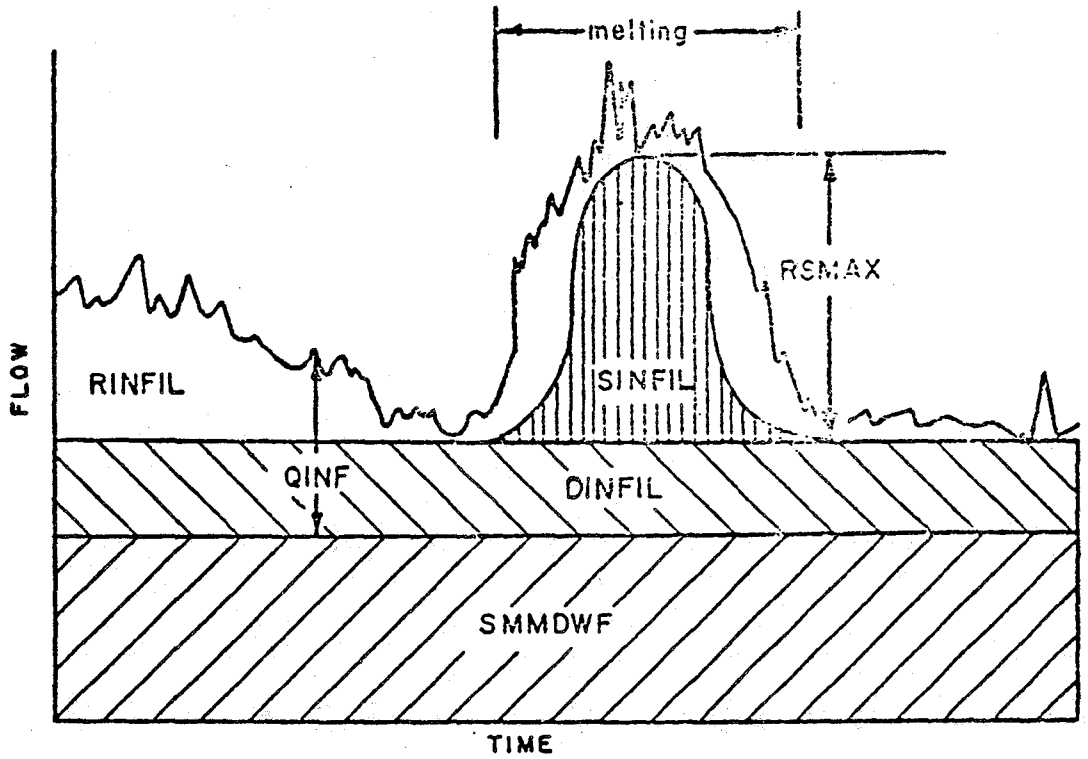


Figure 6-6. Typical Drainage Basin in which Infiltration is to be Estimated



QINF = Total infiltration
DINFIL = Dry weather infiltration
RINFIL = Wet weather infiltration
SINFIL = Melting residual ice and snow infiltration
RSMAX = Residual moisture peak contribution
SMMDWF = Accounted for sewage flow

Figure 6-7. Components of Infiltration

$$QINF = \begin{cases} DINFIL + RINFIL + SINFIL \\ \text{or} \\ GINFIL \text{ for high groundwater table} \end{cases} \quad (6\text{-}5)$$

Throughout the procedure for determining input variables, observations and estimates based upon local data are given preference over generalized estimates for infiltration described below. Thus, the hierarchy for basing estimates should be:

1. Use historical data for the study area under consideration.

2. Use historical data for a nearby study area and adjust results accordingly.

3. Use estimates of local professionals.

4. Use generalized estimates based upon country-wide observations.

Infiltration - inflow studies (e.g., EPA, 1977) have been performed in many cities and should provide much of the needed data.

Dry Weather Infiltration (DINFIL)

If the study area under consideration has been gaged, base dry-weather infiltration can be taken by inspection from the flow data. In the absence of flow data, an estimate of the unit infiltration rate XLOCAL (gpm/inch-diameter per mile) for dry weather must be obtained from local professionals. From data in this form, equation 6-6 can then be used to determine DINFIL (gpm):

$$DINFIL = XLOCAL \cdot DIAM \cdot PLEN \quad (6\text{-}6)$$

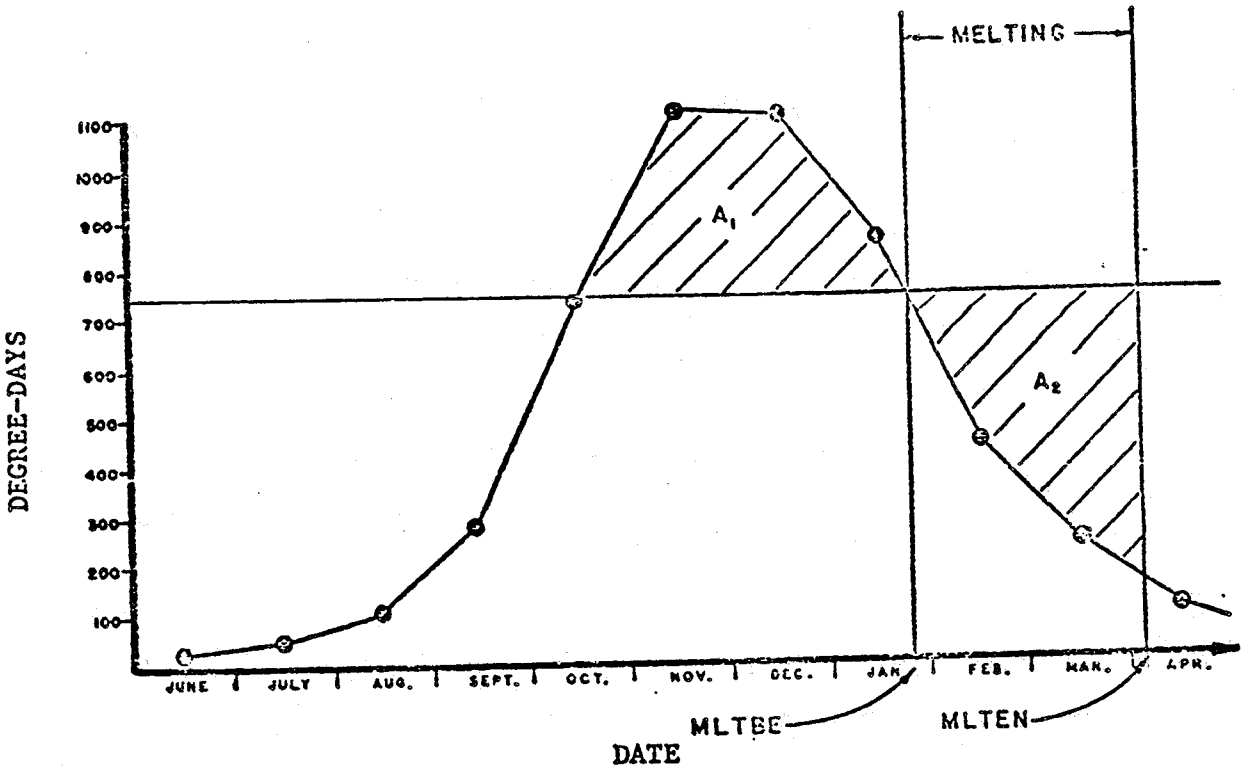
where DIAM = average sewer diameter, in., and
PLEN = pipe length, mi.

Values of XLOCAL range from 250 to 600 gpm/in.-diameter per day (ASCE-WPCF, 1969) and may be even higher for laterals with many stubs and wyes. The importance of local data cannot be over-emphasized.

Residual Melting Ice and Frost Infiltration (SINFIL)

SINFIL arises from residual precipitation such as snow as it melts following cold periods. Published data (American Society of Heating and Air Conditioning Engineers) in the form of monthly degree days (sum of deviations below 65°F) provide an excellent index as to the significance of SINFIL. Average monthly degree-days for cities in the United States are reproduced in Appendix VIII. The onset and duration of melting can be estimated by noting the degree days NDD above and immediately below a value of 750. Refer to Figure 6-8 for the following description.

Within subroutine INFIL, the beginning of melting, MLTBE, is taken as the



MLTBE = Day on which melting period begins
MLTEN = Day on which melting period ends

Figure 6-8. Prescribed Melting Period

day on which NDD drops below 750. Next, MLTEN is determined so that A_1 equals A_2. In the absence of evidence to the contrary, it is assumed that the melting rate is sinusoidal. The maximum contribution RSMAX from residual moisture can be determined from previous gaging of the study area or local estimates. In either case, SINFIL is determined within the program by the following equation:

$$\text{SINFIL} = \begin{cases} \text{RSMAX}\cdot\sin[180^\circ\cdot(\text{NDYUD}-\text{MLTBE})/(\text{MLTEN}-\text{MLTBE})] \\ \\ 0.0 \text{ if NDYUD is not in melting period or if NDD never exceeds 750.} \end{cases} \tag{6-7}$$

where NDYUD = day on which infiltration estimate is desired,
RSMAX = residual moisture peak contribution, gpm,
MLTBE = beginning of melting period, day, and
MLTEN = end of melting period, day.

Note that RSMAX is a required input parameter, in addition to degree day information.

Antecedent Precipitation (RINFIL)

RINFIL depends upon antecedent precipitation occurring within the nine day period prior to an estimate. If antecedent rainfall is unavailable or less than about 0.25 in. (6.4 mm), the RINFIL contribution to QINFIL is usually small. For larger antecedent rainfall contributions, regression techniques offer one method of estimating RINFIL. For example, during development of the SWMM infiltration routine, available rainfall and infiltration data were examined (Metcalf and Eddy et al., 1971a). For three areas in which sewer flow data were not affected by melting, RINFIL was found to satisfy the following linear relationship:

$$\text{RINFIL} = \text{ALF} + \text{ALF0}\cdot\text{RN0} + \text{ALF1}\cdot\text{RN1} + \ldots + \text{ALF9}\cdot\text{RN9} \tag{6-8}$$

where RINFIL = SWFLOW - DINFIL - SMMDWF, gpm,
ALFN = coefficient to rainfall for N days prior to estimate, gpm/in.,
RNn = precipitation on n days prior to estimate, in.,
SWFLOW = daily average sewer flow excluding surface runoff, gpm, and
SMMDWF = otherwise accounted for sewage flow, gpm.

To determine the coefficients in equation 6-8, a multiple linear regression should be run on existing flow and rainfall data. For comparative purposes, the results of regression analyses for study areas in three selected cities (Lentz, 1963; Metcalf and Eddy et al., 1971a) are given in Table 6-5.

High Groundwater Table (GINFIL)

For locations and times of the year that cause the groundwater table to

be above the sewer invert, groundwater infiltration GINFIL supersedes contributions from DINFIL, RINFIL, and SINFIL. GINFIN can be determined from historical sewer flow data by inspection or regression analysis. For example, a regression analysis could involve determination of the BETA coefficients in Equation 6-9, or an alternative formulation could be investigated.

$$GINFIL = BETA + BETA1 \cdot GWHD + BETA2 \cdot GWHD^2 + BETA3 \cdot GWHD^{0.5} \qquad (6\text{-}9)$$

where GWHD = groundwater table elevation above sewer invert, ft, and
BETAn = coefficient for term n.

Table 6-5. RINFIL Equations for Three Study Areas

Study Area	Equation
Bradenton, Florida	RINFIL = 4.1 + 2.9RN0 + 17.5RN1 + 15.0RN2 + 12.8RN3 + 13.0RN4 + 10.4RN5 + 13.2RN6 + 10.1RN7 + 11.8RN8 + 9.5RN9
Baltimore, Maryland	RINFIL = 2.4 + 11.3RN0 + 11.6RN1 + 5.5RN2 + 6.4RN3 + 4.8RN4 + 3.6RN5 + 1.0RN6 1.5RN7 + 1.4RN8 + 1.8RN9
Springfield, Missouri	RINFIL = 2.0 + 18.3RN0 + 13.9RN1 + 8.9RN2 + 5.5RN3 + 6.7RN4 + 16.RN5 + 5.2RN6 4.6RN7 + 4.4RN8 + 1.3RN9

Apportionment of Infiltration

Once an estimate of the total local infiltration QINF has been obtained, this flow must be apportioned throughout the designated study area. The criterion chosen for apportionment is an opportunity factor OPINF which represents the relative number and length of openings susceptible to infiltration. Pipe joints constitute the primary avenue for entry of infiltration (Geyer and Lentz, 1963). The number and length of joints is assumed to be proportional to the relative surface area of each conduit. For each, an equivalent circular pipe diameter will be proportional to the square root of its known cross-sectional area, ft.^{2} Then the fraction of total infiltration ("opportunity" for infiltration) allocated to each conduit, OPINF, is:

$$OPINF = \frac{A_f \cdot DIST}{\Sigma A_f \cdot DIST} \qquad (6\text{-}10)$$

where A_f = cross sectional area of conduit, ft^2, and
DIST = conduit length, ft.

The summation in the denominator is over all conduits. Open trapezoidal chan-

nels are treated the same as all others. The apportioned infiltration enters the system at the non-conduit element immediately upstream of the conduit.

This procedure allocates the most infiltration to the largest and longest conduits. Should local information dictate otherwise, infiltration may be apportioned and entered at appropriate manholes in data group E1.

Infiltration developed using subroutine INFIL is held constant in time. Should hourly or daily corrections be desired, infiltration can be incorporated into dry-weather flow or entered as hydrographs using data group R1.

Quality of Infiltration

Although infiltration is often assumed to be "clean" due to its origin in the soil layers, in-conduit measurements usually indicate non-zero levels of most parameters. These concentrations may be entered in data group K1.

Data Needs

Hydrologic Data --

Concurrent historical rainfall, water table, and sewer flow data of several weeks' duration are needed to completely describe infiltration. In addition, rainfall for several days prior to the flow estimate is required for use in a regression equation for RINFIL. Of course, such data would be required for many different storms for development of such an equation.

Ideally, the rainfall record would be from a raingage which is located near the center of the study area and which records daily rainfall in inches. If more than one raingage is located within the study area, daily measurements from all gages should be averaged. Missing data (e.g., from a malfunctioning gauge) or a total absence of measurements due to no gauging within the study area can sometimes be overcome with measurements taken from a raingage located within a few miles. If National Weather Service (NWS) climatological data recorded at the nearest airport or federal installation are not available, contact the National Climatic Data Center (Asheville, NC) for assistance.

Should some other form of precipitation, e.g., snowfall, be encountered, it will be necessary to convert this to equivalent rainfall. If estimates are unavailable from the NWS, the ratio of ten inches of snow to one inch of rain may be used.

Water table data should also be obtained from gauging within the study area. However, shallow-well data from the U.S. Geological Survey or state geological office can be used to supplement missing data. Water table elevations are not required if they are below the sewer inverts for the day on which QINF is to be estimated.

Sewer Data --

Sewer flow data for regression analysis should be taken from a gage located at the downstream point within the study area. Upstream gaging may

sometimes be used to estimate flows at the downstream point by simply adjusting flows based upon respective surface area. Physical sewer data (e.g., lengths, diameters) are taken from prior input used within TRANS to route sewer flow.

Summary of Infiltration Procedures

Input --

Effective use of the Infiltration Model requires estimates of its component flows, namely:

DINFIL = dry weather infiltration,
RINFIL = wet weather infiltration,
SINFIL = melting residual ice and snow, and
GINFIL = groundwater infiltration.

Step 1. Determine Groundwater Condition --

If the groundwater table is predominantly above the sewer invert, all infiltration is attributed to this source (GINFIL). In this case, an estimate of the total infiltration is made directly (in cfs for the total drainage basin) and read in data line K1. This data line followed by a blank data line (data line K2) would complete the infiltration data input. If the groundwater table is not predominantly above the sewer invert, proceed to Step 2.

Step 2. Build-Up Infiltration from Base Estimates --

From measurements, historical data, or judgment, provide estimates of DINFIL and RINFIL. In this case, GINFIL must be set equal to 0.0. Finally, if needed, provide the peak residual moisture (RSMAX) and the 12 monthly degree-day totals taken from Appendix VII or a local source.

DRY WEATHER FLOW MODEL

Methodology

Subroutine FILTH serves as an option to estimate average sewage flow and quality from residential, commercial, and industrial urban areas. FILTH estimates sewage inputs at discrete locations along the trunk sewers of any specified urban drainage basin. These estimates are calculated from data describing drainage basin subsections (subcatchments and subareas) under which the trunk sewer passes. In this routine, dry-weather flow quantity and quality are developed from regression equations, as explained in the documentation (Metcalf and Eddy et al., 1971a). The estimates are for three specific quality parameters; BOD_5, suspended solids (SS) and total coliforms. Thus, if any different parameters are to be simulated, FILTH cannot be used. However, if a fourth parameter is to be routed in addition to BOD_5, SS and total coliforms, FILTH can be used to provide estimates for the first three but not the additional one. Also bear in mind that a constant base flow for any parameter may be input at manholes in data group E1.

When FILTH is not used, DWF estimates may be input at desired manholes, as discussed previously. In fact, this option may be routinely used in place of FILTH whenever reasonable estimates are available for instream DWF quantity and quality, thus avoiding collection of the many demographic data required for estimates by FILTH.

An example of a hypothetical sewer system and input situation for FILTH is given in Figure 6-9. To avoid confusion with Runoff Block subcatchments, all drainage basin subdivisions will be referred to as subareas in the following discussion. As shown in the figure, an input manhole near the center of each subarea is assumed to accept all sewage flow from that subarea. Criteria for establishing subarea boundaries and input locations are discussed later in the text.

In the context of SWMM, FILTH calculates daily sewage flow (cfs) and characteristics (BOD_5, SS, and total coliforms) averaged over the entire year for each subarea. FILTH is called from Subroutine TRANS by setting the parameter NFILTH equal to one. Flow and quality characteristics estimates and corresponding manhole input numbers are then returned to TRANS where the estimates undergo adjustment depending upon the day of the week and hour of the day during which simulation is proceeding.

The subroutine may be omitted when modeling separate storm sewers unless it is desired to generate a base flow with DWF characteristics. FILTH is designed to handle an unrestricted number of inlet areas and individual process flow contributors. As a safeguard against faulty data, however, a program interrupt is provided if the combined number exceeds 200, which is a limit set by the Transport Model.

Quantity Estimates

Data Categories --

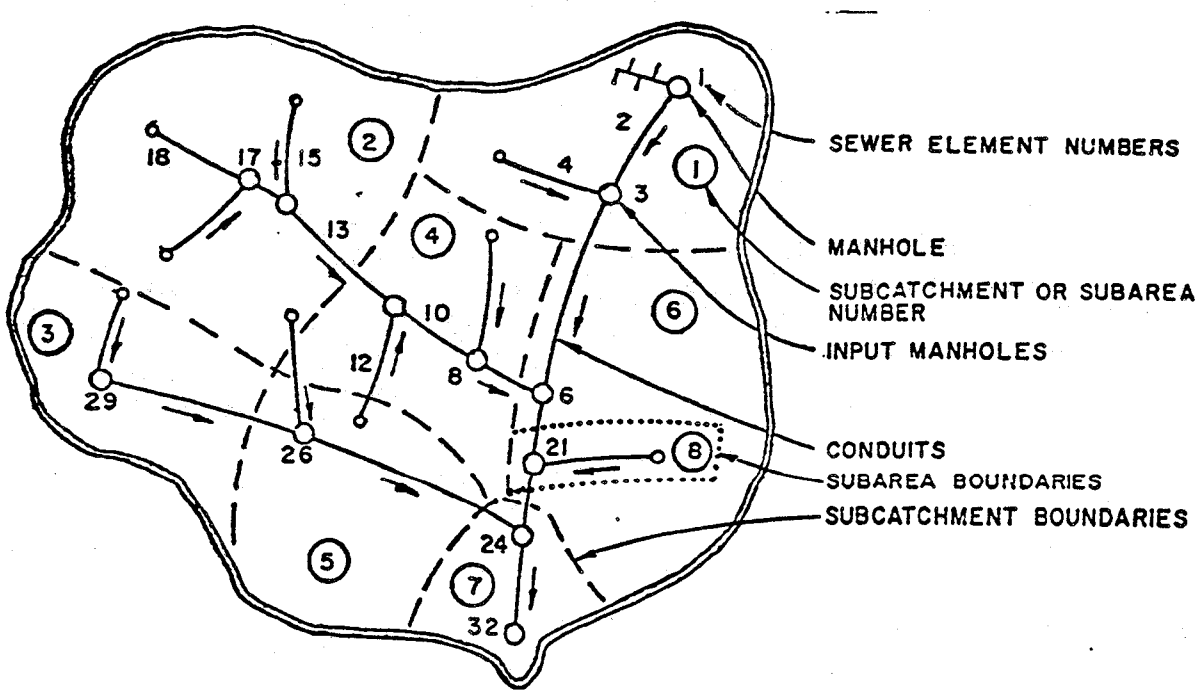
Three data categories are used to estimate sewage flow: (1) drainage basin data, (2) subarea data, and (3) decision and adjustment parameters.

Study area data are TOTA, KTNUM and ADWF. KTNUM denotes the number of subareas into which a drainage basin, having a surface area TOTA (acres), is being divided. ADWF, which is optional depending upon its availability, gives the average sewage flow (cfs) originating from the entire drainage basin (e.g., average flow data from a treatment plant serving the study area). When it is included, the predicted basin flow will be adjusted to match this value.

Subarea data requirements consist of several options depending upon availability and choice of input. Discussion later in the text will assist in data tabulation by noting the order of preference where options exist. Subarea data can be broken into three categories as follows: (1) identification parameters, (2) flow data, and (3) estimating data.

Identification Parameters --

Identification parameters are KNUM, INPUT, AND KLAND. KNUM identifies



Sewer and Subcatchment Data

1. Manhole 32 is the most downstream point.
2. Subcatchments 1,2,3, and 4 are single-family residential areas, each 100 acres in size and each with water metering.
3. Subcatchments 5 and 7 are 220-acre industrial areas.
4. Subarea 6 is a 250-acre park.
5. Subarea 8 is a 50-acre commercial area.

Subareas 6 and 8 constitute a subcatchment draining to input manhole number 21.

Resulting Data

8 sewage estimates
KTNUM, total subcatchments and subareas in drainage basin = 8.
TOTA, total acres in drainage basin = 1,140.

KNUM, subcatchment or subarea	INPUT, input manhole number	KLAND, land use category	ASUB, acres in subcatchment or subarea
1	3	1	100
2	17	1	100
3	29	1	100
4	8	1	100
5	26	4	220
6	21	5	250
7	24	4	220
8	21	3	50

Figure 6-9. Determination of Subcatchment and Identification to Estimate Sewage at 8 Points

each subarea by a number less than or equal to KTNUM. For each of the KTNUM subareas, INPUT indicates the number of the manhole into which DWF is assumed to enter. Land use within each subarea which approximately corresponds to zoning classification is categorized according to Table 6-6. KLAND serves as an important factor in deciding subarea locations and sizes. Figure 6-9 will assist in describing how the above data are determined and tabulated.

Table 6-6. Land Use Classifications

KLAND	Land Use
1	Single-family residential
2	Multi-family residential
3	Commercial
4	Industrial
5	Park and open area

Flow Data --

Flow data are optional inputs that eliminate the need for using predictive equations. Two possible types of flow data are average sewage flow measurements, SEWAGE, and metered water use, WATER. Commercial or industrial sewage flow or water use measurements should be input using the variable SAQPF. Flows from commercial and industrial establishments located in residential or open subareas may be included using SAQPF, also. Metering at lift stations and other flow control structures within the study area is occasionally available and should be used whenever possible. Metered water use offers a more available source of subarea flow data. Unfortunately, considerable effort in locating, tabulating, and averaging these data is often required.

Estimating Data --

For each subarea where SEWAGE or WATER measurements are not available estimated water use must be used as an estimate of sewage flow. In the case of a factory or commercial establishment, estimates can be made by multiplying the number of employees by an established coefficient (gpd per employee). In the case of a large factory or commercial establishment, one subarea may be established with estimated water use tabulated as SAQPF for that subarea. On the other hand, estimates of water use for established non-residential areas (e.g., industrial parks or shopping centers) may be summed and tabulated as SAQPF for one large subarea. A list of the above mentioned coefficients is given in Appendix VIII.

In the case of residential areas, estimating data for each subarea are METHOD, PRICE, ASUB, POPDEN, DWLINGS, FAMILY, and VALUE. Default values and definitions of each of these are given in the description of input data.

Decision and Adjustment Parameters --

These parameters consist of DVDWF, HVDWF, KDAY, CPI, and CCCI. DVDWF and HVDWF are daily and hourly correction factors, respectively, for DWF. DVDWF is comprised of seven numbers that are ratios of daily average sewage flows to weekly average flow. Likewise, HVDWF is comprised of 24 numbers that are ratios of hourly average sewage flows to daily average flow. Both groups of numbers may be derived from observed flow variation patterns throughout the country (e.g., Tucker, 1967; Portland Clement Association, 1968). Their use is to correct measured or estimated average sewage flow to more accurate estimates depending upon the day and hour. Typical sewage flow variations are shown in Figures 6-10 and 6-11. These flow patterns are only examples; locally observed patterns more accurately describe local variations and should be used when available.

KDAY denotes the day of the week at which simulation is to begin. As the simulation proceeds, this value is continually updated. By using the current day and hour, the appropriate values of DVDWF and HVDWF can be multiplied by average flow to determine the correct value. KDAY ranges from 1 to 7 with Sunday being day number 1.

Two cost indices are employed to adjust current house valuations and water prices to appropriate 1960 values and 1963 prices, respectively. This is done because estimating equations within FILTH are based upon 1960 values and 1963 prices. CPI, consumer price index, has been chosen to adjust water price by multiplying water price by 1960 CPI divided by the current CPI. CCCI, composite construction cost index, has been chosen to adjust house valuations similarly. Both indices can be found in most libraries in journals on economic affairs (e.g., U.S. Dept. of Commerce, Survey of Current Business and Statistical Abstracts of the United States).

Quality Estimates

The purpose of the DWF quality computation is to apportion waste characteristics (such as would be measured at a sewage treatment plant before treatment) among the various subareas in the drainage basin under study, or in the event no measured data are available, to estimate and apportion usable average values. The apportionment is based upon the flow distribution, land use, measured or estimated industrial flows, average family income, the use or absence of garbage grinders, and infiltration.

Daily and hourly correction factors for concentrations of BOD_5, SS and total coliforms are input in conjunction with those for flow variations. All are expressed as ratios of instantaneous to annual or daily averages.

Data line N1 includes the total number of subareas and process flow sources to be processed along with the type case (whether the total DWF characteristics are known or to be estimated), the number of process flow contributors, the cost indices, and the total drainage basin population. Depending upon the instructions given, computations proceed along the Case 1 or Case 2 channel.

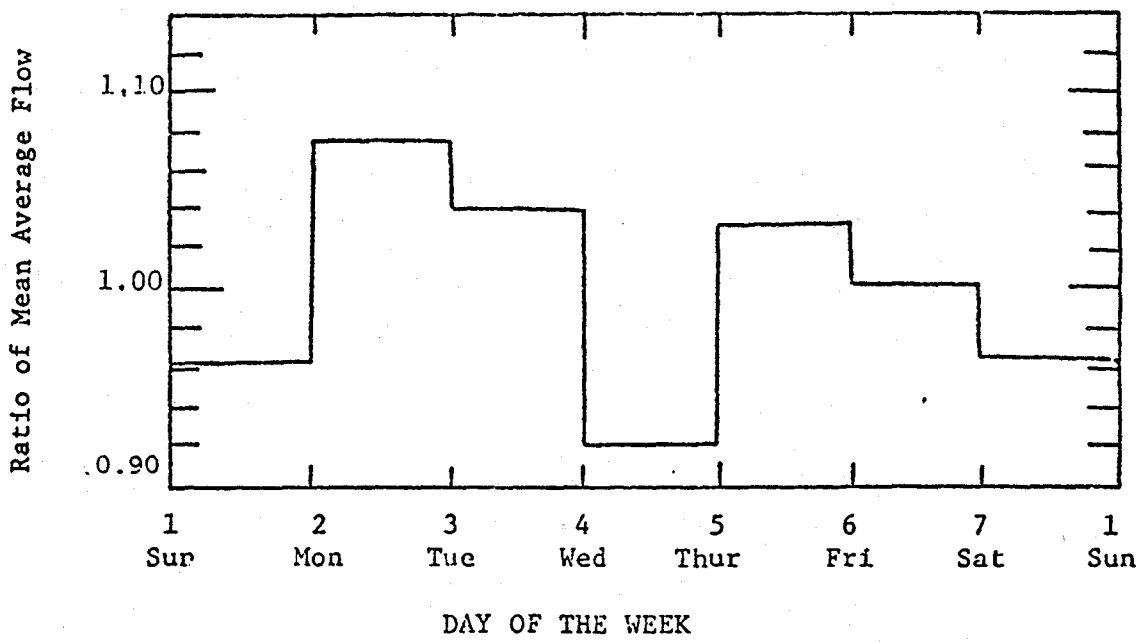


Figure 6-10. Representative Daily Flow Variation

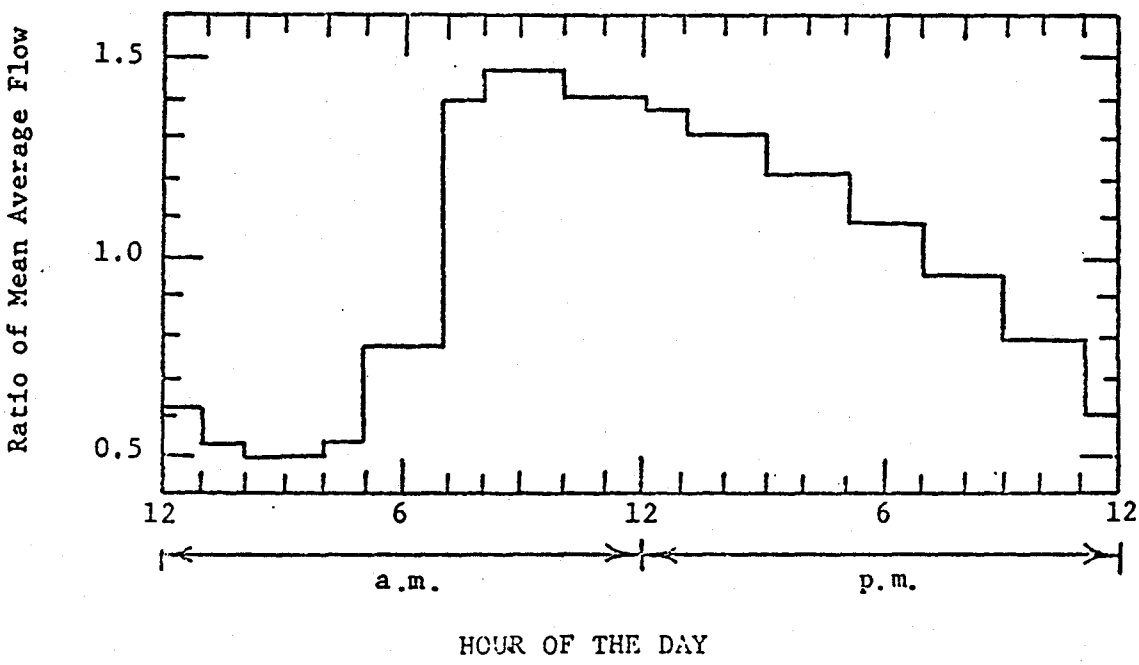


Figure 6-11. Representative Hourly Flow Variation

Case 1--In this instance, the total DWF quality characteristics are known at a point well downstream in the system. These characteristics may be obtained from treatment plant operating records (raw sewage) or by a direct sampling program. The average daily concentrations are read into the program for flow, BOD_5, SS, and total coliforms (data line 01). The total pounds per day of BOD_5 and SS and the total MPN per day of coliforms are then calculated. Then, infiltration and baseflow are subtracted from the average daily flow. Note that infiltration is computed in separate Subroutine INFIL. If it is not executed a default of zero will be assumed.

Next, the known process flow contributions (data group P1) are summed and deducted from the daily totals, yielding a further corrected flow, C2DWF (cfs), and characteristics, C1BOD and C1SS (lb/day). This is the only use of the input from data group P1. Process flow information must be re-entered for each subarea, in data group Q1.

Finally, corrections based on regression equations, are made for personal income variations, degree of commercial use, and garbage grinder status (data line 02). The DWF quantity does not change but the characteristics obtain new, average values, C2BOD and C2SS. Average concentrations of the residual flow, A1BOD, A1SS, and A1COLI are then computed.

Case 2--Here no direct measurements are available; thus, estimates must be made or default values will be assumed. A typical application of Case 2 would be in a situation where several catchments are to be modeled, yet funds will permit monitoring the DWF only in a single area. A1BOD, A1SS, and A1COLI would be computed via the Case 1 subroutine for the known area and the results could be transferred as Case 2 for the remaining catchments.

Default values of A1BOD, A1SS, and A1COLI are 1300 lb/day-cfs (241 mg/l), 1420 lb/day-cfs (263 mg/l) and 6.2×10^7 MPN/100 ml. These values assume 85 gal/capita-day (322 l/capita-day) domestic wastewater flow and 0.02 lb/captia-day (0.09 kg/capita-day) for BOD_5, 0.22 lb/capita-day (0.1 kg/capita-day) for SS and 200 billion MPN/capita-day for total coliforms. All values assume average income families. The default value for ADWF assumes 100 gal/capita-day (376 l/capita-day) which includes an extra 15 gal/capita-day (57 l/capita-day) for infiltration or other sources.

Following estimation of basin totals, average daily flow and quality values are computed for each of the KTNUM subareas. Data are input in data group Q1 for estimation of water use and sewage quality as well as process flow for each subarea.

Dry weather flow quantity (DWF in cfs) is computed for each land use on the basis of the following priorities:

Priority	Method
1	Measured average sewage flow (SEWAGE $\neq$ 0.0).
2	Measured water use (WATER $\neq$ 0).
3	Regression equations, for single and multiple-family residential land use only.

The first two methods are really equivalent since DWF is simply equated to either SEWAGE or WATER, in this order, for all land uses. Regression equations are employed as a third choice for residential land uses. As explained in the documentation (Metcalf and Eddy et al., 1971a), DWF becomes a function of the number of dwelling units within the subarea (DWLNGS) and other parameters as listed below. DWLNGS is required for all regression equations and is computed on the following basis:

Priority	Method
1	Input on data line Q1
2	DWLNGS = POPDEN·ASUB/FAMILY
3	Default to 10 units per acre.

DWF is then computed using DWLNGS and input parameters as listed below:

METHOD = 1		METHOD = 2
PRICE = 0	PRICE $\neq$ 0	
DWLNGS	DWLNGS	DWLNGS
VALUE	PRICE	FAMILY
	CPI	VALUE
	VALUE	

For each technique default values will be used where necessary. It may be inferred that parameters not used in a regression equation may be omitted from input. Note that VALUE is also used in each technique. It is adjusted to the 1960 Composite Construction Cost Index, CCCI, by

$$\text{VALUE} = \text{VALUE} \cdot 103/\text{CCCI} \qquad (6\text{-}11)$$

Finally, the user is reminded that all inputs for the regression equations can be avoided if either SEWAGE or WATER is known.

For commercial, industrial or undeveloped land uses parameter SEWAGE or WATER is the only method used to input DWF, except that process flows are added to the value of DWF previously computed, for all land uses. Thus, they could constitute the only dry-weather flow source for non-residential land use.

Dry-weather flow quality starts with the average BOD_5 and SS concentrations (A1BOD and A1SS) previously computed for the entire subarea. These are used for the concentrations of non-process flows for all subareas, with two exceptions. First, for commercial and industrial areas, the average concentrations are multiplied by 0.9. Second, the strengths of residential flows are adjusted according to average family income, XINCOM, and percent garbage grinders, PCGG, as explained in the documentation.

The process flow load (i.e., flow times concentration) is then added to the loads just computed, for all land uses. For non-residential land use process flows could constitute the only quality loads.

Finally, for all subareas, total coliforms are computed solely on the basis of population using the average concentration, A1COLI, computed earlier along with the total basin populations, POPULA, (data group N1) and subarea populations computed from POPDEN (data group Q1). Thus, there will be a subarea contribution of total coliforms only if POPDEN = 0.

For each of the KTNUM subareas, subtotals (cumulative up to this subarea) of computed flows and quality will be printed for each subarea if MSUPT = 1. Otherwise, only basin totals will be printed. If measured basin averages have been input in group 01 (KASE = 1) all subarea loads are adjusted a constant ratio such that the flow and concentrations computed from the data of group Q1 will agree with the input averages.

Summary of Dry Weather Flow Requirements

Step 1. Establishing Subareas --

Establishment of the subareas constitutes the initial step in applying subroutine FILTH. Both detail of input data and assumptions made in developing FILTH imply constraints on the type, size, and number of subareas. However, most important in subarea establishment is the type of estimating data available and the maintenance of homogenous land use.

Subareas should be located and sized to utilize existing sewer flow measurements taken within the drainage basin. These measurements should be recent and of sufficient duration to provide a current average sewage flow value for the period of time during which simulation is to proceed. Measured daily and hourly flow variation should be used in lieu of generalized values described earlier in the text. A gaging site with less than 200 ac (81 ha) contributing flow often provides a convenient data input situation. A subarea should be established upstream from the gage with average sewage flow tabulated as SEWAGE for that subarea. It is convenient, though not necessary, for the subareas to correspond to subcatchments in the Runoff Block.

If metered water use is to be used to estimate sewage flow, subareas should be located to coincide with meter reading zones or other zones used by the water department that simplify data takeoff. Since water use would be used to estimate sewage flow, average winter readings should be used to minimize the effects of lawn sprinkling and other summer uses.

If neither gaging nor metered water use are input, sewage characteristics must be estimated. Subareas should then be established to yield appropriate input data for the residential estimating equations in FILTH. Zero sewage flow is assumed from commercial, industrial, and parkland subareas for which SEWAGE and WATER are zero and measurements of SAQPF are not given. Since KLAND and VALUE are the significant variables in estimating subarea sewage flow, subareas should be located and sized to include land with uniform land use and property valuation. To utilize existing census data, subarea boundaries should be made to coincide with census tract boundaries.

Criteria for establishing subareas are listed in the following summary:

1) Subareas in general should:
   a. be of homogenous land use;
   b. be less than or equal to 159 in number; and
   c. conform to the branched pipe network.

2) Subareas should be established to employ any existing sewer flow measurements.

3) Subareas for which metered water use is used to estimate sewage flow should be compatible with meter reading zones.

4) Residential subareas for which estimated water use is used to estimate sewage flow should:
   a. be uniform with respect to land use;
   b. be uniform with respect to dwelling unit valuation; and
   c. coincide with census tracts.

Step 2. Collection of Data --

Other than the establishment of measured data described earlier, the primary data source is the Bureau of Census for census tract information. This source provides readily available data on population distribution, family income, and the number and relative age of dwelling units. City records, aerial photographs, and on-site inspection may be necessary to define land use activities, process flow, and dwelling density variations within tracts.

Step 3. Data Tabulation --

Once subareas have been established, several alternatives exist regarding data tabulation. An identification number KNUM should be given to each subarea prior to data takeoff. However, once KNUMs have been established, corresponding INPUT manhole numbers are selected from a previously numbered schematic diagram of the trunk sewer. This numbered schematic serves as the mechanism to coordinate runoff, infiltration, and sewage inputs. Refer to the earlier discussion for additional information about the numbered schematic. If water use estimates are necessary, land use should be determined from city zoning maps and the previously tabulated values for KLAND.

ADWF should be tabulated as average drainage basin sewage flow. As the ADWF, SEWAGE should be averaged from flow data for the appropriate month,

season, or year. ADWF, SAQPF, or SEWAGE may be obtained from routine or specific gaging programs done by the city, consulting engineers, or other agencies. SAQPF may be estimated for commercial and industrial areas using water use coefficients (Appendix VIII). Also, SAQPF and WATER may be determined for all land use categories from water meter records.

INITIALIZATION

Following execution of subroutines INFIL and/or FILTH, flows and concentrations will be initialized to baseflow values simply by summing flows and loads at all junctions (non-conduits) in subroutine INITAL. Baseflow can thus originate from three sources: input at manholes, infiltration (Subroutine INFIL), and/or dry-weather flow (Subroutine FILTH). Inflows from FILTH are always subject to the hourly and daily adjustment factors; inflows from INFIL and manholes are not.

In addition, the buildup of settled pollutant fractions (if simulated) in the sewer system is estimated using Subroutine DWLOAD. For the particle size distribution and specific gravity discussed earlier, daily "solids" deposition is computed for DWDAYS dry-weather days (data group B2) prior to the simulation. The initial pounds of deposition are printed for each conduit. This material is then eligible for erosion during the simulation (computed in Subroutine QUAL). Thus, if flows increase over their initial values, (as expected during a storm) a "first flush" will be provided.

OUTPUT

Input hydrographs and pollutographs will be printed for nonconduit elements selected in data group J1 and ouput hydrographs and pollutographs printed for nonconduit elements selected in group J2. A print interval INTPRT (group B1) is used. For example, if INTPRT = 2, values for every other time step will be printed. If INTPRT = 0, only the average, standard deviation, and total volume of flow (or mass of pollutant) will be printed. Graphical output is useful and is accomplished by saving hydrographs and pollutographs for desired locations using data group H1, followed by application of the Graph Block. Any nonconduit location in the system may be saved for graphing, not just the most downstream points.

A continuity check is printed breaking down the sources of inflow among external hydrographs, infiltration, and dry-weather flow. A continuity check is also performed for each quality constituent that includes external inputs, dry-weather flow and infiltration, and scour and deposition. If surcharging has occured a summary table is printed listing location, duration and ratio of required inflow to pipe capacity. Finally, if the hydraulic design routine is used to re-size conduits (option NDESN on group B3), a final table of dimensions for all conduits is printed.

Table 6-7. Transport Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

   a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

   b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Two Title Lines	
A1	Group identifier	None
TITLE	Title, two lines with heading to be printed on output[1] (max., 80 columns each).	None
	First Control Data Group	
B1	Group identifier	None
NDT	Total number of time-steps, no limit[3].	0
NINPUT	Total number of non-conduit elements into which there will be data input of hydrographs and pollutographs in Group R1 (maximum = 80)[5].	0
NNYN	Total number of non-conduit elements at which input hydrographs and pollutographs are to be printed out (maximum = 80, minimum = 0).	0
NNPE	Total number of non-conduit elements at which routed hydrographs and pollutographs are to be printed out (maximum = 80, minimum = 0)[7].	0
NOUTS	Total number of non-conduit elements at which flow is to be transferred to a subsequent block by disk file (maximum = 100)[8].	0
NPRINT	Control parameter for program-generated error messages (e.g., non-convergence) occurring in the the execution of the flow routing scheme. These errors do not normally affect the program execution[2]. = 0, messages suppressed = 1, messages printed	0
NPOLL	Total number of pollutants being routed (maximum = 4, minimum = 0). When NPOLL = 0, program will route flows only and all quality operations will be bypassed.	0
NITER	Total number of iterations to be used in routing subroutine (4 recommended).	4

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Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
IDATEZ	Starting date of storm, year-month-date e.g., July 20, 1979 = 790720. Superseded by value on interface file from previous block if accessed.	000000
METRIC	Metric input/output = 0, U.S. customary units = 1, Metric units, indicated in brackets [] among input variables.	0
INTPRT	Print interval for input and output elements. Use 1 for printing at each time step. Value of zero will result in printing of total loads and moments only.	0
	Second Control Data Group	
B2	Group identifier	None
DT	Size of time-step for computation, sec[3,4].	0
EPSIL	Allowable error for convergence of iterative methods in routing routine (0.0001 recommended).	0.0001
DWDAYS	Total number of days (dry weather days) prior to simulation during which solids were not flushed from the sewers.	0
TZERO	Starting time of day of storm, hours and fraction, e.g., 5:30 p.m. is 17.5. Superseded by value on interface file from previous block, if accessed.	0
GNU	Kinematic viscosity of water, ft^2/sec [cm^2/sec]. Required only if SPG > 1.0 for any of pollutants in group F1.	10^{-5} [10^{-2}]
TRIBA	Total catchment area, ac [ha]. Superseded by value on interface file from previous block, if accessed.	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
B3	Group identifier	None
NCNTRL	Control parameter specifying means to be used in transferring inlet hydrographs. - 0, Input from a preceding block using interface file JIN (line input, group R1, optional)[5]. - 1, No input from interface file. Line input (data group R1) only (optional).	0
NINFIL	Control parameter in estimating sewer infiltration inflows[6]. - 0, Infiltration not estimated (INFIL not called and corresponding data omitted). - 1, Infiltration to be estimated (subroutine INFIL called).	0
NFILTH	Control parameter in estimating dry-weather sewage inflow[6]. If used with quality simulation, the first three pollutants must be BOD5, SS and total coliforms. - 0, Sewage inflows not estimated (subroutine FILTH not called and corresponding data omitted). - 1, Sewage inflows to be estimated (subroutine FILTH called).	0
NDESN	Control parameter for hydraulic design routine (resizing of undersized conduits). - 0, Hydraulic design routine is not called. - 1, Hydraulic design routine is to be called.	0

Flow Routing Data for New Shapes

C1	Group identifier	None
NKLASS	Number of user-supplied sewer cross-sectional shapes, in addition to the 16 program-supplied, for which element routing parameters are to follow (maximum value = 2). These will become types 17 and 18.	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
KPRINT	Control parameter for printing flow routing parameters for all shapes (about 500 lines). = 0, Suppress printing. = 1, Allow printing (for all shapes, program-supplied and additional)	0
	OMIT GROUPS D1 TO D9 IF NKLASS = 0	
D1	Group identifier	None
NAME(I,17)	16 - letter name of shape 1	'None'
NAME(I,18)	16 - letter name of shape 2	'None'
	Number of values of DNORM to be input (max = 51, min = 2)	
D2	Group identifier	None
NN(17)	Number of DNORM values for shape 1.	0
NN(18)	Number of DNORM values for shape 2.	0
	Number of values of QNORM to be input (max = 51, min = 2)	
D3	Group identifier	None
MM(17)	Number of QNORM values for shape 1.	0
MM(18)	Number of QNORM values for shape 2.	0
	Value of A/A_f[9] corresponding to the maximum Q/Q_f value of each shape	
D4	Group identifier	None
ALFMAX(17)	A/A_f value for shape 1	0
ALFMAX(18)	A/A_f value for shape 2	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Maximum Q/Q_f[11] value for each shape	
D5	Group identifier	None
PSIMAX(17)	Maximum Q/Q_f value for shape 1	0
PSIMAX(18)	Maximum Q/Q_f value for shape 2	0
	Factor used to determine full flow area for each shape, i.e., for use in AFULL = AFACT(GEOM1)[9]	
D6	Group identifier	None
AFACT(17)	Factor for shape 1	0
AFACT(18)	Factor for shape 2	0
	Factor used to determine full flow hydraulic radius for each shape, i.e., for use in equation RADH = RFACT(GEOM1)	
D7	Group identifier	None
RFACT(17)	Factor for shape 1	0
RFACT(18)	Factor for shape 2	0
	REPEAT GROUP D8 FOR EACH ADDED SHAPE	
	Input of tabular data (depth of flow, y, divided by total depth of conduit, y_f, = y/y_f) for each added shape corresponding to the NN-1 equal divisions of A/A_f of the conduit as given by NN in Group D2[10]. 8 values per line.	
D8	Group identifier	None
DNORM(I,1)	First value for y/y_f for shape 1	0
DNORM(I,2)	Second value for y/y_f for shape 1	0
.	.	
.	.	
.	.	
DNORM(I,NN(I))	Last value of y/y_f for shape 1	0
	(Total of NN(17)/8 + NN(18)/8 data groups)	

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Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	REPEAT GROUP D9 FOR EACH ADDED SHAPE	
	Input of tabular data (flow rate, Q, divided by the flow rate of the conduit running full, Q_f, = Q/Q_f) for each added shape corresponding to the MM-1 equal divisions of A/A_f of the conduit as given by MM in group D3.[11] 8 values per line.	
D9	Group identifier	None
QNORM(I,1)	First value of Q/Q_f for shape 1	0
QNORM(I,2)	Second value of Q/Q_f for shape 1	0
.	.	
.	.	
.	.	
QNORM(I,MM(I))	Last value of Q/Q_f for shape 1	0
	(Total of MM(17)/8 + MM(18)/8 groups)	
	REPEAT GROUP E1 FOR EACH NUMBERED SEWER ELEMENT (maximum number of elements = 200). THESE GROUPS MAY BE READ IN ANY ORDER.	
	Sewer Element Data	
	Variables with asterisks can be modified using the Default/Ratio option[13,14].	
E1	Group identifier	None
NOE	External element number[12]. No element may be labeled with a number greater than 10,000, and it must be a positive numeral. However, numbering need not be consecutive or continuous.	None
	EXTERNAL[12] NUMBER(S) OF UPSTREAM ELEMENT(S). UP TO THREE ARE ALLOWED. A ZERO DENOTES NO UPSTREAM ELEMENT (maximum value = 10,000)	
NUE(1)	First of three possible upstream elements.	0
NUE(2)	Second of three possible upstream elements.	0
NUE(3)	Third of three possible upstream elements.	0
NTYPE	Classification of element type. Obtain value from Table 6-2 or 6-4.	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	THE FOLLOWING VARIABLES ARE DEFINED BELOW FOR CONDUITS ONLY. REFER TO TABLE 6-4 FOR REQUIRED INPUT FOR NON-CONDUITS.	
	Requirements for natural channels (type 16) are indicated in bold face. Only required parameters are SLOPE and BARREL (ID number). All other data are entered in data groups E2 - E4.	
DIST*	Element length for conduit, ft [m]. (For manhole, constant inflow into system, cfs [m^3/sec].) **Not required (N.R.) for type 16.**	0.0
GEOM1*	First characteristic dimension of conduit, ft [m]. See Figure 6-3 and Table 6-3 for definition. (For manhole: constant concentration of pollutant 1 in the inflow if simulated. Units according to NDIM, group F1). **N.R. for type 16.**	0.0
SLOPE*	Invert slope of conduit, ft/100 ft (i.e., percent). (For manhole: constant concentration of pollutant 2 in the inflow, if simulated. Units according to NDIM, Group F1.) **Required for type 16.**	0.0
ROUGH*	Manning's roughness of conduit. (For manhole: constant concentration of pollutant 3 in the inflow, if simulated. Units according to NDIM, Group F1.) **N.R. for type 16.**	0.0
GEOM2*	Second characteristic dimension of conduit, ft [m]. See Figure 6-3 and Table 6-3 for definition. (N.R. for some conduit shapes.) (For manhole: constant concentration of pollutant 4 in the inflow, if simulated. Units according to NDIM, group F1).	0.0
BARREL	Number of barrels for this element. The barrels are assumed to be identical in shape and flow characteristics[15]. (Must be integer $\geq$ 1.) For type 16, the cross-section ID number (SECNO, group E3) of the cross section for this channel.	1.0
GEOM3*	Third characteristic dimension of conduit, ft [m]. See Figure 6-3 and Table 6-3 for definition. (N.R. for some conduit shapes.)	0.0
KGEOM	Replaces Geom3 for flow dividers when $ANOM is used. (number in "290")	

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT

The E2 (NC), E3 (X1), and E4 (GR) data lines for any type 16 elements follow as a group after all E1 lines have been entered.

Data groups E2, E3 and E4 correspond to HEC-2 lines NC, X1 and GR. HEC-2 input may be used directly if desired. Lines may be identified either by Transport Block identifiers (E2, E3, E4) or HEC-2 identifiers (NC, X1, GR).

Channel Roughness

This is an optional data line that permanently modifies the Manning's roughness coefficients (n) for the remaining natural channels. This data group may repeated for later channels. It <u>must</u> be included for the first natural channel modeled. XNCH is used to normalize the cross-sectional flow-area relationship.

E2 or NC	Group identifier	None
XNL	n for the left overbank. = 0.0, No change, > 0.0, New Manning's n.	0.0
XNR	n for the right overbank. = 0.0, No change, > 0.0, New Manning's n.	0.0
XNCH	n for the channel. = 0.0, No change, > 0.0, New Manning's n.	0.0

Cross Section Data

Required for type 16 elements in earlier E1 data lines.
Enter pairs of E3 and E4 lines.

E3 or X1	Group identifier	None
SECNO	Cross section identification number.	1
NUMST	Total number of stations on the following E4 (GR) data group lines. NUMST must be < 99.	0
STCHL	The station of the left bank of the channel, ft [m]. Must be equal to one of the STA(N) on the E4 (GR) data lines.	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
STCHR	The station of the right bank of the channel, ft [m]. Must be equal to one of the STA(N) on the E4 (GR) data lines.	0.0
XLOBL	Not required for Transport (enter 0.0).	0.0
XLOBR	Not required for Transport (enter 0.0).	0.0
LEN(N)	Length of channel reach for this cross section, ft [m].	0.0
PXSECR	Factor to modify the horizontal dimensions for a cross section. The distances between adjacent E4 (GR) stations (STA) are multiplied by this factor to expand or narrow a cross section. The STA of the first E4 (GR) point remains the same. The factor can apply to a repeated cross section or a current one. A factor of 1.1 will increase the horizontal distance between the E4 (GR) stations by 10 percent. Enter 0.0 for no modification.	0.0
PSXECE	Constant to be added (+ or -) to E4 (GR) elevation data on next E4 (GR) line. Enter 0.0 to use E4 (GR) values as entered.	0.0

Cross-Section Profile

Required for type 16 elements in data group E1.
Enter E3 and E4 lines in pairs.

E4 or GR	Group identifier	None
EL(1)	Elevation of cross section at STA(1). May be positive or negative, ft [m].	0.0
STA(1)	Station of cross section 1, ft [m].	0.0
EL(2)	Elevation of cross section at STA(2), ft [m].	0.0
STA(2)	Station of cross section 2, ft [m].	0.0

Enter NUMST elevations and stations to describe the cross section. Enter 5 pairs of elevations and stations per data line[16]. Stations should be in increasing order progressing from left to right across the section. Cross section data are traditionally oriented looking downstream (HEC, 1982).

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	SKIP TO GROUP G1 IF NPOLL = 0 (GROUP B1)	
	Quality Input Data	
F1	Group identifier	None
KPOL	Pollutant selector from interface file e.g., if KPOL = 7, seventh constituent on interface file will be this pollutant. User must know contents on interface file from preceding block. If KPOL = 0, this pollutant is defined below and not taken from interface file[17].	0
	The following three parameters, PNAME, PUNIT, NDIM are required if KPOL is equal to 0. If KPOL is > 0 enter nothing for PNAME, PUNIT and NDIM and skip to parameter DECAY.	
PNAME	Pollutant name[18] (Character data - 8 columns).	None
PUNIT	Pollutant units[18] (Character data - 8 columns).	None
NDIM	Type of units[18] = 0, mg/l. = 1, "other" per liter, e.g., MPN/l. = 2, other concentration units, e.g. pH, JTU.	0
DECAY	First order decay coefficient, day^{-1}	0.0
SPG	Specific gravity. If SPG > 1.0, pollutant will be subject to scour-deposition calculations.	0.0
	The following parameters are <u>not entered</u> if SPG <= 1.0.	
	Particle Size Distribution. First point, PSIZE(1) = 0.0 mm, PGR(1) = 100.0 is automatically included. See Figure 6-5[19].	
PSIZE(2)	Particle size, mm.	0.0
PGR(2)	Percent greater than, %	0.0
PSIZE(3)	Particle size, mm	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
PGR(3)	Percent greater than, %	0.0
PSIZE(4)	Particle size, mm	0.0
PGR(4)	Percent greater than, %	0.0
PSIZE(5)	Particle size, mm	0.0
PGR(5)	Percent greater than, %	0.0
PSDWF	Maximum particle size contained in dry-weather flow input (either through manholes or using subroutine FILTH). MUST BE <= PSIZE(5).	0.0
	GROUPS G1 THROUGH G5 ARE FOR INTERNAL STORAGE (NTYPE = 22). OMIT IF INTERNAL STORAGE IS NOT DESIRED AND SKIP TO GROUP H1. REPEAT GROUPS G1-G5 FOR EACH INTERNAL STORAGE ELEMENT, IS. (Maximum of 30 storage elements.)	
G1	Group identifier	None
LOUT(IS)	Outflow routing parameter = 0, the depth-outflow relationship is described by as many as 16 data pairs on the G2 cards. = 1, the depth-outflow relationship is described by a single power equation in Group G3. = 2, the depth-outflow relationship is governed by two power equations in Group G3. = 3, the depth-outflow relationship is controlled by the pumps described in Group G4.	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Depth - Surface Area - Volume - Outflow Data	
	Each line contains a column of a unit depth and the corresponding values of area, volume and treated (e.g., weir overflow) outflow. The column for outflow may be left blank depending on the value of LOUT(IS) in Group G1. If no values for volume are entered, the program estimates volume from the depth-surface area relationship. Order the lines from the bottom of the unit (TSDEP(IS,1) = 0.0) to the maximum depth including as many as sixteen lines.	
G2	Group identifier	None
TSDEP(IS,MM)	A unit depth, ft [m].	0.0
TSAREA(IS,MM)	Surface area corresponding to the above depth, ft^2 [m^2]	0.0
TSTORE(IS,MM)	Volume corresponding to the above depth, ft^3 [m^3]	0.0
TSQOU(IS,MM)	Outflow at the above depth, cfs [m^3/sec]	0.0
	Depth-Outflow Power Equation	
	Required only if LOUT(IS) = 1 or 2 (Group G1). See Equation 7-3 for definition of coefficient, depth, and exponent.	
G3	Group identifier	None
A1(IS,1)	Depth-outflow equation coefficient. (Units depend on A2 and whether ft or m are used.)	0.0
DO(IS,1)	Depth-outflow equation minimum flow depth, ft [m].	0.0
A2(IS,1)	Depth-outflow equation exponent.	0.0
	The following parameters required only if LOUT(IS) = 2 (Group G1).	
A1(IS,2)	Depth-outflow equation coefficient for second outlet. (Units depend on A2 and whether ft or m are used.)	0.0
DO(IS,2)	Depth-outflow equation minimum flow depth for second outlet, ft [m].	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
A2(IS,2)	Depth-outflow equation exponent for second outlet.	0.0
GEOM3	External element number into which flows the outflow from the second outlet.	0.0
	Outflow Pumping	
	Required only if LOUT(IS) = 3 (Group G1)	
G4	Group identifier	None
TDSTAR(IS,1)	Depth at which pumping rate TQPUMP(IS,1) begins, ft. [m].	0.0
TDSTAR(IS,2)	Depth at which pumping rate TQPUMP(IS,2) begins, ft. [m] Must be $\geq$ TDSTAR(IS,1)	0.0
TQPUMP(IS,1)	Pumping rate when depth $\geq$ ft [m]. TDSTAR(IS,2) cfs [m^3/sec].	0.0
TDSTOP(IS)	Depth below which all pumping stops ft [m]. Must be $\leq$ TDSTAR(IS,1)	0
	Initial conditions in internal storage element IS	
G5	Group identifier	None
STORL(IS)	Total volume of water in unit at the start of the simulation, ft^3 [m^3]	0.0
	The initial pollutant concentrations are required only if STORL(IS) > 0.0. The concentrations must be given with dimensions consistent with those entered in Group F1.	
PTCO(IS,1)	Concentration of pollutant in the storage unit at the start of the simulation. Required only if NPOLL $\geq$ 1.	0.0
PTCO(IS,2)	Concentration of pollutant in the storage unit at the start of the simulation. Required only if NPOLL $\geq$ 2.	0.0

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Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
PTCO(IS,3)	Concentration of pollutant 3 in the storage unit at the start of the simulation. Required only if NPOLL $\geq$ 3.	0.0
PTCO(IS,4)	Concentration of pollutant 4 in the storage unit at the start of the simulation. Required only if NPOLL = 4.	0.0
	SKIP TO GROUP I1 IF NOUTS = 0 IN GROUP B1	
	List of external non-conduit element numbers for which outflows are to be transferred to subsequent blocks for a total of NOUTS (Group B1) non-conduit elements[20].	
H1	Group identifier	None
JN(1)	First element number[21]	0
.	.	
.	.	
.	.	
JN(NOUTS)	Last element number	0
	SKIP TO GROUP J1 IF NINPUT =0 (GROUP B1)	
	Non-conduit element numbers into which hydrographs and pollutographs (from input using group R1) enter the sewer system. These must be the order in which hydrograph and pollutograph ordinates appear at each time step in group R1. A total of NINPUT values required[20].	
I1	Group identifier	None
NORDER(1)	First element number	0
.	.	
.	.	
.	.	
NORDER(NINPUT)	Last element number	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	SKIP TO GROUP J2 IF NNYN = 0 (GROUP B1)	
	List of external non-conduit element numbers at which input hydrographs and pollutographs are to be stored and printed out, for a total of NNYN (Group B1) non-conduit elements[20].	
J1	Group identifier	None
NYN(1)	First input location number	0
.	.	
.	.	
.	.	
NYN(NNYN)	Last input location number	0
	SKIP TO GROUP K1 IF NNPE = 0 (GROUP B1)	
	List of external non-conduit element numbers at which output hydrographs and pollutographs are to be stored and printed out for a total of NNPE (Group B1) non-conduit elements[20].	
J2	Group identifier	None
NPE(1)	First output location number	0
.	.	
.	.	
.	.	
NPE(NNPE)	Last output location number	0
	IF SUBROUTINE INFIL IS TO BE CALLED (NINFIL = 1), INSERT GROUPS K1 THROUGH K2, OTHERWISE OMIT.	
	Estimated Infiltration	
K1	Group identifier	None
DINFIL	Base dry weather infiltration, cfs [m^3/sec].	0.0
GINFIL	Groundwater infiltration, cfs [m^3/sec].	0.0
RINFIL	Rainwater infiltration, cfs [m^3/sec].	0.0
RSMAX	Peak residual moisture, cfs [m^3/sec].	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Constant concentrations of pollutants in infiltration. Not required if NPOLL = 0. Units of each according to NDIM, Group F1.	
CPINF(1)	Concentration of pollutant 1	0.0
CPINF(2)	Concentration of pollutant 2	0.0
CPINF(3)	Concentration of pollutant 3	0.0
CPINF(4)	Concentration of pollutant 4	0.0
	Monthly Degree-Days[22]	
K2	Group identifier	None
NDD(1)	January degree-days, ^{o}F-day, [no metric units]	0.0
NDD(2)	February degree-days	0.0
.	.	
.	.	
.	.	
NDD(12)	December degree-days	0.0
	IF SUBROUTINE FILTH IS TO BE CALLED (NFILTH = 1), INSERT GROUPS L1 THROUGH Q1, OTHERWISE OMIT	
	Factors to correct yearly average sewage flows to daily average by accounting for daily variations throughout a typical week.	
L1	Group identifier	None
DVDWF(1)	Flow correction for Sunday	1.0
DVDWF(2)	Flow correction for Monday	1.0
.	.	
.	.	
.	.	
DVDWF(7)	Flow correction for Saturday	1.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	IF NPOLL = 0, SKIP TO GROUP M1. (NOTE: IF POLLUTANTS ARE SIMULATED AND FILTH IS CALLED, FIRST THREE POLLUTANTS MUST BE BOD5, SUSPENDED SOLIDS AND TOTAL COLIFORMS[23].	
	Factors to correct BOD yearly averages to daily averages.	
L2	Group identifier	None
DVBOD(1)	BOD correction for Sunday	1.0
.	.	
.	.	
.	.	
DVBOD(7)	BOD correction for Saturday	1.0
	Factors for correction of yearly SS averages to daily averages	
L3	Group identifier	None
DVSS(1)	SS correction for Sunday	1.0
.	.	
.	.	
.	.	
DVSS(7)	SS correction for Saturday	1.0
	(No daily correction factors for coliforms)	
	Factors to correct daily average sewage flow to hourly averages by accounting for hourly variations throughout a typical day. Enter all factors on one line.	
M1	Group identifier	None
HVDWF(1)	Midnight to 1 a.m.	1.0
.	.	
.	.	
.	.	
HVDWF(24)	11 p.m. to midnight factor.	1.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	IF NPOLL = 0, SKIP TO GROUP N1	
	Factors for BOD hourly corrections (one line).	
M2	Group identifier	None
HVBOD(1)	Midnight to 1 a.m. factor.	1.0
.	.	
.	.	
.	.	
HVBOD(24)	11 p.m. to midnight factor.	1.0
	Factors for SS hourly corrections (1 line).	
M3	Group identifier	None
HVSS(1)	Midnight to 1 a.m. factor.	1.0
.	.	
.	.	
.	.	
HVSS(24)	11 p.m. to midnight factor.	1.0
	Factors for total coliform hourly corrections (1 line).	
M4	Group identifier	None
HVCOLI(1)	Midnight to 1 a.m.	1.0
.	.	
.	.	
.	.	
HVCOLI(24)	11 p.m. to Midnight factor.	1.0
	Study Area Data	
N1	Group identifier	None
KTNUM	Total number of subareas within a given study area in which sewage flow and quality are to be estimated.	1
KASE	Indicator as to whether study area data, such as treatment plant records, are to be used to estimate sewage quality? = 1, Yes = 2, No	0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
NPF	Total number of process flows within the study area for which data are included in one of the following groups.	0
KDAY	Number indicating the day of the week during which simulation begins (Sunday = 1).	1
CPI	Consumer Price Index	125.0
CCCI	Composite Construction Cost Index	110.0
POPULA	Total population in all areas, thousands.	None
	IF KASE = 1, INCLUDE GROUPS 01,02, AND P1	
	Average study area data[24]	
01	Group identifier	None
ADWF	Total study area average sewage flow e.g., from treatment plant records, cfs [m^3/sec].	0.0
ABOD	Total study area average BOD,mg/l	0.0
ASUSO	Total study area average SS, mg/l	0.0
ACOLI	Total study area average coliforms MPN/100 ml.	0.0
	Categorized study area data.	
02	Group identifier	None
TOTA	Total study area from which ABOD and ASUSO were taken, acres [ha].	0.0
TINA	Total contributing industrial area, acres [ha].	0.0
TCA	Total contributing commercial area, acres [ha].	0.0
*** Valuations	for the following three parameters are for 1963 dollars! ***	
TRHA	Total contributing high income (above $15 000) residential area, acres [ha]	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
TRAA	Total contributing average income (above $7000 but below $15 000) residential area, acres [ha].	0.0
TRLA	Total contributing low income (below $4 000) residential area, acres [ha].	0.0
TRGGA	Total area from the above three residential areas that contribute additional waste from garbage grinders, acres [ha].	0.0
TPOA	Total park and open area within the study area, acres [ha].	0.0
	IF PROCESS FLOW DATA ARE AVAILABLE (NPF NOT EQUAL 0 AND KASE = 1), REPEAT GROUP P1 FOR EACH PROCESS FLOW (NPF DATA). OTHERWISE, SKIP TO GROUP Q1.	
	Process flow characteristics	
P1	Group identifier	None
INPUT	External manhole number into which flow is assumed to enter (maximum value = 10,000, minimum value = 1).	0
QPF	Average daily process flow entering the study area system, cfs [m^3/sec][26].	0.0
BODPF	Average daily BOD of process flow, mg/l.	0.0
SUSPF	Average daily SS of process flow, mg/l.	0.0
	REPEAT GROUP Q1 FOR EACH OF THE KNUM SUBAREAS. THESE SUBAREAS DO NOT NECESSARILY HAVE TO CORRESPOND TO RUNOFF SUBCATCHMENTS.	
	Subarea data	
Q1	Group identifier	None
KNUM	Subarea number.	0
INPUT	External number of the manhole into which flow is assumed to enter for subareas KNUM (Maximum value = 10,000, minimum value = 1).	0

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Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
KLAND	Predominant land use within subarea = 1, single family residential = 2, multi-family residential = 3, commercial = 4, industrial = 5, undeveloped or park lands	5
METHOD	Parameter indicating whether or not water usage within subarea KNUM is metered. = 1, metered water use = 2, incomplete or no metering	2
KUNIT	Parameter indicating units in which water usage estimates (WATER) are tabulated = 0, thousand gal/mo. [10^3 cu.m/mo] = 1, thousand cu.ft./mo [10^3 cu.m/mo]	0
MSUBT	Subtotal printed after each subarea? = 0, No = 1, Yes	0
SAGPF	Total industrial process flow originating within subarea KNUM, cfs [m^3/sec][25]	0.0
SABPF	BOD contributed from industrial process flow originating within subarea KNUM, mg/l	0.0
SASPF	SS contributed from industrial process flow originating within subarea KNUM, mg/l	0.0
Several of the following parameters are optional. See text.		
WATER	Measured winter water use for subarea KNUM in the units specified by KUNIT[26].	0.0
PRICE	Cost of the last thousand gal [10^3 cu.m] of water per billing period for an average consumer within subarea KNUM, cents/1000 gal [cents/10^3cu.m]	0.0
SEWAGE	Measured average sewage flow from entire subarea KNUM, cfs [cu.m/sec] but not including process flows (SAQPF)[26].	0.0
ASUB	Total area within subarea KNUM, acres[ha].	0.0

Table 6-7 (continued). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	The next six parameters are not required if KLAND > 2.	
POPDEN	Population density within subarea KNUM, persons/acre [pers/ha][27]	0.0
DWLNGS	Total number of dwelling units within subarea KNUM[28].	10.0/ac
FAMILY	Number of people living in average dwelling unit within subarea KNUM[28].	3.0
VALUE	Market value of average dwelling unit within subarea KNUM, thousands of dollars.	20.0
PCGG	Percentage of dwelling units possessing garbage grinders within subarea KNUM	0.0
XINCOM	Income of average family living within subarea KNUM, thousands of dollars per year.	VALUE/2.5
	END OF FILTH DATA CARDS	
	Include group R1 only if NINPUT not = 0 (Group B1)	
	REPEAT GROUP R1 FOR EACH INLET FOR FIRST TIME AND THEN REPEAT GROUP R1 FOR EACH INLET FOR SECOND TIME, ETC. REPEAT THIS COMBINATION FOR ALL INPUT TIMES. ORDER OF INLET GROUP MUST BE THE SAME AS INDICATED IN GROUP I1.	
	Hydrograph and pollutograph input ordinates	
R1	Group identifier	None
TEO	Time of day, decimal hours, e.g., 6:30 p.m. = 18.5. The first time must equal TZERO. The program will automatically set TEO = TZERO for entries for the first time[29].	0.0 or TZERO
QE2	Input flow for this time step at first inlet, cfs [m^3/sec].	0.0

Table 6-7 (concluded). Transport Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** Enter pollutant concentration only for NPOLL pollutants *** (Enter no fields if NPOLL = 0)	
PE2(1)	Pollutant 1 for this time at first inlet, concentration according to NDIM (Group F1).	0.0
PE2(2)	Pollutant 2 for this time at first inlet, concentration according to NDIM (Group F1).	0.0
PE2(3)	Pollutant 3 for this time at first inlet, concentration according to NDIM (Group F1).	0.0
PE2(4)	Pollutant 4 for this time at first inlet, concentration according to NDIM (Group F1).	0.0

END OF TRANSPORT BLOCK DATA GROUPS

At this point the program seeks new input from the Executive Block.

Footnotes to Table 6-7

1. The title from the first of any preceding blocks run will also be printed.

2. Except in unusual cases, these errors will only indicate that a small continuity violation will occur. These errors can usually be cured by shortening the time step or increasing the length of the conduit.

3. The Transport Block time step does not have to equal that of a preceding block. The total simulation time is NDT*DT. If this is greater than that of an input file, the simulation will end earlier. Although there is no limit on the length of a simulation, output is geared toward single events. That is, daily or monthly totals are not printed and zeroes are not suppressed.

4. If the time step for Transport is different than that for a preceding block, input hydrograph and pollutograph ordinates will be found by linear interpolation at the required time.

5. If both local (keyboard) and interface file input is used, hydrographs and pollutograph loads entered at common locations will be summed. Transport can be run without hydrograph input if it were desired to route only dry-weather flows (base flows).

6. Constant base flows and concentrations may be entered at manhole elements (Type 19) in group E1 if desired, thus eliminating the need to call FILTH or

INFIL. They may still be called if desired; infiltration, dry-weather flow and base flow will be summed for entry at non-conduits. Base flows and concentrations entered in group E1 will not be subject to daily and hourly correction factors.

7. Inlet hydrographs from a preceding block will automatically be accepted, but a match must be found for each inlet (element) number on the interface file with an element number entered in Transport.

8. These locations should include any elements for which graphical output is desired since only locations on the interface file may be plotted using the Executive Block.

9. A/A_f = ANORM is the cross-sectional flow area divided by the cross-sectional flow area of the pipe running full. Tabular values of ANORM are generated in the program by dividing the ANORM axis (0.0,1.0) into NN1 or MM1 equal divisions.

10. y/y_f = DNORM is the depth of flow, y, divided by the maximum flow depth, y_f (e.g. diameter of a circular conduit).

11. Q/Q_f = QNORM is the flow rate divided by the flow rate of the conduit flowing full.

12. "External" numbers are those assigned by the user to the various sewer system components. "Internal" numbers are subscripts assigned within the program in the order in which elements in Group E1 are entered. All input to the Transport Block is in terms of external numbers.

13. Input values in this group indicated with asterisks are multiplied by ratios, initially set equal to 1.0. If the ID number (NOE) = -1, non-zero entries for parameters with asterisks will replace old values of the ratios. These will become new ratios for all future entries of these parameters. Ratios may be altered or reset to 1.0 any number of times. The intention of the use of ratios is to simplify sensitivity analyses, etc., by allowing easy changes of data values without editing data. The altered ratios apply to all subsequent input of a given parameter (until changed by another default/ratio line).

14. Input parameters in this group indicated with asterisks will take on default values if input values are zero. If the ID number (NOE) = -2, non-zero data entries for parameters with asterisks will become new default values for all future entries of these parameters. Default values may be altered or reset to their original values (except zero) any number of times. It is not possible to reset a default value exactly to zero since only non-zero values are changed. However, the value may be made arbitrarily small, for example, 1.0E-50. The altered default values apply to all subsequent input of a given parameter (until changed by another default/ratio line).

15. For example, a two-barreled conduit would consist of two identical parallel conduits adjacent to each other, as in a double box culvert.

16. Enter the group identifier (E4) on every line of input.

17. If NFILTH = 1 (Group D3), it will be assumed that the first pollutant is BOD5, the second is suspended solids and the third is total coliforms. Hence, the selection indicated by NPOLL must be in this order. The fourth pollutant, if simulated, is unaffected by the value of NFILTH.

18. See the discussion for the Runoff Block.

19. Up to the five available points (including 0.0 mm, 100%) may be used to define the particle size distribution. For instance, if a triangular distribution were satisfactory with 0.1 mm being the largest particle size, then PSIZE(2) = 0.1, PGR(2) = 0.0 would be the only entries needed. (But trailing zeroes are still needed to complete the free-format input.)

20. May require multiple lines of input.

21. Be careful in subsequent blocks to ensure that element numbers will correspond to those transferred in the interface file. However, any element number may be placed on the interface file, e.g., for plotting purposes.

22. See Table VIII-1, Appendix VIII, for representative values. Degree days are not needed if RSMAX = 0.0 in Group K1 (but 12 zeroes must still be included for Group K2). Degree days are in ^{o}F-day, and there is no metric input for this parameter.

23. When subroutine FILTH is used to generate dry-weather flow and pollutants, the only pollutants included are BOD5, suspended solids (SS) and total coliforms (T.C.). NPOLL must be 3 or 4, and the three pollutants entered in the given order in group F1. The fourth pollutant is arbitrary (if used) and is not affected by FILTH calculations.

24. Predicted total average daily dry-weather flow from downstream end(s) of the system will be adjusted to these values.

25. These industrial process flows described by SAQPF, SABPF and SASPF will be added to flows and quality already generated.

26. If process flows are too large it is possible for ADWF - infiltration - QPF < 0 in which case the program defaults to KASE = 2.

27. Either SEWAGE or else WATER is required to generate dry-weather flow from commercial areas. If both are zero, only process flows will be considered. SEWAGE and WATER should = 0, for industrial land use; for KLAND = 4, let entire flow be process flow.

28. DWLNGS and FAMILY can be used to calculate the population and the population density. If both are given, the value of POPDEN will be overridden.

29. The program will interpolate linearly between entries of TE2 to obtain intermediate values of flow and concentrations. Hence, the difference between two time entries, TE2, should not be less than the time step, DT, unless a

step function change is desired. Time entries need not be equally spaced, but the last time entered must extend past the end time of the run. Time TZERO is read from the interface file or else entered in Group D2. If simulation extends beyond midnight (i.e., TE2 > 24), continue the running time into the next day or days (i.e., let TE2 be greater than 24). Note that the time TE2 must be the same for all inlets. (The program will use the value for TE2 entered on the line for the last inlet.)

SECTION 7

STORAGE/TREATMENT BLOCK*

BLOCK DESCRIPTION

Introduction

The Storage/Treatment Block has been developed to simulate the routing of flows and pollutants through a dry- or wet-weather storage/treatment plant containing up to five units or processes. The block will accept any number of time steps; therefore, a single-event or a continuous simulation is possible. Each unit may be modeled as having detention or non-detention characteristics. The various units may be linked in a variety of configurations. Sludge handling may also be modeled using one or more units. Additionally, capital cost and operation and maintenance cost may be estimated for each unit.

The S/T Block will route, in addition to flow, up to three different pollutants. These pollutants may be input to the block from any external block via the interface file, directly from keyboard input to this block, or a combination of both. Characterization of the pollutants may be by magnitude (i.e., concentration) or by magnitude and a particle size/specific gravity settling velocity distribution. All input flows and pollutant concentrations are assumed to be instantaneous values. However, the instantaneous values at the beginning and end of each time are used to compute average values for each time step. Thus, the user is cautioned that the output from the S/T Block consists of average values, not instantaneous values as in the rest of SWMM.

This section describes the program operations of the S/T Block, provides instructions for preparing input data groups, defines program variables, and presents test applications. Theoretical development and explanations are given in Appendix IV..

Program Operation

The Storage/Treatment Block consists of approximately 2000 Fortran statements grouped in eight subroutines. The relationships among the S/T Block, the rest of SWMM and the various subroutines are shown in Figure 7-1.

Subroutine STRT is called by the Executive Block to initiate the operation of the S/T Block. STRT provides the main driving loop for the block and generally acts as the central coordinating subroutine. Input flow and

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*This block was originally developed by Dr. Stephen J. Nix.

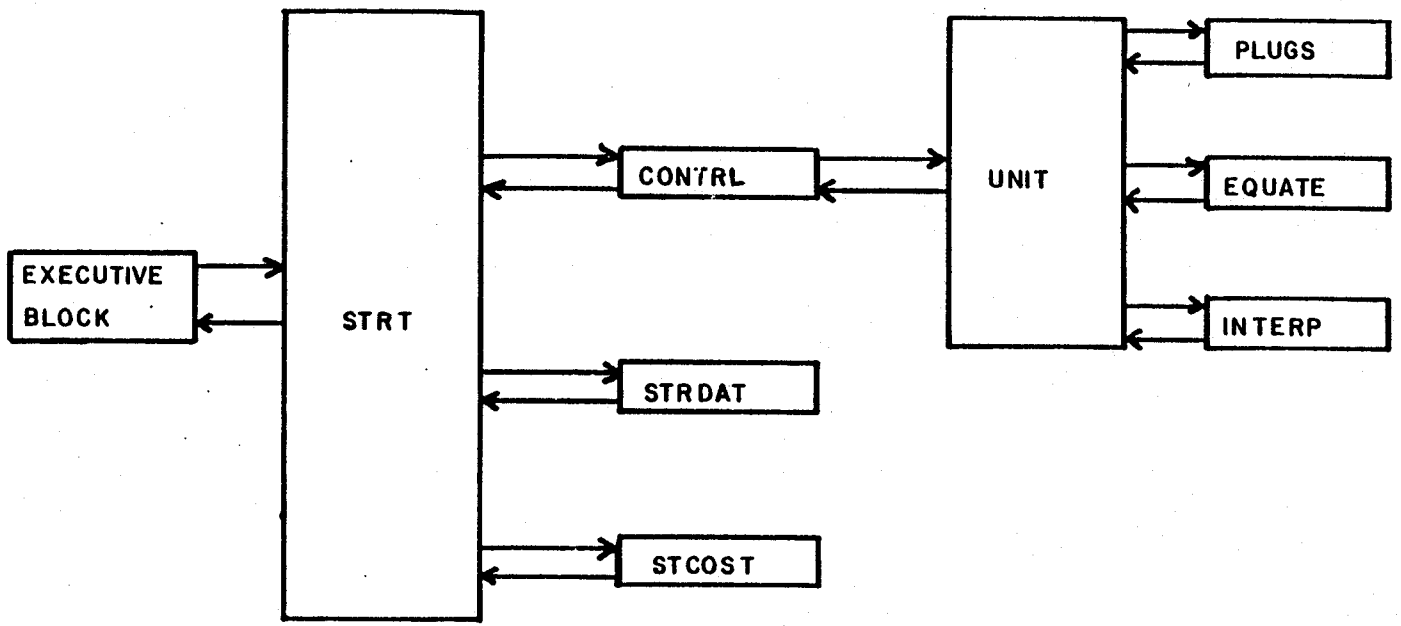


Figure 7-1. Storage/Treatment Block.

pollutants from any external block are read in this subroutine. Output from the S/T Block transferred to other blocks is also handled by STRT (through the Executive Block). The information transferred to other blocks is discussed in the next paragraph. Subroutine STRDAT is called in STRT at the start of a run and is responsible for reading the input data describing the units, their configuration, the pollutant removal mechanisms, the method of characterizing pollutants and the remainder of the data provided by the user (excluding flow and pollutant inputs). STRDAT also prints the input data for verification. Subroutine CONTRL is called each time step from the main driving loop in Subroutine STRT. CONTRL directs flow and pollutants between units and any subsequent block. CONTRL also coordinates the accounting and printout of detailed and summarized performance information. Flow and pollutant inputs from input data groups (or data "lines") are also read in this subroutine. Subroutine UNIT is called from Subroutine CONTRL for each unit and is the heart of the S/T Block. UNIT has the flexibility and capability to model detention and non-detention units with a variety of pollutant removal mechanisms, residual removal schemes and outflow structures. Subroutine EQUATE is used by UNIT to provide a variety of pollutant removal equations. Subroutine INTERP is employed by UNIT for linear interpolation in routing flows through detention units. Subroutine PLUGS is used by UNIT to model pollutant routing through a detention unit when perfect plug flow is specified. Subroutine STCOST is called from STRT to estimate the capital cost and operation and maintenance cost for each unit.

Use of Off-line Computer Storage

No scratch data sets are required to run the Storage/Treatment Block. However, disks files may be used as an input source (from an external block) or to transfer output to other blocks. This interface file consists of descriptive titles, user-supplied pollutant names and dimensions, the simulation starting date and time, the name of the external block generating the output (input) file, the total catchment or tributary area, the number of elements (inlets, outfalls, nonconduits, etc.) and pollutants found on the output (input) file, and the elements for which flow and pollutant data are placed (read from) the output (input) file. This preliminary information is followed by the flows and pollutant data for each time step (up to the total number of time steps) for each of the specified elements. The user should refer to Section 2 for a detailed description of the interface file.

Flow and up to three pollutants are transferred unchanged from an input file to an output file if the data are from locations or are pollutants not selected for used in the S/T Block. In other words, the flow and pollutant data from an input file (external block) are altered only if they pass through a storage/treatment facility. However, the dimensions of the data on the input file will be made to conform to the standard SWMM dimensions before being placed on an output file (see Section 2). The methods of selecting these data from particular location (i.e., inlet, element) numbers and processing specific pollutants is discussed in the next subsection.

Importance of Data

The Storage/Treatment Block is a user-intensive model, i.e., the user

should have a thorough knowledge of what he/she is modeling. This is an obvious, but often overlooked, axiom and especially true whan a model provides some default values. The user is required to describe each unit in some detail with data of his/her own choosing. S/T performance depends on local pollutant characteristics, flow rates, etc.; thus, the user is encouraged to use local operating data, whenever possible, to aid in the modeling effort.

Instructions for preparing the input data are presented below with suggestions and examples. All entries not described in the text are considered to be self-explanatory or covered sufficiently in Table 7-4, which gives the input order. All data groups are required unless otherwise stated. The general structure of the data groups is shown in Table 7-1.

Table 7-1. Structure of Data Groups for the Storage/Treatment Block

Data Group	Type of Data
A1	Title
B1	General data
C1 - C2	Starting time and print instructions
D1	Evaporation
E1 - E6	Pollutant characterization
F1 - F2	General unit characteristics
G1 - G4	Pollutant removal
H1 - H8	Detention units
I1	Costs
J1	Flow and pollutants

PRELIMINARY INFORMATION

Title (Data Group A1)

This data group allows a descriptive heading to be displayed at the start of the printed output. The heading is also transferred to the next block. Two lines are required.

General Information (Data Group B1)

The variable NOTAPE allows the user to specify the source of flow and pollutants used for input to the S/T Block. If NOTAPE = 0, the input is provided by an external input file (arranged by the Executive Block).. When NOTAPE = 1, the input is provided by data group J1. If NOTAPE = 2, the input is the sum of the entries for each time step from the external file and data group J1. The parameter JNS selects the location number (from an external file, NOTAPE = 0 or 2) from which flows and pollutants will be taken and passed through the S/T Block. If the input is provided solely by data group J1 (NOTAPE = 1 or 2), the user may label the output of the S/T Block with a

location number.

When NOTAPE = 0 or 2, the variables NDT (number of time steps) and DS (time step) are read from the external input file. However, the value of NDT from an external block may be altered by specifying a non-zero value on data line B1. There is no limit on the number of time steps. This is useful for extending the simulation beyond the limit of the external block or input file. The value of DS from an external block will supersede any value for DS entered on data line B1. If run independently (NOTAPE=1), there is no restriction on time step size for the S/T Block. However if DS is too large, Puls routing may result in too-rapid drawdown of detention units.

The variable NU specifies the number of storage/treatment units, including the residuals (sludge) handling units, to be modeled and the number of times that data groups F1 through I1 are repeated. The model as written is limited to five units. The variable NP specifies the number of pollutants to be routed through the storage/treatment system. If NP = 0, then only flows are routed. A maximum of three pollutants may be selected for routing. The specific pollutants are selected on data line E1. However, NP may not be greater than the number of pollutants transferred from other blocks (NOTAPE = 0 or 2).

If ICOST = 1, the capital and operation and maintenance costs are computed for each unit. Cost equation parameters are entered in data group J1. The value of METRIC determines whether U.S. customary or metric units are used for all data input, output and internal calculations. The value of TRIBA is the service area of the S/T plant. It does not enter into the computations but is transferred to the next block.

Starting Time and Print Instructions (Groups C1 and C2)

The values of IDATE and ITIME are used to start the date/time algorithm of the S/T Block. The Julian date and time of day in seconds are updated for each time step. If NOTAPE = 0 or 2 (data group B1) the values of IDATE and ITIME read from the external file supersede the values entered on data group C1.

The user is cautioned against printing large quantities of unwanted information. The first runs should have as little printout as possible (ISUM = 0) and IDET = 0) to check for obvious errors in the input data. As simulation efforts proceed, mure detailed printouts may be desired.

Data group C2 (one line) is used to enter the first and last dates of the detailed print periods specified by NPR (data line C1).

Evaporation Data (Group D1)

Monthly evaporation rates are required to correct for evaporation from detention units. However, two groups must be included even if there are no detention units. If needed, values of evaporation (parameters E(1) through E(12)) are entered for the months during which the simulation occurs; others may be left blank.

Pollutant Characterization (Groups E1 - E6)

Data groups E1 through E6 are omitted if NP = 0 (data group B1).

Data Group E1 --

These groups (up to two) allow the user to select the NP (data group B1) pollutants to be routed through the S/T Block. The variables IPOLL(1), IPOLL(2), and IPOLL(3) are used to select pollutants from an external input file (NOTAPE = 0 or 2, data group B1). For example, if IPOLL(1) = 5, then the first pollutant routed through the S/T Block is the fifth pollutant found on the input file. If data from data group J1 are to be added to the external input file data (NOTAPE = 2, data group B1), the pollutants entered on that data group must be in the same order as specified by IPOLL(1), IPOLL(2), and IPOLL(3).

Pollutants may be characterized by their magnitude alone (concentration) or by their magnitude and a particle size/specific gravity or settling velocity distribution by specifying IPART(IP) = 0 or 1, respectively. If IPART(IP) = 1, the user is required to enter these distributions on data groups E2 through E6. Using these distributions, however, limits the type of unit that may be modeled (discussed in later data groups.)

The variables NDIM(1), NDIM(2), and NDIM(3) are used to describe the dimensions of the pollutant data on data group J1 when NOTAPE = 1. When NOTAPE = 0 or 2 (data group B1) this information is provided by the external input file. For example, if NDIM(1) = 0, then the first pollutant has dimensions of mg/l. If NDIM(1) = 1, then the first pollutant has dimensions of $liter^{-1}$. This is used when pollutants such as coliforms are routed. When NDIM(1) = 2, pollutant 1 has other concentration dimensions such as JTU, mho, ^{o}C, pH, etc.

The entry of pollutant names PNAME(IN,1), PNAME(IN,2), and PNAME(IN,3) and dimension names PUNIT(IN,1), PUNIT(IN,2), and PUNIT(IN,3) is required only when the source of flow and pollutant data is solely data group J1 (NOTAPE = 1, data group B1). If flow and pollutant data are read from an external input file (NOTAPE = 0 or 2, data group B1) this information is already provided.

Naturally, if NP = 2 (data group B1), for example, then the values for IPOLL(3), IPART(3), NDIM(3), PNAME(IN,3), and PUNIT(IN,3) are not required under any circumstances. The order in which this pollutant information is entered determines the numbering of the pollutants.

Data groups E2 through E6 are required only if IPART(IP) = 1 for <u>any</u> pollutant. Refer to Appendix IV for a more detailed discussion of this form of pollutant characterization.

Data Group E2 --

The variable NVS specifies the manner in which the particles in the waste stream are classified. If NVS = 0, the particles are classified by size and

specific gravity. The variable NNR specifies the number of size/specific gravity ranges used to delineate the distribution (up to a maximum of 10 ranges). The size/specific gravity classification remains constant throughout the simulation for each pollutant characterized in this manner. The size and specific gravity ranges are established in data groups E3 and E4. These groups and data group E5 (which enters waste stream temperature data) provide the information with which an average settling velocity is computed for each range (see Appendix IV for details). If NVS =1, the particles are classified by NNR settling velocity ranges specified on data group E3. The average settling velocity for each size range is the average of the range endpoints. Groups E4 and E5 are not required. As with the size/specific gravity ranges, this classification remains constant throughout the simulation for each pollutant characterized by settling velocity. Obviously, a particle size or settling velocity distribution may change as it passes through the storage/treatment plant. This is accomplished by altering the pollutant fractions associated with the various size/specific gravity or settling velocity ranges as they pass through the units. The initial pollutant distributions are entered on the E6 groups. These distributions remain constant, however, at the input to the S/T plant.

The results of a literature review to characterize the pollutants in sanitary sewage, combined sewer overflows, and urban runoff by particle size and specific gravity are shown in Table 7-2. The data presented in the table are not default values and are presented only as a guide in setting up data groups E2 through E6. Local data, through sieve and/or settling column analyses, are always to be preferred.

Data Group E3 --

Data group E3 is used to enter particle size (if NVS = 0, data group E2) or settling velocity (if NVS = 1, data group E2) ranges. A maximum of ten ranges (as indicated by NNR, data group E2) may be entered. The variables RAN(1,1) and RAN(1,2) through RAN(NNR,1) and RAN(NNR,3) represent the lower and upper bounds of the diameters of settling velocities of particles found in ranges 1 through NNR. The ranges entered in this data group remain constant through a simulation. When NVS = 0 (data group E2), corresponding constant values of specific gravity are read on data group E4.

Data Group E4 --

This group is required only if NVS = 0 (data group E2). The variables SPG(1) through SPG(NNR) represent the specific gravity of the particles found in size ranges 1 through NNR(data group E2). Literature values are shown in Table 7-2.

Data Group E5 --

This group is required only if NVS = 0 (data group E2). The variables TEMP(1) through TEMP(12) represent the average wastewater temperatures for each month of the year. Water temperature has a direct effect on the settling velocity of a particle. This is reflected through the viscosity of the wastewater which is a function of temperature. Refer to Appendix IV for details.

Table 7-2. Particle Size Distributions.

SANITARY SEWAGE[a]

Percent Weighted in Each Size Range

Particle Size, Microns	Total Solids (1)	(2)	(3)	(4)	(5)	Volatile Solids (1)	(2)	(3)	(4)	(5)	Organic Nitrogen (6)	(3)	(7)	Total P (4)
< 0.001	69	68	64	64	64	50	42	41	31	46	53	22	37	68
0.001-1	6	6	7	7	7	9	9	10	14	11		11	20	9
1-100	11	11	11	12	29	18	18	19	24	43	47	34	20	15
> 100	14	15	18	17		23	25	30	31			33	23	8

Specific gravity: Suspended solids, 0.80-1.60(6); Settleable Solids, excluding grit, 1.05-1.20(11); Grit, 2.65(11)

COMBINED SEWAGE[a]

Particle Size, Microns	Percent Weight in Each Size Range: Suspended Solids (8)
< 74	48
74-295	22
295-991	16
991-3327	9
> 3327	5

Specific gravity: Suspended solids, 0.80-2.60(10); Settleable solids, excluding grit, 1.05-1.20(11); Grit, 2.65(11)

STORMWATER RUNOFF (STREET CONTAMINANTS)[a]

Particle Size, Microns	Percent Weight in Each Size Range: Suspended Solids (9)
< 43	14
43-104	11
104-246	18
246-840	22
840-2000	14
> 2000	21

Specific gravity: Same as reported by reference 11 for combined sewage.

[a]Numbers in parentheses refer to the literature cited below:

(1) Rickert and Hunter, 1967
(2) Rickert and Hunter, 1971
(3) Hunter and Heulekekian, 1965
(4) Heulekekian and Balmat, 1959
(5) Metcalf and Eddy, Inc., 1972
(6) Helfgott et al., 1970
(7) Painter and Viney, 1959
(8) Envirogenics Co., 1970
(9) Sartor and Boyd, 1972
(10) Dalrymple et al., 1975
(11) Sullivan et al., 1974

Data Group E6 --

An E6 data group is required for each pollutant characterized by a particle size/specific gravity or settling velocity distribution (IPART(IP) = 1, data group E1). For example, if IPART(1) = 1(data group E1) the variables PSD(1,1) through PSD(1,NNR) represent the fraction of pollutant 1 found in the particle size/specific gravity or settling velocity ranges 1 through NNR entering unit 1 (all flows and pollutants must enter the S/T plant at unit 1). Naturally, these fractions should sum to 1.0. Table 7-2 contains some literature values for several pollutants (particle size/specific gravity distributions only).

The distribution entering the S/T plant remains constant throughout the simulation; however, it may change as the pollutants move through the various units. This is an approximation of the more probable situation in which the plant influent distributions change with time. This limitation was necessary due to the fact that no other SWMM blocks generate such distributions for input to the S/T Block. However, the S/T Block can be easily modified to accept time-varying distributions should such a capability be developed in the future.

STORAGE/TREATMENT UNIT INFORMATION

Numbering

Data groups F1 through I1 are repeated for each storage/treatment unit (up to NU, data group B1). The unit number, I, is determined by the order in which each set of data groups F1 through I1 appears. This numbering scheme is important to the permissible configurations of units. There are two rules for numbering units; 1) flows and pollutants exiting from one unit must be directed to a unit with a number greater than its own; and 2) all flows and pollutants entering the S/T system must enter unit 1. The flows entering and exiting a unit are shown in Figure 7-2. Several examples of storage/treatment plant configurations are shown in Figure 7-3.

General Unit Information

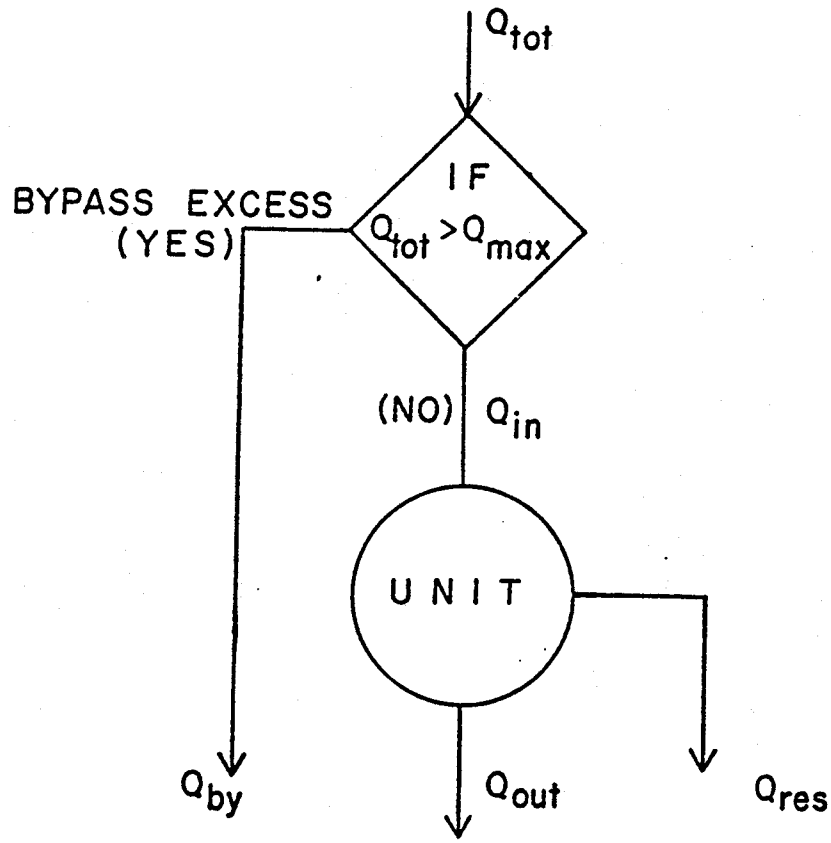
Data Group F1 --

This data group is used to enter the name of unit I.

Data Group F2 --

The variable IDENT(I) describes the unit I as a non-detention (IDENT(1) = 0) or detention process (IDENT(I) = 1). If IDENT(I) = 1, all or portions of data group H must be included.

Each unit is assigned a maximum inflow, QMAX(I), beyond which all flows and pollutants are bypassed. However, this variable may be set to an abnormally high value for design purposes (i.e., responses at all possible inputs) or set at a realistic value for modeling existing or proposed facilities. The



LEGEND

Q_{tot} = TOTAL INFLOW, ft^3/sec

Q_{max} = MAXIMUM ALLOWABLE INFLOW, ft^3/sec

Q_{by} = BYPASSED FLOW, ft^3/sec

Q_{in} = DIRECT INFLOW TO UNIT, ft^3/sec

Q_{out} = TREATED OUTFLOW, ft^3/sec

Q_{res} = RESIDUAL STREAM, ft^3/sec

Figure 7-2. Flows Into, Through, and Out of a Storage/Treatment Unit.

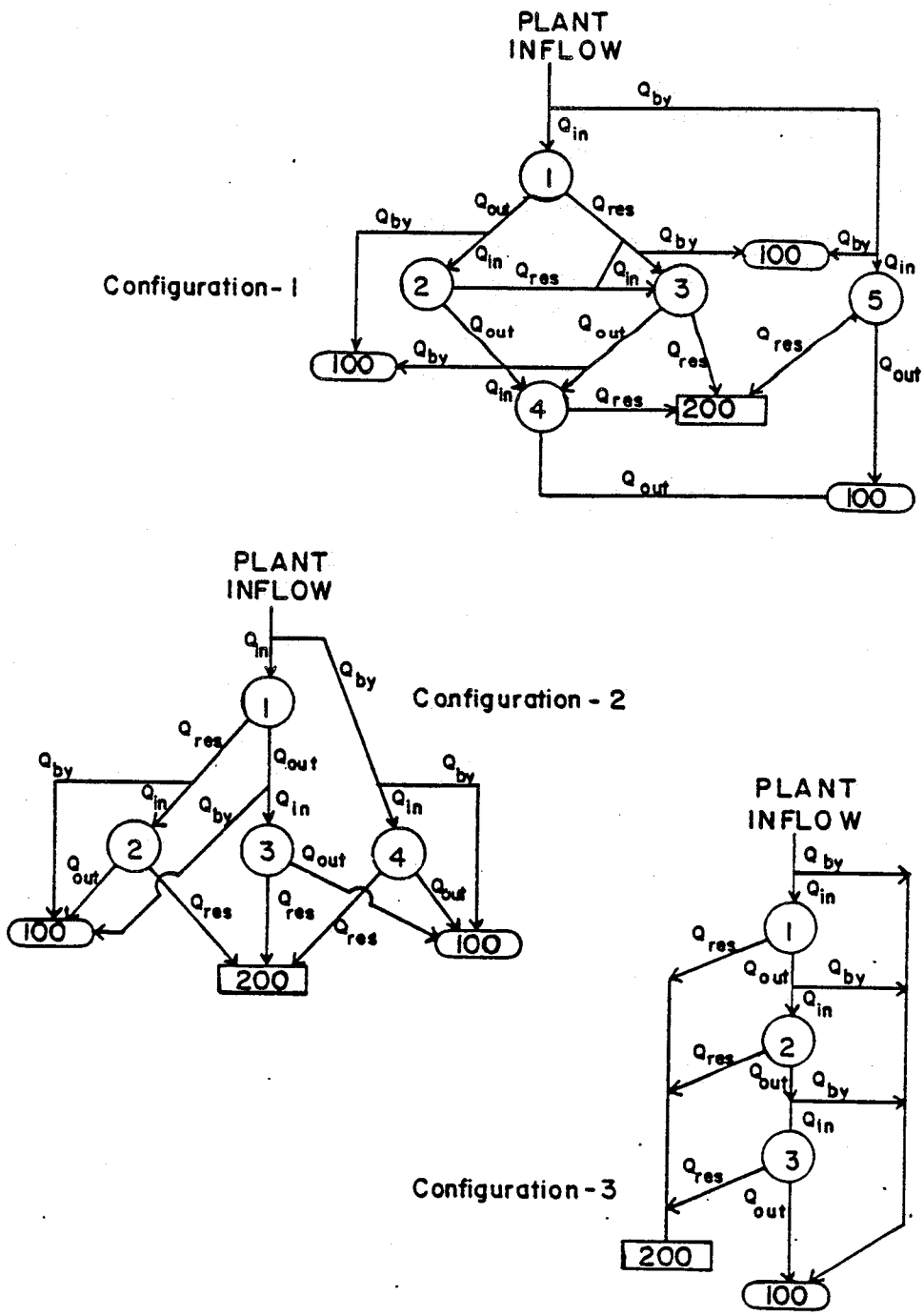


Figure 7-3. Storage/Treatment Plant Configurations.

variable QRF(I) is used to specify the residual flow, as a fraction of the inflow, for non-detention units only (IDENT(I) = 0).

The variables IDIREC(I,1), IDIREC(I,2) and IDIREC(I,3) are used to direct bypassed flow and pollutants, treated outflow, and residuals from unit I to other units. The values entered for these variables represent the unit numbers to which these flows and pollutants are to be directed. Additionally, these flows may be sent directly a downstream block or to ultimate disposal (which simply removes them from the simulation) by specifying IDIREC(I,ID) = 100 or 200, respectively. The flows and pollutants directed to the next block are summed for all the units and transferred as a single stream. Any unit to which flows are directed must have a unit number greater than the source unit (see Figure 7-3 for examples).

Pollutant Removal

Options --

Pollutants are removed by settling or obstruction when characterized by particle size/specific gravity or settling velocity distributions. When they are characterized by magnitude (concentration) alone, removal is simulated through removal equations. Data groups G1 through G3 are used to establish these removal equations. When a particle size/specific gravity or settling velocity distribution is used and the unit is classified as a non-detention process, then a critical size or settling velocity is selected. The model removes all particles with a size or settling velocity greater than or equal to the critical size. Data group G4 is used to enter this parameter.

Data groups G1 through G4 are repeated for each pollutant unless a detention unit is specified (IDENT(1) = 1, data group F2) and a particle size/specific gravity or settling velocity distribution is specified for pollutant IP (IPART(IP) = 1, data group E1). Naturally, these data groups are omitted if no pollutants are routed (NP = 0, data group B1). Again, data groups G1 through G3 are used only if the pollutant is characterized solely by magnitude. Data group G4 is used only if a pollutant is characterized by magnitude and a particle size/specific gravity or settling velocity distribution (IPART(IP) = 1, data group E1) and a non-detention unit is specified (IDENT(I) = 0, data group F2).

Data Group G1 --

A single flexible functional form is available for use as a pollutant removal equation (see Appendix IV):

$$R = \left(a_{12} e^{a_1 x_1} x_2^{a_2} + a_{13} e^{a_3 x_3} x_4^{a_4} + a_{14} e^{a_5 x_5} x_6^{a_6} + a_{15} e^{(a_7 x_7 + a_8 x_8)} x_9^{a_9} x_{10}^{a_{10}} x_{11}^{a_{11}} \right)^{a_{16}} \qquad (7\text{-}1)$$

where x_i = removal equation variables,

a_j = coefficients, and
R = removal fraction, $0 \leq R \leq 1.0$.

Each removal equation variable, x_i, may represent, one of several parameters available in the program at each time step; these options are discussed below (data group G2). With these variables and the coefficients, a_i, the user can develop the desired removal equation. The coefficients are entered on data group G3.

A maximum removal fraction is specified by RMX(I,IP). This is particularly useful for equations which mathematically generate values of the removal fraction, R, that may exceed a reasonable value or 1.0. RMX(I,IP) provides an upper bound on such equations.

Data Group G2 --

Data group G2 allows the user to assign various program variables to the variables in equation 7-1. For example, if pollutant 1 (IP = 1) is to be removed in unit I by a removal equation, the values given INPUT(I,1,1) through INPUT(I,1,11) assign program variables to the corresponding variables x_1 through x_{11} in equation 7-1. The program variables available for inclusion are shown in Table 7-3. An example removal equation is discussed below.

Data Group G3 --

The variables A(I,IP,1) through A(I,IP,16) represent the variables a_1 through a_{16} in equation 7-1 as applied to pollutant IP in unit I.

An example of applying equation 7-1 is provided by a suspended solids removal equation used in an earlier version of the Storage/Treatment Block for sedimentation (detention) units:

$$R_{SS} = R_{max} (1 - e^{-kt_d}) \tag{7-2}$$

where R_{SS} = suspended solids removal fraction, $0 \leq R_{SS} \leq R_{max}$,
R_{max} = maximum removal fraction,
t_d = detention time, seconds, and
k = first order decay coefficient, 1/sec.

This equation can be constructed from equation 7-1 by setting a_{12} (or A(I,IP,12)) = R_{max}, a_{13} (or A(I,IP,13)) = $-R_{max}$, a_3 (or A(I,IP,3)) = -k, a_{16} (or A(I,IP,16)) = 1.0, and letting x_3 = detention time, t_d, by setting INPUT(I,IP,3) = 1 (data group G2). All other coefficients, a_j (or A(I,IP,J)), would equal zero. RMX(I,IP) (data group G1) would not be necessary, as R_{max} limits the value of R. Appendix IV contains other examples.

Data Group G4 --

The variable PSC(I) specifies a critical particle size (if NVS = 0, data group E2) or settling velocity (if NVS = 1, data group E2) that denotes the point above which all particles are removed from the influent. This parameter

Table 7-3. Program Variables Available for Pollutant Removal Equations

Value of INPUT(I,IP,K)[a] (G2 cards)	Non-Detention Units, IDENT(I) = 0 (card F2)	Detention Units, IDENT(I) = 1 (card F2)	
		Perfect plug flow is used, to route pollutants, IROUTE(I)=0 (card I2)	Complete mixing is used to route pollutants, IROUTE(I) = 1 (card I2)
0	Not used.	Not used.	Not used.
1	Not used.	Detention time of each plug in detention unit I, seconds.	Time step size, seconds.
2	Concentration of pollutant 1 passing through unit I.[b]	Initial concentration of pollutant 1 in each plug in detention unit I.[b]	Not used.
3	Concentration of pollutant 2 passing through unit I.[b]	Initial concentration of pollutant 2 in each plug in detention unit I.[b]	Not used.
4	Concentration of pollutant 3 passing through unit I.[b]	Initial concentration of pollutant 3 in each plug in detention unit I.[b]	Not used.
5	Removal fraction of pollutant 1 in unit I (used only for pollutants 2 and 3).	Removal fraction of pollutant 1 for each plug in detention unit I (used only for pollutants 2 and 3).	Removal fraction of pollutant 1 in detention unit I (used only for pollutants 2 and 3).
6	Removal fraction of pollutant 2 in unit I (used only for pollutant 3).	Removal fraction of pollutant 2 for each plug in detention unit I (used only for pollutant 3).	Removal fraction of pollutant 1 in detention unit I (used only for pollutant 3).
7	Inflow rate, ft^3/sec [m^3/sec].	Not used.	Not used.

[a] I = unit number.
IP = pollutant number.
K = Subscript of x in equations 7-1.

[b] Dimensions determined by NDIM(IP) on card E1.

is included primarily to model such non-detention units as microscreens, fine screens, and coarse screens. An approximation of the removal effectiveness of screens may be obtained by letting PSC(I) equal the aperture size of the screen (see Appendix IV). Data group G4 is required only if IPART(IP) = 1 (data line E1) and IDENT(I) = 0 (data line F2).

Detention Unit Data

Options --

Data groups H1 through H8 are used to describe the special characteristics of detention units. Sedimentation, dissolved air flotation, chlorination, and sludge thickening are some of the processes that may be modeled by a detention unit.

These groups primarily describe the hydraulic characteristics of a detention unit and, thus, are required only if IDENT(I) = 1 (data group F2).

Data Group H1 --

The variable IROUTE(I) specifies the manner in which pollutants are routed in detention unit I. When IROUTE(I) = 0 the unit routes pollutants under the assumption of perfect plug flow. Perfect plug flow is recommended for long, rectangular tanks where settling is the most important removal mechanism and is required when any pollutant is characterized by a particle size/specific gravity or settling velocity distribution (IPART(IP) = 1, data group E1). Removed pollutants are accumulated in plug-flow units, without decay, until removed by the residual flow. When IROUTE(I) = 1 the unit routes pollutants under the assumption of perfect mixing. Complete mixing is most applicable to small tanks where the primary purpose is to thoroughly mix the contents (e.g., rapid-mix chlorination, flocculators, and mixing tanks). Removed pollutant quantities are not allowed to accumulate in completely-mixed units (i.e., no settling). Appendix IV provides further explanation.

The variable IOUT(I) is used to describe the depth-treated outflow relationship that characterizes the discharge of treated outflow (e.g., weir flow) from unit I. There are three options. The first (IOUT(I) = 0) is to provide the model with as many as 16 data pairs describing the depth-outflow relationship (entered in data group I3). The second option (IOUT(I) = 1) is to approximate the relationship by a power equation (entered in data group H4). The third option (IOUT(I) = 2) specifies a constant pumping rate between certain depths (entered in data group H5).

In addition to treated outflow, a residual stream may be drawn from the unit during periods of no inflow or treated outflow. When a residual stream occurs from a plug-flow unit the entire unit contents (including the removed pollutant quantities) are mixed (i.e., the remaining plugs lose their identity) and drawn off until the unit is empty or inflow occurs. If inflow begins before the unit is empty the remaining contents are placed in a single plug for further routing. In a completely-mixed unit, the pollutant concentrations in the residual flow are identical to the concentrations in the treated outflow. Again, the flow is suspended when inflow occurs. The vari-

able IDRAW(I) simply specifies the conditions under which a residual stream begins. If IDRAW(I) = 0, a residual stream is never drawn and the accumulated pollutants (if IROUTE(I) = 0) remain in the unit. If IDRAW(I) $\leq$ -1, the residuals are drawn off starting at every -IDRAW(I) time steps (but the flow is delayed if inflow and/or treated outflow is in progress). This option corresponds with the situation in which the unit is drained on a regular (e.g., scheduled) basis. If IDRAW(I) $\geq$ 1, the residuals are drawn after IDRAW(I) time steps of no inflows or treated outflow. The conditions specified by IDRAW(I) $\geq$ 1 apply directly to the case in which the unit contents are drained after each runoff event.

The variable IRES(I) is used to describe the depth-residual flow relationship that characterizes the draw-off of the residual stream from unit I. If IRES(I) = 0, the user provide the model with as many as 16 data pairs describing the depth-residual flow relationship (entered on the H3 groups). If IRES(I) = 1, the relationship is approximated by a power equation (entered in data group H6).

Data Group H2 --

The parameters in this data group are required <u>only</u> when a particle size/specific gravity or settling velocity distribution is used to characterize <u>any</u> pollutant (IPART(IP) = 1, data group E1) and unit I is a plug-flow detention unit (IROUTE(I) = 0, data group H1).

The variable ALEN(I) represents the travel length for plugs in unit I. The variable AMAN(I) is the Manning's roughness coefficient for the surfaces of unit I and is commonly available for many materials. These values are required for the pollutant removal algorithms used when a particle size/specific gravity or settling velocity distribution characterizes a pollutant (see later).

Data Group H3 --

These groups are used to enter up to 16 sets of data describing the geometry and hydraulics of detention unit I. Each data group enters a value for depth, SDEPTH(I,MM), along with the corresponding values of surface area, SAREA(I,MM), volume, SSTORE(I,MM), treated outflow, SQQOU(I,MM), and residual flow, SQQRS(I,MM).

The only required parameters are DEPTH(I,MM) and SAREA(I,MM); the need for the other parameters depends on other factors. If SSTORE(I,MM) is left blank in <u>every</u> H3 data group, the program will estimate the volume at each depth by averaging the surface area at each depth and the lower adjacent depth, multiplying by the difference in depth, and adding the result to the estimated volume at the lower adjacent depth (i.e., by a trapezoidal rule integration). A value for treated outflow, SQQOU(I,MM), is required for each depth only if IOUT(I) = 0 (data group H1). If IOUT = 1 or 2 (data group H1), this relationship is provided by data group H4 or data group H5, respectively. Likewise, a value for residual flow, SQQRS(I,MM), is required for each depth only if IRES(I) = 0 (data group H1). If IRES(I) = 1 (data group H1), this relationship is described by data group H6. The values entered for

SQQRS(I,MM) are used during periods in which a residual stream is drawn from the unit (IDRAW(I), data group I1).

The values specified on these groups (or computed as a result of groups H4, H5, and H6) are used to establish relationships between depth, surface area, volume, treated outflow, and residual flow. The program also generates a relationship between depth and the evaporation rate (see data group D1). These relationships are used to route flows through a detention unit using the Puls method (Viessman et al., 1977). This method is described in detail in Appendix IV.

Data Group H4 --

This data group is required only if a power equation is to describe the depth-treated outflow relationship (IOUT(I) = 1, data group H1). The equation is:

$$Q_{out} = C_1(D - D_0)^{C_2} \tag{7-3}$$

where Q_{out} = treated outflow, ft^3/sec [m^3/sec],
C_1, C_2 = coefficients,
D = water depth in detention unit, ft [m], and
D_0 = depth below which there is no treated outflow, ft [m].

The user supplies the values of D_0, C_1, and C_2 (program variables DO, C1, and C2, respectively).

Two common outlet structures that may be modeled with equation 7-3 are the orifice and the broad-crested weir. For example, a weir could be modeled by letting $C_1 = 3.33 \cdot L$ where L = length of the weir in feet, $C_2 = 1.5$, and D_0 = depth at the bottom of the weir in feet. These substitutions yield the familiar weir equation.

Data Group H5 --

This data group is required only if pumping is specified for the treated outflow from a detention unit (IOUT(I) = 2, data group H1). The variables DSTART(I,1) and DSTART(I,2) represent the depths at which the pumping rates QPUMP(I,1) and QPUMP(I,2) begin. The variable DSTOP(I) specifies the depth at which all pumping stops. In other words, the rate QPUMP(I,1) occurs when the depth is equal to or exceeds DSTART(I,1) and the rate QPUMP(I,2) occurs when the depth is greater than or equal to DSTART(I,2). The pumping rate reverts to the rate QPUMP(I,1) when the depth falls below DSTART(I,2) and continues at that rate until the depth falls to DSTOP(I). The value of DSTART(I,1) must be less than or equal to DSTART(I,2) and DSTOP(I) must be less than or equal to DSTART(I,1).

Data Group H6 --

This data group is required only if a power equation is used to describe the depth-residual flow relationship (IRES(I) = 1, data group H1). The equa-

tion is:

$$Q_{res} = C_3(D - D_1)^{C_4} \tag{7-4}$$

where Q_{res} = residual flow, ft^3/sec [m^3/sec],
C_3, C_4 = coefficients,
D = water depth in detention unit, ft [m], and
D_1 = depth below which there is no residual flow, ft [m].

The user supplies the values of D_1, C_3, and C_4 (program variables D1, C3, and C4, respectively). Recall that a residual flow occurs only when dictated by IDRAW(I) (data group H1).

Data Group H7 --

This data group is used to indicate the build up of sludge in a plug-flow detention unit (IROUTE(I) = 0, data group H1). The user specifies the pollutant used to calculate the sludge volume, NPSL(I); the concentration of pollutant NPSL(I) in sludge has accumulated to an unacceptable level. The sludge volume is increased by dividing the amount of pollutant NPSL(I) removed each time step by SLDEN(I). The model assumes that the sludge volume has no effect on the available storage volume and that no compression occurs. The information on this data group is only used to warn the user of possible maintenance/performance problem.

Data Group H8 --

This data group specifies the total volume, WARN(I), and pollutant concentrations, PCO(I,IP), present in the unit at the start of the simulation. Obviously, the values of PCO(I,IP) are not required if NP = 0 (data group B1) or WARN(I) = 0.0.

Cost Data

Data Group I1 --

This data group is required only if ICOST = 1 (data group B1).

The capital cost for each unit is computed as a function of a design flow or volume specified by the user or is calculated by the model as a function of the maximum value recorded during the simulation:

$$C_{cap} = a\ Q^b_{max} \tag{7-5}$$

or

$$C_{cap} = a(Q_{in})^b_{max} \tag{7-6}$$

or

$$C_{cap} = a\ V^b_{max} \tag{7-7}$$

or

$$C_{cap} = a(V_{obs})^b_{max} \tag{7-8}$$

where C_{cap} = initial capital cost, dollars,

Q_{max} = maximum allowable inflow, ft^3/sec [m^3/sec],
$(Q_{in})_{max}$ = maximum inflow encountered during the simulation, ft^3/sec [m^3/sec],
V_{max} = maximum allowable storage (detention units only), ft^3 [m^3],
$(V_{obs})_{max}$ = maximum storage encountered during the simulation (detention units only), ft^3 [m^3], and
a, b = coefficients (specified by the user).

Equations 7-5 through 7-8 differ only in the variable used to compute the initial capital cost of unit I. The variable KPC(I,1) specifies which variable is used (as shown in Table 7-4) and CC(I,1) and CC(I,2) represent the coefficients a and b.

The operation and maintenance costs are calculated as a function of the variables listed above and the total operating time (calculated as the number of time steps with flow to or from the unit).

$$C_{om} = d\ Q^f_{max} + hD_{op} \tag{7-9}$$

or

$$C_{om} = d(Q_{in})^f_{max} + hD_{op} \tag{7-10}$$

or

$$C_{om} = d\ V^f_{max} + hD_{op} \tag{7-11}$$

or

$$C_{om} = d(V_{obs})^f_{max} + hD_{op} \tag{7-12}$$

where C_{om} = operation and maintenance cost, dollars,
D_{op} = total operating time during the simulation period, hours, and
d, f, h = coefficients (supplied by the user).

Equations 7-9 through 7-12 differ only in the variable used to compute the operation and maintenance costs for unit I. The variable KPC(I,2) specifies which variable is used and CC(I,3), CC(I,4), and CC(I,5) represent the coefficients d, f, and h.

The user is cautioned not to misinterpret the cost calculated by the model. For example, in a single-event simulation the calculated capital cost can only be considered an estimator of the true capital cost when the simulated event is a design event. Likewise, when operating time is a factor in computing operation and maintenance costs, the calculated costs can be a valid estimator of the true costs only when a long-term simulation is performed. Recent EPA publications provide useful information for the proper selection of the coefficients required in equations 7-5 through 7-12 (EPA, 1976; Benjes, 1976).

INPUT FLOW AND POLLUTANT DATA (GROUP J1)

If NOTAPE = 1 or 2 (data group B1), user-supplied time series input of hydrographs and pollutographs are input in data group J1. The input is in the form of time-flow-concentration(s). Linear interpolation is used to provide intermediate input values if the S/T time step (DS) is not the same as the

time interval used in data group J1. (A similar interpolation scheme is used for time series entry from an upstream block via the interface file.) Of course, since linear interpolation is used, the time interval for data input need not be constant. A step function input can be achieved by inputting two flow-concentration values at each time. For instance, assuming DS = 1 hr, the simulation begins at 8:00 a.m., and their are no pollutants, the following J1 entries would result in constant inflows of 5, 8 and 9 cfs over the first three time steps:

```
*  TCAR   QCAR
J1  8.0    5.0
J1  9.0    5.0
J1  9.0    8.0
J1 10.0    8.0
J1 10.0    9.0
J1 11.0    9.0
etc.
```

Pollutant concentration time series are entered only if NP > 0 (data group B1). The pollutant concentrations, PCAR(IP), must be entered in the same order as in data group E1 and have the same dimensions specified by NDIM(IP) and PUNIT(IN,IP) (data group E1). If NOTAPE = 2 (data group B1), the flow and concentrations are added to the values from the external file. All values are instantaneous flows or concentrations (at the end of the time step).

OUTPUT

Summary and detailed (time step) output is available for each of up to five units depending on the parameters of data groups C1 and C2. Output may be graphed using the Graph Block only for location 100 (outflow to downstream block), using the interface file. If more than one input location is found on the input interface file, the unaltered time series for these locations will be placed on the output interface file along with that predicted for location 100.

Table 7-4. Storage/Treatment Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

   a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

   b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Title: two lines with heading to be printed on output.	
A1	Group identifier	None
TITLE2	Title	Blank
	General Data	
B1	Group identifier	None
NOTAPE	Input data source = 0, Input is from an external input file = 1, Input is supplied in Group J1 = 2, Input is from an external input file and Group J1	0
JNS	External element number from the external block (e.g., JN, Group H1, in Transport Block) which routes flow to the S/T Block. If NOTAPE = 1, the value of JNS is placed on the output file.	None
NDT	Total number of simulation time steps	0
DS	Size of time step, seconds. Required only if NOTAPE = 1	None
NU	Number of storage/treatment units. (Maximum = 5)	1
NP	Number of pollutants routed. (Maximum = 3)	0
ICOST	Cost calculations performed? = 0, No = 1, Yes	0

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
METRIC	Metric input-output. = 0, Use U.S. customary units = 1, Use metric units. Metric input indicated in brackets [ ].	0
SAREA	Service area, acres [ha]. Required if NOTAPE = 1.	0.0
	Starting Time and Print Instructions	
C1	Group identifier	None
IDATE	Date at beginning of simulation (6 digit number; year, month, day -- e.g. March 10, 1979 = 790310)	0
TIME	Time at beginning of simulation (24 hour clock, e.g., 5:30 p.m. = 17.5)	0
ISUM	Summary print control parameter = 0, Print a summary at the end of the simulation only = 1, Print an annual summary and a summary at the end of the simulation = 2, Print monthly and annual summaries and a summary at the end of the simulation	0
IDET	Detailed print control parameter = 0, No detailed print of simulation results. > 0, Detailed print of results is provided at every time step that is a multiple of IDET (e.g., IDET = 2, gives a detailed report at every other time step) during specified periods (see below and group C2).	0
NPR	Number of detailed print periods. Up to 8 periods may be specified (See Group C2). Required only if IDET > 0.	0

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Detailed Print Periods	
	NPR (Group C1) periods must be specified. Only date to date periods may be used (e.g., 790720 to 790806). Required only if IDET > 0 (Group C1).	
C2	Group identifier	None
ISTART(1)	First detailed print period starting date (e.g., July 20, 1979 = 790720).	None
IEND(1)	First detailed print period ending date (e.g., August 6, 1979 = 790806).	None
.	.	
.	Repeat for second period, etc. up to NPR Group C1 periods - place all ISTART and IEND pairs on a single line.	
.	.	
ISTART(NPR)	Last detailed print period starting date.	
IEND(NPR)	Last detailed print period ending date.	None
	Evaporation Data	
	Evaporation data. Required only if there are detention units. (IDENT(I) = 1 for some units, see Group F2).	
D1	Group identifier	None
E(1)	Evaporation rate, January in./day [mm/day]	0.0
.	.	
.	.	
E(12)	Evaporation rate, December in./day [mm/day]	0.0

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Groups E1 - E6: Pollutant Characterization	
	REQUIRE GROUPS E1 - E6 ONLY IF NP > 0 (GROUP B1)	
	General Pollutant Characteristics	
E1	Group identifier	None
IPOLL(1)	Pollutant 1 selector. Required only if NOTAPE = 0 or 2 (Group B1). The value selected depends on the order in which the pollutants were placed on the external input file. For example, if suspended solids was the third pollutant listed on the file and it was desired for use in the S/T block, then IPOLL(1) = 3.	None
NDIMI(1)	Dimensions for pollutant 1. Required only if NOTAPE = 1 (Group B) = 0, Dimensions are mg/l = 1, Dimensions are liter (-1) = 2, Other concentration dimensions are used. (e.g., JTU, deg. C. pH)	0
IPART(1)	Particle size/specific gravity or settling velocity distribution parameter = 0, Distribution not used to characterize pollutant 1. = 1, Distribution used to characterize pollutant 1	0
PNAME1(IN,1)	Pollutant 1 name. Required only if NOTAPE = 1 (Group B1)	None
PUNIT1(IN,1)	Pollutant 1 dimension label. Required only if NOTAPE = 1 (Group B1)	None
IPOLL(2)	Pollutant 2 selector. Required only if NP $\geq$ 2 and NOTAPE = 0 or 2 (Group B1). See above.	None
NDIMI(2)	Dimensions for pollutant 2. Required only if NP $\geq$ 2 and NOTAPE = 1 (Group B1). See above.	0

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
IPART(2)	Particle size/specific gravity or settling velocity distribution parameter. Required only if NP $\geq$ 2 (Group B1) See above.	0
PNAMEI(IN,2)	Pollutant 2 name. Required only if NP $\geq$ 2 and NOTAPE = 1. (Group B1)	0
PUNITI(IN,2)	Pollutant 2 dimension label. Required only if NP $\geq$ 2 and NOTAPE = 1. (Group B1)	None
IPOLL(3)	Pollutant 3 selector. Required only if NP = 3 and NOTAPE = 0 or 2 (Group B1) See above.	0
NDIMI(3)	Dimensions for pollutant 3. Required only if NP = 3 and NOTAPE = 1 (Group B1). See above.	0
IPART(3)	Particle size/specific gravity or settling velocity distribution parameter. Required only if NP = 3. (Group B1). See above.	0
PNAMEI(IN,3)	Pollutant 3 name. Required only if NP = 3 and NOTAPE = 1 (Group B1)	None
PUNITI(IN,3)	Pollutant 3 dimension label. Required only if NP = 3 and NOTAPE = 1 (Group B1)	None
	GROUPS E2 - E6 ARE REQUIRED ONLY IF IPART (IP) = 1 (GROUP E1) FOR ANY POLLUTANTS.	
E2	Group identifier	None
NVS	Classification parameter = 0, Particle size/specific gravity distribution is used to classify particles in waste stream. = 1, Settling velocity distribution is used	0
NNR	Number of particle size ranges or settling velocities used to classify particles in waste stream (Max of 10).	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Particle size (if NVS = 0, group E20 or settling velocity (if NVS = 1, group E2) range data.	
E3	Group identifier	None
RAN(1,1)	Lower bound of size or velocity range 1, microns or ft/sec [cm/sec]	None
RAN(1,2)	Upper bound of size or velocity range 1, microns or ft/sec [cm/sec]	None
RAN(2,1)	Lower bound of size or velocity range 2, microns or ft/sec [cm/sec]	None
RAN(2,2)	Upper bound of size or velocity range 2, microns or ft/sec [cm/sec]	None
. . .	. . .	
	Repeat for each size or velocity range, up to NNR (Group E2) ranges.	
	Specific gravity data.	
	Required only if NVS = 0 (Group E2).	
E4	Group identifier	None
SPG(1)	Specific gravity for particles in size range 1.	None
SPG(2)	Specific gravity for particles in size range 2.	None
. . .	. . .	
	Repeat for each size range, up to NNR (Group E2) ranges.	

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Waste Stream Temperature Data	
	* * * Required only if NVS = 0 (Group E2). * * *	
E5	Group identifier	None
TEMP(1)	Waste stream temperature, January °F. [°C]	None
. . .	. . .	
TEMP(12)	Waste stream temperature, December °F. [°C]	None
	Fraction of pollutant associated with each particle size/specific gravity or settling velocity range (Group E3). Repeat these lines for each pollutant for which IPART(IP) = 1 (Group E1).	
E6	Group identifier	None
PSD(IP<1)	Fraction of pollutant IP in range 1.	None
PSD(IP,2)	Fraction of pollutant IP in range 2.	None
. . .	. . .	
	Repeat for each range up to NNR (Group E2) ranges.	
	REPEAT GROUPS F1 - I1 FOR EACH UNIT I. THERE WILL BE NU (GROUP B1) SETS. THE UNIT NUMBER IS DICTATED BY THE ORDER IN WHICH THE SETS OF GROUPS F1 - I1 ARE READ.	
	Unit Name	
F1	Group identifier	None
UNAME(I,ID)	Name of unit	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	General Unit Parameters and Flow Directions	
F2	Group identifier	None
IDENT(1)	Detention modeling parameter = 0, Unit is the non-detention type = 1, Unit is the detention type	0
QMAX(I)	Maximum inflow (above which bypass occurs), cfs [cu.m/sec].	None
QRF(I)	Residual flow as a fraction of the inflow. Required only if IDENT(I) = 0. Residual flows for detention units (IDENT(I) = 1) are determined in Groups H1, H3, and H6.	None
IDIREC(I,1)	Unit number to which bypass is directed (must be greater than 1) = 1 - 5, Downstream S/T unit = 100, Next block = 200, Ultimate disposal	None
IDIREC(I,2)	Unit number to which treated outflow is directed (must be greater than 1). See above.	None
IDIREC(I,3)	Unit number to which residuals stream is directed (Must be greater than 1). See above. If IDRAW(I) = 0 (Group H1), set equal to any number > 1.	None
	Data Groups G1 - G4: Pollutant Removal REQUIRED ONLY IF NP > 0 (GROUP B1) REPEAT GROUPS G1 - G3 FOR EACH POLLUTANT FOR WHICH IPART(IP) = 0	
G1	Group identifier	None
RMX(I,IP)	Maximum removal fraction ($\leq$ 1.0)	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Removal Equation Variable Group (Equation 7-1)	
	Requires two input lines.	
G2	Group identifier	None
INPUT(I,IP,1)	Program variable for equation variable x_1. = 0, Not used. For values = 1 - 7, see Table 7-3 in text.	0
INPUT(I,IP,2)	Program variable for equation variable x_2. See above.	0
. . .	. . .	
	Repeat for each program variable x_i.	
	Equation 7-1 Coefficients	
	The coefficients must be consistent with the units used (see METRIC Group B1).	
G3	Group identifier	None
A(I,IP,1)	Value of coefficient a_1	0.0
A(I,IP,2)	Value of coefficient a_2	0.0
. . .	. . .	
	Repeat for each coefficient a_j.	
	Critical Particle Size or Settling Velocity	
	Required only if IPART(IP) = 1 (Group E1) for <u>any</u> pollutant and unit I is a non-detention unit, IDENT(I) = 0 (Group F2)	
G4	Group identifier	None
PSC(I)	Critical particle size, microns, (if NVS = 0, Group E2) or settling velocity, ft/sec [cm/sec], (if NVS = 1, Group E2)	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Data Groups H1 - H8: Detention Unit Data	
	Required only if IDENT(I) = 1 (Group F2)	
	General Detention Unit Parameters	
H1	Group identifier	None
IROUTE(I)	Pollutant routing parameter = 0, Plug flow mode is used. = 1, Complete mixing mode is used. (Note: Particle size or settling velocity distribution are not routed through completely-mixed units.)	0
IOUT(I)	Treated outflow routing parameter = 0, The depth-treated outflow relationship is described by as many as 16 data pairs in Group H3. = 1, The depth-treated outflow relationship is described by a power equation in Group H4. = 2, The depth-treated outflow relationship is controlled by the pumps described in Group H5.	0
IDRAW(I)	Residuals stream draw-off scheme $\leq$ -1, A residual stream is drawn off starting at every -IDRAW(I) time step (if possible). = 0, Residuals are never drawn off. $\geq$ 1, A residuals stream (if available) is drawn off only after IDRAW(I) time steps of no inflow or treated outflow.	0
IRES(I)	Residual stream routing parameter Required only if IDRAW(I) not = 0 = 0, The depth-residual flow relationship is described by as many as 16 data pairs in Group H3. = 1, The depth-residual flow relationship is described by a power equation in Group H6.	0

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Detention unit (plug flow only) parameters, required when pollutants are characterized by a particle size/ specific gravity or settling velocity distribution. Thus, this line is required only if IPART(IP) = 1, for any pollutant (Group E1) and IROUTE(i) = 0 (Group E2)	
H2	Group identifier	None
ALEN(I)	Travel length for plug flow, ft [m]	0
AMAN(I)	Manning's roughness coefficent for detention unit surfaces.	None
	Data for Sets of Depth, Surface Area, Volume, Treated Outflow and Residual Flow Each line contains a column for a unit depth and the corresponding values of area, volume, treated outflow, and residual flow. The columns for treated outflow and residual flow may be left blank depending on the values of IOUT(I) and IRES(I) in Group H1. If no values for volume are entered, the program estimates volume from the depth-surface area relationship. Order the data from the bottom of the unit (SDEPTH(I,1) = 0.0) to the maximum depth (including freeboard). There may be as many as 16 lines.	
H3	Group identifier	None
SDEPTH(I,MM)	A unit depth, ft [m]	None
SAREA(I,MM)	Surface area corresponding to the above depth, sq. ft [sq. m]	None
SSTORE(I,MM)	Volume corresponding to the above depth cu. ft [cu. m]	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
SQQOU(I,MM)	Treated outflow at the above depth cfs [cu.m/sec]	None
SQQRS(I,MM)	Residuals stream flow at the above depth cfs [cu.m/sec]. Occurs only when IDRAW(I) (Group H1) permits.	None
	Depth vs. Treated Outflow Power Equation (Equation 7-3)	
	Required only if IOUT(I) = 1 (Group H1). Coefficients must be consistent with the units used. (See METRIC, Group B1.)	
H4	Group identifier	None
C1	Depth-treated outflow equation coefficient, C_1	0.0
DO	Depth below which no treated outflow occurs, D_0	0.0
C2	Depth-treated outflow equation coefficient, C_2	0.0
	Treated Outflow Pumping	
	Required only if IOUT(I) = 2 (Group H1)	
H5	Group identifier	None
DSTART(I,2)	Depth at which pumping rate QPUMP(I,1) begins, ft [m]	None
DSTART(I,2)	Depth at which pumping rate QPUMP(I,2) begins, ft [m]. Must be $\geq$ DSTART(I,1)	None
QPUMP(I,1)	Pumping rate when depth $\geq$ DSTART(I,1) cfs [cu.m/sec]	None
QPUMP(I,2)	Pumping rate when depth $\geq$ DSTART(I,2) cfs [cu.m/sec]	None
DSTOP(I)	Depth below which all pumping stops, ft [m]. Must be $\leq$ DSTART(I,1).	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Depth vs. Residual Flow Power Equation (Equation 7-4)	
	Required only if IRES(I) = 1 (Group H1). Coefficients must be consistent with the units used (see METRIC, Group B1).	
H6	Group identifier	None
C3	Depth-residual flow equation coefficient C_3	0.0
D1	Depth below which no residual flow occurs D_1	0.0
C4	Depth-residual flow equation coefficient C_4	0.0
	Sludge Generation in Unit I	
	Required only if I is a plug-flow detention unit (IROUTE(I) = 0, Group H1) and NP > 0 (Group B1).	
H7	Group identifier	None
NPSL(I)	Pollutant responsible for sludge generation. Required only if a sludge depth warning message is desired = 0, Not used. = 1, 2, or 3, Pollutant used to generate sludge volume (must correspond to the position in Group E1).	0
SLDEN(I)	Concentration of pollutant NPSL(I) in sludge. Required only if NPSL(I) $\geq$ 1 The dimensions used must be consistent with those indicated by NDIM(I) (Group E1).	None
SLDMAX(I)	Maximum sludge depth, ft [m] A warning message is printed if this depth is exceeded by the accumulated sludge. Required only if NPSL(I) $\geq$ 1.	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Initial Conditions in Detention Unit I	
H8	Group identifier	None
WARN(I)	Total volume of water in unit at the start of the simulation, cu.ft [cu.m]	0.0
	The following concentrations must be given with dimensions consistent with those entered in Group E1 (NDIM(IP)) if NOTAPE = 1 (Group B1) or on the external input file if NOTAPE = 2.	
PCO(I,1)	Concentration of pollutant 1 in the unit at the start of the simulation. Required only if NP $\geq$ 1 (Group B1) and WARN(I) > 0.0.	0.0
PCO(I,2)	Concentration of pollutant 2 in the unit volume at the start of the start of the simulation. Required only if NP $\geq$ 2 (Group B1) and WARN(I) > 0.0	0.0
PCO(I,3)	Concentration of pollutant 3 in the unit volume at the start of the start of the simulation. Required only if NP = 3 (Group B1) and WARN(I) > 0.0	0.0
	REQUIRED ONLY IF ICOST = 1 (GROUP B1)	
	Cost Data for Equations 7-5 to 7-8 (Capital Costs) and Equations 7-9 to 7-12 (Operation and Maintenance Costs)	
	The coefficients must be consistent with the units used (see METRIC, Group B1).	
I1	Group identifier	None

Table 7-4 (continued). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
KPC(I,1)	Type of cost variable used in calculating initial capital cost. = 0, Not used. = 1, Maximum allowable inflow, QMAX(I), cfs [cu.m/sec] is used. = 2, Maximum inflow observed during simulation, QMAXS(I), cfs [cu.m/sec], is used. = 3, Maximum allowable storage, VMAX(I) cu.ft [cu.m] is used. (Not applicable if IDENT(I) = 0, Group F2) = 4, Maximum storage observed during simulation, VMAXS(I), cu.ft. [cu.m] is used (Not applicable if IDENT(I) = 0 (Group F2)	0
CC(I,1)	Initial capital cost equation coefficient, a.	0.0
CC(I,2)	Initial capital cost equation coefficient, b.	0.0
KPC(I,2)	Type of cost variable used in calculating operation and maintenance costs. See list for initial capital cost (above).	0
CC(I,3)	Operation and maintenance costs equation coefficient, d	0.0
CC(I,4)	Operation and maintenance costs equation coefficient, f	0.0
CC(I,5)	Operation and maintenance costs equation coefficient, h	0.0

Table 7-4 (concluded). Storage/Treatment Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Input Flow and Pollutant Time Series	
	REQUIRED ONLY IF NOTAPE = 1 OR 2 (GROUP B1)	
	All flows and concentrations are instantaneous values at the indicated time. A constant time interval is not required; linear interpolation is used to obtain intermediate values of flow and concentrations. Hence, the difference between two time entries, TCAR, should not be less than the time step, DS, unless a step function input is desired.	
	The concentration units must be identical to those in Group E1 (NDIM(IP)) if NOTAPE = 1, Group B1, or on the external input file if NOTAPE = 2.	
J1	Group identifier	None
TCAR	Time of day, decimal hours, e.g., 6:30 p.m. = 18.5. If the first TCAR value is $\leq$ initial time, the program will read succeeding J1 data groups until TCAR $\geq$ initial time. If simulation goes beyond one day, i.e., times > 24.0, then continue with times greater than 24. I.e., TCAR should not be reset at beginning of day.	0.0
QCAR	Flow entering S/T plant (at unit 1), cfs [m^3/sec].	0.0
PCAR(1)	Concentration of pollutant 1 entering S/T plant (at unit 1). Required only if NP $\geq$ 1 (Group B1) and QCAR > 0.0	0.0
PCAR(2)	Concentration of pollutant 2 entering S/T plant (at unit 1). Required only if NP $\geq$ 2 (Group B1) and QCAR > 0.0	0.0
PCAR(3)	Concentration of pollutant 3 entering S/T plant (at unit 1). Required only if NP = 3 (Group B1) and QCAR > 0.0	0.0

END OF STORAGE/TREATMENT BLOCK INPUT DATA

At this point, the program seeks new input from the Executive Block.

SECTION 8

RECEIVING WATER MODELING

A receiving water may receive combined sewer overflows and stormwater runoff from point and non-point sources. The overflows and runoff may contain toxic chemical pollution as well as nutrients, suspended solids, and BOD_5. One of the objectives in the creation of the SWMM was coupling runoff, routing and receiving water models in a single package. A receiving water model (RECEIV) was part of the SWMM package from its conception (Metcalf & Eddy Inc. et al., 1971a; Huber et al., 1975).

RECEIV was dropped from the SWMM package in 1981 (Huber et al., 1981b) since it was felt better models (Dynamic Estuary Model and RECEIV derivatives) were currently being written at EPA but were not immediately available for inclusion in the 1981 version of SWMM. This did not reflect a lessening of the importance of the coupling of land and receiving water models. It was planned to link the new receiving water model with SWMM. However, Runoff, Transport, Storage-Treatment and Extran were never linked to the new EPA model DYNHYD (currently DYNHYD3) (Ambrose et al., 1986).

The current EPA receiving water models are: (1) DYNHYD3, a dynamic, branching one-dimensional link node model that simulates the flow, velocities, and depths of a lake, river, and estuary, and (2) WASP3, a water quality model that simulates nutrients (EUTROWSP3), and toxic chemicals (TOXIWSP3) in receiving waters (Ambrose et al., 1986).

SWMM is coupled to both models through the SWMM interface file. Overland flows, routed pipe and channel flows, and the effluent from storage and treatment facilities can be input into DYNHYD3 as a variable-flow input. DYNHYD3 reads the SWMM interface file (see Section 2) to find first the location of the requested nodes and secondly the time history of the node flow. The flows are converted to negative numbers since DYNHYD3 <u>input</u> is negative and withdrawals are positive.

The SUMRY2.OUT file created by DYNHYD3 is then read by either EUTROWSP3 or TOXIWSP3 during the simulation of water quality. The SWMM interface file may also be read by WASP3, except that only the loadings are input to model by subroutine SMWASP.

SECTION 9

STATISTICS BLOCK*

INTRODUCTION

The Statistics Block performs simple statistical analyses on continuous event or single-event data, although the latter is seldom necessary. Both quantity and quality parameters may be analyzed. The options available include event separation with a table depicting the sequential series of events, a table of magnitude, return period and frequency of events, a graph of magnitude versus return period, a graph of magnitude versus frequency, and the first three moments of the event data.

Statistical analyses are performed on data read from an interface file arranged in the standard SWMM format (refer to Section 2). The Statistics Block may be called after any block that generates such a file. In addition, the user may create an interface file of rainfall or other data and, through an understanding and alteration of various conversion factors, use the Statistics Block to analyze rainfall, rather than stormwater events.

Separation of the data into events depends on the unique series of zero and non-zero instantaneous flow values found at each location within the system being simulated. The results of the analyses would be expected to vary from location to location. The Statistics Block can analyze only one location at a time. Multiple locations can be analyzed by making multiple calls to the Statistics Block from the Executive Block of SWMM using the same JIN interface file.

This section describes the program operation of the Statistics Block, identifies output options, provides instructions for preparing input data groups, defines program variables, presents the equations utilized within the block and explains the messages and labels that may be printed.

PROGRAM OPERATION

The Statistics Block is a FORTRAN program of approximately 1700 Fortran statements and consists of nine subroutines. The relationships among the Statistics Block, the rest of SWMM and the various subroutines are shown in Figure 9-1.

Subroutine STATS comprises the major portion of the block. Input data and data from the interface file are read, and descriptive information from

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*This block originally developed by Mr. Donald J. Polmann.

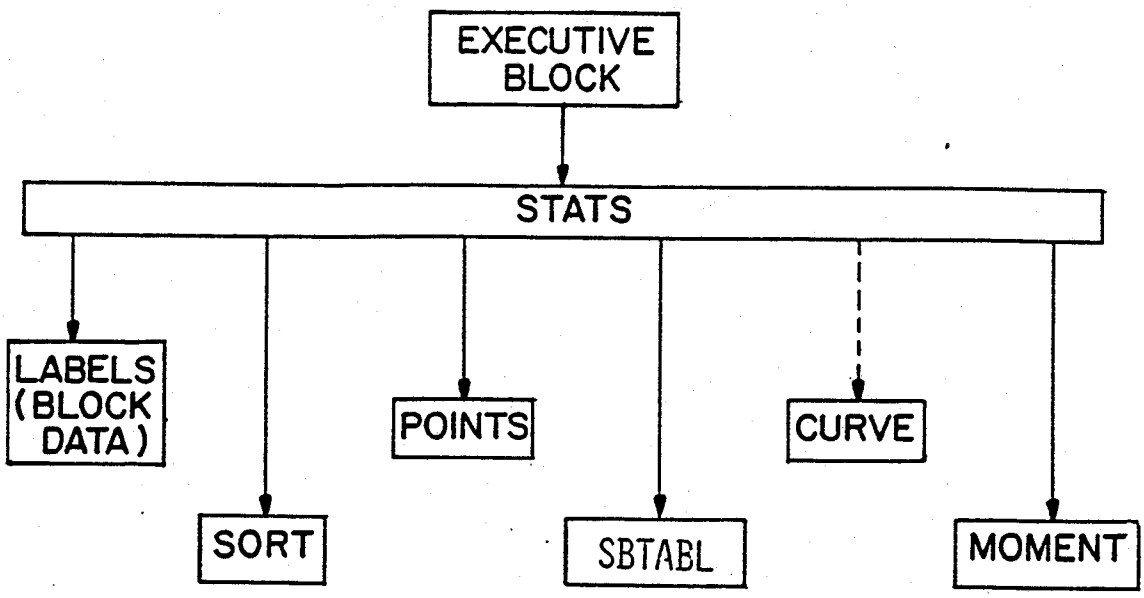

Figure 9-1. Structure of the Statistics Block Subroutines.

the file header is printed, followed by a summary of the input data. The flow/pollutant data are separated into events and this new data set is written into an scratch file. There is an internal program limit of 4000 events per location. This is sufficient to analyze 100 storm events per year for 40 years. The user must have sufficient disk space to store the scratch file. The unformatted scratch file at the limit of 4000 events will require less than 100 k bytes for total storage. The event limit can be modified by altering the parameter statement accompanying the INCLUDE file 'TAPES.INC' (see Section 2 for more detail).

After the entire simulation period has been examined, a table of the sequential series of events is printed (if requested). If a table of return period and frequency or a graph of either of these is requested, the series is sorted into descending order by Subroutine SORT. SBTABL generates and prints the tables of magnitude, return period and frequency. POINTS generates an array of (X,Y) pairs to be plotted as points on either the return period or frequency graphs. MOMENT calculates and prints the mean, variance, standard deviation, coefficient of variation and coefficient of skewness of the event data. LABELS is a Block Data subroutine that initializes the constants in labeled common blocks that are used for labeling graphs.

OUTPUT OPTIONS

Introduction

The table of sequential series of events depicts the original time series of flow data after the time steps have been grouped into events. The table includes the date and time of day that each event began, flow volume of each event, total rainfall during the flow event, duration of each event and inter-event duration (time from the end of the previous event).

The table of magnitude, return period and frequency is a rank order table showing the date and time that each event began, the magnitude of the event being analyzed, the return period (in years or months) of that magnitude and the percent of occurrences that are less than or equal to the given magnitude.

The graph of magnitude versus return period is a plot of two columns of the table, except that return period is presented as the base ten logarithm. The graph of magnitude vs. frequency is a similar plot with frequency presented as a percent. Although the graphing routines plot information centered in the table, it is not necessary to select the table option in order to select the graph options. Any of these may be printed independently of the others. The last option available is a calculation of the mean, standard deviation, coefficient of variation and skewness of the event data.

The table of sequential series pertains only to the volume of the flow events. The remaining options can be requested for flow or pollutants. Any (or all) of these can be selected for any (or all) of the five flow parameters and for any (or all) of the five pollutant parameters. Different pollutant parameters can be analyzed for different pollutants. Events are identified on the basis of flows greater than or equal to a cutoff baseflow (user input), so that the duration of events and interevents will be identical for flow and

any of the pollutants selected.

Sequential Series of Events

This option prints a table of the original series of events before any sorting has taken place. Printing of the table, which contains 120 events per page, may be accessed in several ways. First, the table may be printed directly as an option under normal program execution. Second, when the number of events in the time series exceeds the designated limit (4000) and termination of the program has not been requested, the table may be printed (ignoring the rest of the series). Third, in the case where termination has been selected, the option remains to print a table for that portion of the series that has been separated into events.

Table of Magnitude, Return Period and Frequency

For those parameters where this option is requested, one table will be printed for each parameter chosen for each constituent chosen. For example, if, for the constituent 'FLOW', two parameters are chosen (e.g., total flow and event duration), and for each of two pollutants two parameters are chosen (e.g., total load and peak concentration), then six separate tables are printed, each containing magnitude, return period and frequency for the appropriate parameter. Therefore, although it is unlikely that one would have reason to do so, up to 60 tables can be printed in one run (five flow parameters, five rainfall parameters and five pollutant parameters for ten pollutants). The length of each table depends on the number of events within the period of analysis (180 events are printed per page).

Graphs of Magnitude vs. Return Period or vs. Frequency

This paragraph applies to either type of graph. As with the tables above, one graph is printed for each parameter chosen of each constituent for which a graph is requested. Each graph comprises one page of output. Again, up to 55 graphs can be printed, although this would be an unlikely choice.

Moments

This option calculates and prints unbiased estimates for the mean, variance, standard deviation, coefficient of variation and coefficient of skewness. These values will be printed for each parameter chosen for each constituent chosen. The output incorporates approximately 15 lines and will appear in sequence where space is available (i.e., a new page is not printed for each set of moments).

PREPARATION OF INPUT DATA

Extent of Data

The Statistics Block requires a minimal amount of input data under normal use. The flow/pollutant data to be analyzed will be read from interface files generated by other blocks of SWMM. The input data required simply indicate what type of analysis should be performed on the interface data. Use of the

block for rainfall data is discussed later.

Line by line instructions for preparing the input data will be presented. The user is referred to the table of Statistics Block Input Data later in this manual for input details. The general structure of the data groups is given in Table 9-1.

Table 9-1. Statistics Block Input Data Sequence

Data Group	Description
$STATS	Calls the Statistics Block
A1	Starting and Ending Dates
B1	General Data
B2	Print Control
B3	Pollutant Locations
C1	Table and Graph Requests for Flow
D1	Table and Graph Requests for Pollutants
E1	Table and Graph Requests for Rainfall

Flow, Pollutant and Rainfall Input Files

The Statistics Block reads the interface file JIN(1) for flow, pollutant, and rainfall information. It uses NSCRAT(1) as the temporary scratch file holding the event information it reads from JIN(1). The source of the interface file JIN(1) may be the output from the Runoff, Transport, or Storage/Treatment Block or the rainfall file created by the Rain Block. The Statistics Block can read flow, pollutants, and rainfall from the Runoff, Transport, or Storage/Treatment outputs. It can only read rainfall from the Rain Block output rainfall file.

Data Group A1

The variables ISTART and TSTART indicate the date and time, respectively, at which this block should begin searching for events. The variables IEND and TEND indicate the last point on the file that should read. In this manner, the user may choose any period within the record (e.g., one particular year, five sequential years, etc.) on which to perform statistical analyses. Default values of zero for both date and time can be chosen for starting and/or ending. Zero starting values indicate that analyses should commence with the first value on the interface file. Zero ending values indicate that analyses should continue to the end of the available record. Formats for date and time correspond to the standard interface format (Section 2).

Data Group B1

Minimum Interevent Time --

The minimum interevent time (MIT) indicates the minimum number of dry hours (or fractional hours) that will constitute an interevent. In other words, the number of consecutive dry hours encountered in the search must be equal to or greater than MIT in order that the preceding wet period (made up of at least one nonzero flow value) be considered a separate event. Dry periods of duration less than MIT may exist within an event preceded and followed by wet time steps. The number of events in a given period of analysis is directly dependent on the value of MIT. If a value of zero is chosen for MIT, every wet time step will be viewed as a separate event.

No "correct" value of MIT can be suggested, although a value of 3 to 30 hours is often used to separate rainfall events (Hydroscience, 1979). Various event definitions for rainfall time series are available in the literature, e.g., Tavares (1975), Heaney et al. (1977), Hydroscience (1979), Restrepo-Posada and Eagleson (1982). Several urban runoff studies (e.g., EPA, 1983b) have evaluated MIT for rainfall events on the basis of the coefficient of variation (CV) of interevent times, where the CV is the ratio of the standard deviation to the mean. The MIT that gives a CV near 1.0 is usually chosen as the gage MIT. This assumes that the interevent times have an exponential distribution for which the mean equals the standard deviation (hence, CV = 1.0). Thus, the MIT is chosen to make the empirical data fit the theory. If this method is selected, two trial values of MIT are used and the corresponding CV values for interevent times determined through two runs of the Statistics Block. A plot (or linear extrapolation) of MIT versus CV will generally give a good estimate of the MIT value for which CV is approximately 1.0. Depending upon the site, this definition applied to the runoff time series can yield large values of MIT, on the order of 100 hours.

Baseflow --

The events are separated using a baseflow or cutoff flow (BASE on Data Group B1). Flows greater than BASE are part of the event, conversely flows less than or equal to BASE are part of the interevent period. This parameter may be set equal to 0.0 cfs [m^3].

Location --

The analyses are performed at one location (LOCRQ) within the system. The interface file may contain data for up to 100 locations, each identified in the array LOCNOS(K). The LOCRQ must be specified in one of the elements in the array LOCNOS(K).

Rainfall statistics can be calculated for one raingage (LOCRN) on the interface file. Rainfall may be analyzed in conjunction with flow and pollutants or separately by using an LOCRQ of 0 for the flow inlet.

Number of Pollutants --

The number of pollutants requested for statistical analysis (NPR) must be less than or equal to the number of pollutants on the interface file (NPOLL). If NPR equals 0 then Data Group D1 is not read by STATS.

Number of Events Printed --

The user can limit the number of events printed by setting NPOINT greater than 0. A value of 0 will print every event in the simulation. Otherwise, a maximum of NPOINT values will be printed.

Units --

The variable METRIC indicates the system of units in which output should be reported. To implement U.S. customary units, use METRIC = 0. For metric units, use METRIC = 1.

Return Period Units and Plotting Position Parameter --

Return periods will be calculated using either months or years as the basic time unit. The user decides by picking LRET = 0 (years) or LRET = 1 (months). The plotting position is adjusted by selecting parameter A on data group B1. This parameter is discussed in more detail later in the description of computations.

Data Group B2

Table of Events --

The variable KSEQ indicates whether or not a table of the sequential series of events should be printed.

Limit on Number of Events --

The variable KTERM indicates whether or not to terminate analyses in the case where the number of events exceeds the allowable computer memory space. The number of events that can be sorted and analyzed has been set within the program to 4000. This value corresponds to 200 events per year for a 20 year period. As noted, the user may alter this value. If the number of events exceeds the limit set, the program will either (a) perform the analyses on the events already identified, ignoring the remainder of the record (KTERM = 0), or (b) terminate execution of the block, performing no event analysis (KTERM = 1). If the analyses are being performed, a table of the sequential series will be printed if KSEQ = 1. If the analyses are not performed, the option still exists to print the table of sequential series before termination. The variable KTSEQS indicates that the table should or should not be printed in this case.

Data Group B3

The variable array IPOLRQ will contain up to ten elements, corresponding

to the maximum value of NPR (and NPOLL, the number of pollutants on the interface file). The pollutants requested for analysis must be identified by their position on the interface file (not by name). Therefore, the elements of IPOLRQ will contain integer values from 1 to 10. For example, if the first pollutant to be analyzed is BOD, and BOD is the third pollutant on the interface file, then IPOLRQ(1) would have the value 3. Similarly, if the second pollutant to be analyzed is TSS, and TSS is the fifth pollutant on the interface file, then IPOLRQ(2) would have the value 5.

Data Group C1

Data group C1 indicates the statistical options requested for flow. There are five input variables in each line of input, one for each of the five flow parameters. The five parameters are (1) total flow for the event, measured as a volume and reported as inches [mm], (2) average flow for the event, measured as a rate and reported as in./hr [mm/hr], (3) peak flow for the event, measured as an instantaneous rate and reported as in./hr [mm/hr], (4) duration of the event, measured as the number of time steps making up the event and reported as hours, and (5) duration of the inter-event, measured as the number of dry hours preceding the event and reported as hours. Two tables and two plots may be generated for each of the five parameters: (1) a table of event magnitude, return period and frequency (column 1), (2) a graph of magnitude vs. return period (column 2), (3) a graph of magnitude vs. frequency (column 3), and (4) a table of the first three moments of the event data (column 4).

The user selects the tables and graphs to be printed by entering a four digit number containing either a 0 or a 1 in each column. The columns pertain to the columns described in the previous paragraph. For a given group, those fields containing a 1 indicate the flow parameters for which that option has been selected. Values of zero indicate that the analyses should not be performed. For example, entering 1111 in parameter one's field means two tables and two plots are generated for total flow. Entering 0000 or 0 means no tables or graphs are generated. See Table 9-3 for more details.

Data Group D1

Data group D1 is identical in format to group C1. The four statistical options available for flow are also available for pollutants. One D1 data line must be included for each of the NPR pollutants requested, indicating which options for which parameters should be performed for each pollutant. The D1 lines should be arranged in a sequence corresponding to the order in which the pollutants were requested. Again, there are five input fields on each D1 line, one field for each of the five pollutant parameters. The four-digit entry for each field indicates which of the two tables and two graphs are requested. The five parameters are: (1) total load, measured as a sum of the concentration times the flow rate and reported as pounds [kg], (2) average load, measured as a rate of pollutant loading and reported as lbs/hr [kg/hr], (3) peak load, measured as an instantaneous rate of pollutant loading and reported as lbs/hr [kg/hr], (4) flow-weighted average concentration (event mean concentration), reported as mg/l, and (5) peak concentration, reported as mg/l.

Data Group E1

Data Group E1 is also identical in format to group C1. The four statistical options available for flow are also available for rainfall. Again, there are five input fields, one field for each of the five rainfall parameters. The five parameters are (1) total event volume reported as inches [mm], (2) average intensity reported as in./hr [mm/hr], (3) peak intensity, reported as in./hr [mm/hour], (4) duration of the event, measured as the number of time steps making up the event and reported as hours, and (5) duration of the inter-event, measured as the number of dry hours preceding the event.

COMPUTATIONS

Return Period and Frequency

In Subroutine STATS, variables T1 and T2 indicate the beginning and end, respectively, of the period of analysis, measured as elapsed time from the beginning of the simulation, in hours. The return period of an event may be reported in either months or years. If years are chosen, the simulation duration is rounded to the nearest number of years (NYRS). If months are chosen, it is necessary to calculate the number of months (NOMOS) within the period of analysis. The average number of hours per month in a year of 365.25 days is 730.5. This value is used to find a value for NOMOS, rounded to the nearest month, by the equation

$$\text{NOMOS} = \text{Integer}[(T2-T1)/730.5 + 0.5] \qquad (9\text{-}1)$$

For short periods of analysis (e.g., of the order of one year) NOMOS may be in error by one month depending on which months of the year are included in the period. This should pose little difficulty as a return period analysis for such a short period is generally not undertaken (or at best is of questionable worth).

Empirical return period (plotting position) is calculated by the general equation first proposed by Gringorten (1963) and analyzed by Cunnane (1978):

$$T = (NMY + 1 - 2A)/(M - A) \qquad (9\text{-}2)$$

where T = return period in months or years (depending on the option selected in data group B1 (LRET),
NMY = number or months, NOMOS, or number of years, NYRS,
M = rank of event (ranked in descending order), and
A = parameter of the equation (data group B1).

A value of A = 0 gives the familiar Weibull plotting position (Gumbel, 1958),

$$T = (NMY + 1)/M \qquad (9\text{-}3)$$

The Weibull formula is often used in hydrology but has been criticized by Cunnane (1978) who suggested a value of A = 0.4 as a good compromise for the customary situation in which the underlying frequency distribution of the

parameter is unknown. (The references only analyze return periods in years. No guidance is available for units of months.)

Large uncertainties exist in return periods computed in this manner (Gumbel, 1958)! A refined analysis would compute return periods and exceedance probabilities by fitting an assumed probability density function, as in flood-frequency analysis, for which confidence intervals may be established.

The discussion of return period assumes the events are independent, on the basis of the event separation criterion discussed earlier. However, the frequency, FREQ, computed for each event is merely the percent of total events less than or equal to the given magnitude

$$FREQ = 100\,[1 - (M-1)/N] \tag{9-4}$$

where M = rank, and
N = total number of events within the period of analysis.

The largest event is assigned a frequency of 100 percent, etc.

Moments

Calculations are made of estimates for the mean ($\bar{x}$), variance (S^2), standard deviation (S), coefficient of variation (CV) and coefficient of skewness (C_s). The equations utilized for these calculations are:

$$\bar{x} = \Sigma x/N \tag{9-5}$$

$$S^2 = [\Sigma x^2 - N\,\bar{x}^2]/(N - 1) \tag{9-6}$$

$$S = (S^2)^{1/2} \tag{9-7}$$

$$CV = S/\bar{x} \tag{9-8}$$

$$C_s = (\text{Numer} \cdot \text{Factor})/\text{Denom} \tag{9-9}$$

where $\text{Numer} = \Sigma x^3/N - 3\bar{x}\,\Sigma x^2/N + 2\bar{x}^3$

$\text{Denom} = [\Sigma x^2/N - \bar{x}^2]^{1.5}$

$\text{Factor} = [N(N-1)]^{1/2}/(N-2)$

The forms given above for Numer and Denom are for computational convenience and correspond to the more usual forms,

$\text{Numer} = \Sigma(x-\bar{x})^3/N$
$\text{Denom} = [\Sigma(x-\bar{x})^2/N]^{1.5}$

For the above equations, x is the magnitude of the event parameter, and N is the total number of events within the period of analysis. All summations are from 1 to N. Equations 9-6 and 9-9 are unbiased estimates for the variance and skewness, respectively.

MESSAGES AND LABELS

Most of the messages printed as part of the block execution are self-explanatory and do not require discussion here. A notable exception to this involves the units printed for pollutants. As a prelude to this discussion, an explanation of the units provided in the tables and graphs is called for. Table 9-2 summarizes the units printed for flow and three types of pollutants. The labels printed for the ordinate of the graphs are also presented.

All flow parameters are normalized to depth or depth/hr (i.e., in. or mm or in./hr or mm/hr). Should true volumes be desired, they may be obtained by multiplying by the catchment area, printed after reading the interface file.

When NDIM = 2, a special message is printed on the graph or table. Rather than printing the units described in The Statistics Block Input data later, the output contains "SEE NOTE" and the note "Magnitude has units of .... See user manual for explanation." The explanation referred to is included in the following discussion.

The user is referred to Sections 2 and 4 for an introduction to the variable NDIM. For NDIM = 0, pollutant concentration is given in mg/l. In this case, a direct conversion is possible for loading rates and concentrations. For NDIM = 1, pollutant concentration is given in "other quantity" per liter (e.g., MPN/l). Here, no conversion is possible to mass loading or mass per unit volume. "Mass" must be presented as "quantity" and the user must be aware of what "quantity" refers to for the pollutant involved. The units printed for flow weighted average concentration and peak concentration will correspond to the variable PUNIT found on the interface file for the particular pollutant. For NDIM = 2, pollutant concentration is given in some other units, not on a "per liter" basis (e.g., JTU). Therefore, no units conversion can be made. Magnitudes reported for total load will have units of a volume multiplied by the appropriate PUNIT. The magnitude is obtained by summing the pollutant values found on the interface file (which are in units of an instantaneous flow rate multiplied by a concentration) and multiplying this value by the time step size (DTSEC) of the event. Interpretation of the significance of these magnitudes is left strictly to the user, who should exercise caution in selecting this statistical option. A similar caution applies to average load and peak load. These magnitudes will have units of a flow rate multiplied by the appropriate PUNIT. The average load is the mean of the values found on the interface file for a given event, with a units conversion for flow rate. The peak load is the largest of the values within an event, with a similar units conversion for flow rate. Flow weighted average concentration and peak concentration will have units corresponding to PUNIT for the particular pollutant and an interpretation of these magnitudes may be simpler than the above parameters. The calculation of these two parameters is self-evident.

ANALYSIS OF RAINFALL DATA

The Statistics Block now has the capability of analyzing rainfall either directly from a SWMM interface file or a rainfall file from the Rain Block.

Table 9-2. Labels and Units

	Parameters	Ordinate Label	U.S. Customary Units	Metric Units
Flow	Total Flow	Total Q	inches	mm
	Average Flow	Aver Q	inches/hr	mm/hr
	Peak Flow	Peak Q	inches/hr	mm/hr
	Event Duration	Duration	hours	hours
	Interevent Duration	Interevt	hours	hours
Rainfall	Volume	Total V	inches	mm
	Average Intensity	Aver In	inches/hr	mm/hr
	Peak Intensity	Peak In	inches/hr	mm/hr
	Event Duration	Duration	hours	hours
	Interevent Duration	Interevt	hours	hours
Pollutant with NDIM = 0	Total Load	Tot Load	pounds	kilogram
	Average Load	Ave Load	lbs/hr	kg/hr
	Peak Load	Peakload	lbs/hr	kg/hr
	Flow Weighted Average Concentration	Ave Conc	mg/l	mg/l
	Peak Concentration	PeakConc	mg/l	mg/l
Pollutant with NDIM = 1	Total Load	Tot Load	Quantity	Quantity
	Average Load	Ave Load	Quan/hr	Quan/hr
	Peak Load	Peakload	Quan/hr	Quan/hr
	Flow Weighted Average Concentration	Ave Conc	PUNIT	PUNIT
	Peak Concentration	PeakConc	PUNIT	PUNIT
Pollutant with NDIM = 2	Total Load	Tot Load	ft^3*PUNIT	Liter*PUNIT
	Average Load	Ave Load	cfs PUNIT	Liter/S*PUNIT
	Peak Load	Peakload	cfs PUNIT	Liter/S*PUNIT
	Flow Weighted Average Concentration	Ave Conc	PUNIT	PUNIT
	Peak Concentration	PeakConc	PUNIT	PUNIT

It performs the analysis on raingage LOCRN (from data group B1) for the rainfall parameters selected on the E1 data line.

The Runoff Block places all raingage information on its output interface file. Thus, there may be up to 10 raingages on the interface file. The raingage name is a negative number from 1 to 6 digits long that is either the user designated raingage number or a National Weather Service precipitation station. It has units of inches/hour and is located in the same position as inlet flows on the interface file. Its distinguishing characteristic is its negativity. This information is carried through to following blocks such as Transport and Storage/Treatment and placed on their output interface file. Extran does not carry rainfall information to its output interface file. (It is unlikely anyone would use the Statistics Block to analyze Extran output.)

The output file from the Rain Block contains only rainfall. The raingage number (LOCRN) is the NWS, AES, or user defined raingage number in the Rain Block input data. Subroutine SREAD is sophisticated enough to decide the source of data on the JIN(1) interface file. The data to be analyzed by Subroutine STATS <u>must</u> be on file JIN(1).

Table 9-3. Statistics Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 9-3 (continued). Statistics Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Starting and Ending Date/Time	
A1	Group identifier	None
ISTART	Starting date, yr/mo/day	000000
TSTART	Starting time, decimal hours	00.00
IEND	Ending date, yr/mo/day	000000
TEND	Ending time, decimal hours	00.00
	General Data	
B1	Group identifier	None
MIT	Minimum intervent time, decimal hours.	0.0
BASE	Cutoff flow (baseflow), cfs [m^3/s]. Flow used to separate events.	0.0
LOCRQ	Flow location requested.	0
LOCRN	Rainfall gage for analysis.	0
NPR	Number of pollutants requested.	0
NPOINT	Number of events printed in tables. Print only the top NPOINT flows etc. IF NPOINT is 0 then all events are printed.	0
METRIC	Requests type of units for output = 0, U.S. customary, = 1, Metric.	0
LRET	Units of return period, = 0, Return period in years, = 1, Return period in months.	0
A	Plotting postion parameter (see text for explanation).	0.0

Table 9-3 (continued). Statistics Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Print Control	
B2	Group identifier	None
KSEQ	Request to print sequential series of flow events? No = 0, Yes = 1	0
KTERM	Code for terminating program if number of events exceeds allowable memory space. =0, Do not terminate (perform analyses on those events already identified). =1, Terminate program (no event analysis performed).	0
KTSEQS	Code for printing sequential series if the number of events exceed limit and KTERM = 1. = 0, Do not print sequential series. = 1, Print sequential series of those events already identified.	0
	* * * Required only if NPR > 0 on Data Group B1 * * *	
	* * * If NPR = 0 then skip to Data Group C1 * * *	
B3	Group identifier	None
IPOLRQ(1)	First pollutant requested, identified by position on interface file.	None
.	.	
.	.	
.	.	
IPOLRQ(NPR)	Last pollutant requested, identified by position on interface file.	None

Table 9-3 (continued). Statistics Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	* * * Required only if LOCRQ on Data Group B1 is > 0 * * *	
	Stat Options for Flow	

This data group controls the printing or plotting of information on magnitude, return period and frequency for each of the five flow parameters. In all cases, No = 0, Yes = 1. The control information is entered as a four digit integer number with each column controlling a different table or graph.

First column - table of magnitude, return period and frequency.
Second column - print graph of magnitude versus return period.
Third column - print graph of magnitude versus frequency.
Fourth column - print moments.

For example, enter 1111 to print/plot all tables/graphs, 1000 to print the table only, 1100 to print the table and the graph of magnitude versus return period only, and 0000 to bypass printing/plotting of the flow parameter.

C1	Group identifier	None
ISFLOW(1,1)	Request for total flow?	0
ISFLOW(1,2)	Request for average flow?	0
ISFLOW(1,3)	Request for peak flow?	0
ISFLOW(1,4)	Request for event duration?	0
ISFLOW(1,5)	Request for interevent duration?	0

* * * Data Group D1 is only required if NPR > 0 on Data Group B1 * * *

Stat Options for Pollutants

If NPR > 0 use one D1 Data Group for each pollutant requested, up to ten sets of D1 lines, in the order defined by Group B2. The first index of ISPOLL(K,I,J) identifies the pollutant. Follow the instructions for Data Group C1 in entering data for Data Group D1.

D1	Group identifier	Blank
ISPOLL(1,1,1)	Request for total load?	0

Table 9-3 (continued). Statistics Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
ISPOLL(1,1,2)	Request for average load?	0
ISPOLL(1,1,3)	Request for peak load?	0
ISPOLL(1,1,4)	Request for flow weighted average concentration?	0
ISPOLL(1,1,5)	Request for peak concentration?	0

* * * Required only if LOCRN on Data Group B1 is > 0 * * *

Stat Options for Rainfall Analysis

Follow the instructions for Data Group C1 in entering data for Data Group E1.

E1	Group identifier	None
ISFLOW(2,1)	Request for total volume?	0
ISFLOW(2,2)	Request for average intensity?	0
ISFLOW(2,3)	Request for peak intensity?	0
ISFLOW(2,4)	Request for event duration?	0
ISFLOW(2,5)	Request for interevent duration?	0

END OF STATISTICS BLOCK DATA.

Data lines following these will be read by the Executive Block.

SECTION 10

RAIN BLOCK

BLOCK DESCRIPTION

Introduction

Precipitation is the one of the principal driving forces in the SWMM package. The Runoff Block reads precipitation data and generates overland flows for input into the Transport or Extran Blocks. The purpose of the Rain Block is to read long time series of precipitation records, perform an optional storm event analysis, and generate a precipitation interface file for input into Runoff.

The Rain Block takes the place of Subroutine CTRAIN in SWMM 3 (Huber et al., 1981b). It incorporates the rainfall analysis capability of the SYNOP program (Hydroscience, 1979). It is able to read two National Weather Service (NWS) precipitation input formats and a simple user-generated precipitation time series.

This section describes the program operation of the Rain Block, its statistical capabilities, the program variables, how the user can modify the program, and provides instructions for preparing input data lines.

Program Operation

The Rain Block consists of seven Fortran subroutines. The main subroutine (RAIN) reads the input data, performs the statistical analysis, and prints the precipitation echo, storm event summary, statistical summary, and output tables. Subroutine GTRAIN reads the NWS precipitation input tapes or files. SETIA, IDATE, and INTCHR are utility functions used by RAIN. Subroutines SHELL and SHELR use the shell sort routine for integer and real data, respectively.

Input Options

The program is designed to read (NWS) precipitation Card Deck 488 (old format) and Tape Deck 3240 (new format) hourly precipitation data. A simple user-defined time series can also be read by Subroutine GTRAIN. This may be inadequate, however, for complicated formats with special codes and messages. GTRAIN can be easily modified by a person familiar with Fortran to read any input file (see Figure 10-1).

```
      SUBROUTINE GTRAIN(IDO,IGO)
C                                THIS PROGRAM READS TWO VERSIONS OF
C                                THE NWS PRECIPITATION TAPES
C                                IFORM - 0 MEANS POST 1980 FORMAT
C                                IFORM - 1 MEANS PRE  1980 FORMAT
C
      COMMON/PRECIP/HOUR(366,27),IYEND(3),IYBEG(3),
     *       X(2000,7),IFORM,IO,NEWYR,ISTA,SUM(2)
 1000 FORMAT(3X,A6,10X,I2,I2,I4,3X,I2,3X,I5,A1)
 1040 FORMAT(A6,3I2,I1,12A3)
C
C     IFORM 0 - SHOWS INPUT FORMAT FOR 1 RAINFALL VALUE PER LINE
C     IFORM 1 - SHOWS INPUT FORMAT FOR MULTIPLE RAINFALL VALUES PER LINE
C               IF YOU WANT TO MODIFY GTRAIN FOR YOUR TIME SERIES OF RAINFALL
C               USE THE APPROPRIATE FORMAT AND THEN INSERT THE RAINFALL INTO
C               ARRAY HOUR AS SHOWN IN THE NEXT SECTION.
C
10    IF(IFORM.EQ.0) THEN
                     READ(IO,1000,ERR=10,END=40) STA,YEAR,MONTH,
     *               DAY,IHR,IRAIN,ICODE
                     ELSE
                     READ(IO,1040,ERR=10,END=40) STA,YEAR,MONTH,
     *               DAY,ICARD,XRA
                     ENDIF
C
C       INSERT RAINFALL INTO ARRAY HOUR
C              AT THE END OF EVERY YEAR HOUR WILL BE PROCESSED BY
C              SUBROUTINE RAIN
C                                                NEW FORMAT
      IF(IFORM.EQ.0) THEN
          HOUR(IDAY,IHR) - IRAIN
C                                                OLD FORMAT
                      ELSE
                      IF(ICARD.EQ.1) J1 -  0
                      IF(ICARD.EQ.2) J1 - 12
                      DO 35 J - 1,12
35                    HOUR(IDAY,J+J1) - INTCHR(XRA(J))
```

Figure 10-1. Guide for Modifying Subroutine GTRAIN.

Output Options

The output of Rain potentially may be voluminous depending on the output options chosen on data group B1. If the user selects to echo the precipitation data, 1-3 pages per year are generated. A storm event summary is printed by year, generating an additional 1-2 pages. The statistical summary is contained on only two pages. Return period tables are generated for storm volume, average intensity, duration, and interevent time. Each return period table may be 10 to 20 pages long for a 30-year rainfall record.

INPUT AND OUTPUT FILES

File Identification

The Rain Block uses the JIN series as the precipitation input file. This applies to both the NWS data and the user-created data. The JOUT file will contain the rainfall interface file for the Runoff or Statistics Block. The user has the option of saving the storm event summary table in a formatted file. NSCRAT(1) is used to save the file. The formatted file then can be read by a spreadsheet, database, or statistical program for further analysis.

A JIN value is always required since it contains the input rainfall. JOUT and NSCRAT(1) are optional depending on the parameters chosen on data group B1.

National Weather Service Precipitation Data

Hourly precipitation values (including water equivalent of snowfall depths) are available for most first-order NWS stations around the U.S., with the periods of record usually beginning in the 1940s. (Similar data are available in Canada from the Atmospheric Environment Service.) Magnetic tapes containing card images of NWS Tape Deck (TD) 3240, "Hourly Precipitation Data" are available from the NOAA National Climatic Data Center (NCDC) in Asheville, NC (phone (704) 259-0682). The cost for the entire state of Florida was $154 in 1984. Similarly, for 15-min rainfall data, TD-3260 should be requested; the cost for the State of Florida for the period of record (approximately 1971 to 1986) was $531 in 1988. (Part of the reason for higher cost is the extra charge for combining recent years with the archive file.) Typically, purchasing the entire state record is actually cheaper than purchasing a single station due to extra processing costs for a one station retrieval.

The NWS sells fixed format and variable block/length precipitation tapes. This version of RAIN is written to read both fixed format and variable block/length tapes. However, the IBM mainframe at the University of Florida cannot read variable block/length records. Hence, the variable block/length code is obviously unverified. User beware. It is recommended that the user purchase fixed format (record length of 43, blocksize of 6300), ASCII tapes from the NWS.

The NWS NCDC has recently made hourly and 15-min rainfall data available in ASCII files on floppy disks, five years per disk. These may be read one disk at a time following on-screen prompts during execution on a PC. (TD-3200 "Summary of Day" for use in the Temp Block is also available on floppy disks. This option is not included in SWMM4.)

Special Considerations

Long precipitation records are subject to meter malfunctions and missing data (any reason). The NWS has special codes on its old Card Deck 488 and new Tape Decks 3240 and 3260 denoting these conditions. The Rain Block reads the special codes and the date, and the total number of missing hours is printed in the storm event summary table. Subroutine Rain lists the estimated total

missing rainfall by multiplying the total rainfall for the year times the missing hours divided by the total number of hours in a year. This information is printed only for the user's benefit. The rainfall interface file contains only good non-zero precipitation data.

If the codes for missing data or meter malfunction are present during the time between storm events that interevent duration is not used in the analysis of interevent duration. The number of interevent durations analyzed may be substantially less than the number for volume, average intensity, and storm duration. Some raingages (especially during the 1940s and 1950s) have long periods of missing data. The user should not use these data in a continuous simulation.

Rainfall Interval

When ordering the rainfall tape from the NCDC, either hourly (TD-3240, Hourly Precipitation) or 15-minute (TD-3260, 15-min Precipitation) rainfall must be specified. The program automatically detects the rainfall interval from the input tape or file. Hourly rainfall is available at most stations for 40 to 45 years, typically beginning in the 1940s. Fifteen minute rainfall is available for a shorter period of record, typically beginning in the 1970s.

PREPARATION OF INPUT DATA

Extent of Data

There are only three data groups in the input of the Rain Block. Table 10-1 presents the general structure of the data input. The input data formats for the Rain Block are shown in Table 10-2 at the end of this section.

Table 10-1. Rain Block Input Data

Data Group	Description
$RAIN	Calls the Rain Block
A1	Two Title Lines
B1	General Control Data
B2	General Data for User-Defined Time Series

Data Group A1

Data group A1 consists of two 80-column lines of character data. These descriptive titles will be printed at the top of each page of output.

Data Group B1

Rainfall Format --

Parameter IFORM indicates the format of the rainfall data. The Rain

Block supports four rainfall formats, including NWS TD-3240 or TD-3260, the new NWS precipitation format (actually two formats since the data are obtainable with fixed length or variable length records), and NWS Card Deck 488, which is the old (pre-1980) format. An indication of whether hourly or 15-min NWS data are being entered is found among the data and does not need to be indicated by the user. A rainfall time series created by the user may also be read by the Rain Block if IFORM = 3. NWS-format floppy disk input is indicated by IFORM = 4.

Station Number --

ISTA is the precipitation station number. These are 6-digit numbers for NWS stations. Alternatively, for a user-generated time series, this is the number used to identify the rainfall time series when the Runoff Block reads the rainfall input file.

Program Purpose --

The Rain Block has three modes of operation: (1) it can simply generate a rainfall interface file, (2) it can generate an interface file and perform the synoptic rainfall analysis, or (3) it can analyze the rainfall data and not create an interface file. The value of IDECID determines the program mode.

Starting Date --

Parameter IYBEG is the starting date to begin reading the rainfall data. This is a six-digit number in format of YR/MO/DY. If this number is 0 then the program will start at the first rainfall record of station ISTA.

Ending Date --

Parameter IYEND is the ending date to stop reading the rainfall data. This is a six-digit number in format of YR/MO/DY. If this number is 0 then the program will stop at the last rainfall record of station ISTA.

Echo Print of Rainfall --

The actual rainfall read by the program may be echoed back to the Rain Block output file (or printer) using the parameter IYEAR. The month/day/year and hour/rainfall are printed, five across a line, for each <u>non-zero</u> rainfall. This may generate one to three pages of printout per year.

Storm Summary Printout --

A storm event summary table by year may be generated if ISUM is 1 on data group B1. The table has the storm volume, average intensity, average intensity, storm duration, beginning storm date, previous seven days rainfall, missing data, and number of meter malfunctions. One to two pages will be printed depending on the average number of storms per year.

Minimum Interevent Time --

The minimum interevent time (MIT, integer only) indicates the minimum number of zero-rainfall hours that will constitute an interevent period. In other words, the number of consecutive dry hours encountered in the search must be equal to or greater than MIT in order that the preceding wet period (made up of at least one nonzero rainfall value) be considered a separate event. Dry periods of duration less than MIT may exist within an event preceded and followed by wet periods. The number of events in a given period of analysis is directly dependent on the value of MIT. If a value of 1 (the minimum) is chosen for MIT, every contiguous rainfall sequence will be viewed as a separate event.

No "correct" value of MIT can be suggested, although a value of 3 to 30 hours is often used to separate rainfall events (Hydroscience, 1979). Various event definitions for rainfall time series are available in the literature, e.g., Tavares (1975), Heaney et al. (1977), Hydroscience (1979), Restrepo-Posada and Eagleson (1982). Several urban runoff studies (e.g., EPA, 1983b) have evaluated MIT for rainfall events on the basis of the coefficient of variation (CV) of interevent times, where the CV is the ratio of the standard deviation to the mean. The MIT that gives a CV near 1.0 is usually chosen as the station MIT. This assumes that the interevent times have an exponential distribution for which the mean equals the standard deviation (hence, CV = 1.0). Thus, the MIT is chosen to make the empirical data fit the theory. If this method is selected, two trial values of MIT are used and the corresponding CV values for interevent times determined through two runs of the Rain Block. A plot (or linear extrapolation) of MIT versus CV will generally give a good estimate of the MIT value for which CV is approximately 1.0.

An MIT value is necessary only if storm event data are to be analyzed. Users who simply want to generate an input rainfall file for Runoff need not be concerned with this parameter.

Number of Events Printed --

Parameter NPTS controls the number of points printed in the return period tables for volume, average intensity, storm duration, and interevent duration. If NPTS is 0 then all events will printed, ranked from highest to lowest.

Formatted Output File --

The rainfall interface file saved on JOUT is unformatted and thus unreadable by most programs. The user has an option (parameter IFILE) of saving the storm event summary table as a formatted ASCII file on NSCRAT(1). This file then can be read by spreadsheet, database or statistical programs. The output file has the same appearance as the printed storm event summary. Also at the head of each column of numbers, on the first line, is a short one or two word description of the variable.

Plotting Position Parameter --

See equation 10-1 and the discussion of "Return Period" below.

Storm Event Tables --

The sorted events from largest to smallest may be printed for storm volume, average intensity, storm duration, and interevent duration (i.e., time between storm event midpoints). Parameter NOSTAT governs which tables are printed. No tables are printed if NOSTAT = 0. If NOSTAT > 0 then either all the events are printed or only the largest NPTS, depending on NPTS.

Data Group B2

The Rain Block has a rudimentary ability to read a user-generated precipitation file. It reads only files that are similar to the fixed format NWS Tape Deck 488. The input file is always the JIN interface file.

Rainfall Interval --

THISTO is the duration of each rainfall interval for the time series, in minutes. Each rainfall value is assumed to be constant for THISTO minutes. Only non-zero rainfall need be entered when creating the JIN input file.

Rainfall Units --

The type and units of rainfall are defined by parameters METRIC, KUNIT and CONV on data group B2. "Standard" units are in./hr or mm/hr for intensity and inch [mm] for volume (depth).

Rainfall Format and Date Positions --

FIRMAT is the format of the input data. Enough fields should be included to account for the site, date, time, and rainfall variables. Example formats are:

'(I6,5I2,F10.0)'	-- I6 field for site, 5I2 for yr/mo/dy/hr/mn, and F10.0 for rainfall
'(5I3,F10.0,I6)'	-- 5I3 for yr/mo/dy/hr/mn, F10.0 for rainfall, and I6 for the site

The exact position of each field is user defined. The parameters F1-F7 on data group B2 communicate the correct field position for year, months, days, hours, minutes, and rainfall.

COMPUTATIONS

Return Period

The return period of an event is reported in years. The simulation duration is rounded to the nearest number of years (NYRS).

Empirical return period (plotting position) is calculated by the general equation first proposed by Gringorten (1963) and analyzed by Cunnane (1978):

$$T = (NYRS + 1 - 2A)/(M - A) \qquad (10\text{-}1)$$

where T = return period in years,
M = rank of event (ranked in descending order), and
A = parameter of the equation (data group B1).

A value of A = 0 gives the familiar Weibull plotting position (Gumbel, 1958),

$$T = (NYRS + 1)/M \qquad (10\text{-}2)$$

The Weibull formula is often used in hydrology but has been criticized by Cunnane (1978) who suggested a value of A = 0.4 as a good compromise for the customary situation in which the underlying frequency distribution of the parameter is unknown.

Moments

Calculations are made of estimates for the mean ($\bar{x}$), variance (S^2), standard deviation (S), coefficient of variation (CV) and coefficient of skewness (C_s). The equations utilized for these calculations are

$$\bar{x} = \Sigma x/N \qquad (10\text{-}3)$$

$$S^2 = [\Sigma x^2 - N\,\bar{x}^2]/(N - 1) \qquad (10\text{-}4)$$

$$S = (S^2)^{1/2} \qquad (10\text{-}5)$$

$$CV = S/\bar{x} \qquad (10\text{-}6)$$

$$C_s = (\text{Numer} \cdot \text{Factor})/\text{Denom} \qquad (10\text{-}7)$$

where $\text{Numer} = \Sigma x^3/N - 3\bar{x}\Sigma x^2/N + 2\bar{x}^3$

$\text{Denom} = [\Sigma x^2/N - \bar{x}^2]^{1.5}$

$\text{Factor} = [N(N-1)]^{1/2}/(N-2)$

The forms given above for Numer and Denom are for computational convenience and correspond to the more usual forms,

$\text{Numer} = \Sigma(x-\bar{x})^3/N$
$\text{Denom} = [\Sigma(x-\bar{x})^2/N]^{1.5}$

For the above equations, X is the magnitude of the event parameter, and N is the total number of events within the period of analysis. All summations are from 1 to N. Equations 10-4 and 10-7 are unbiased estimates for the variance and skewness, respectively.

Table 10-2. Rain Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 10-2 (continued). Rain Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Two Title Lines	
A1	Group Identifier	None
SITE	Two 80-column descriptive titles.	'Blank'
	Control Information	
B1	Group identifier	None
IFORM	Format of precipitation (rainfall) data. - 0, Post-1980 NWS format (NWS Tape Deck 3240 or 3260), fixed length records. - 1, Post-1980 NWS format (NWS Tape Deck 3240 or 3260), variable length records. - 2, NWS Card Deck 488. - 3, User-defined rainfall format. - 4, NWS diskette rainfall format ("Release B, condensed"). Provide first 5-yr diskette on unit JIN and provide others in response to interactive prompts.	0
ISTA	NWS station number, or alternatively for user defined data, an arbitrary integer station number.	0
IDECID	Controls the program purpose and output. - 0, Create a rainfall interface file on JOUT. - 1, Create a rainfall interface file on JOUT, and perform the synoptic rainfall analysis. - 2, Only do the synoptic rainfall analysis.	0
IYBEG	Starting date, six digits, yr/mo/dy. If zero the program searches for beginning year.	0
IYEND	Ending date, six digits, yr/mo/dy. If zero the program reads all the station data.	0
IYEAR	Echo print of the rainfall values read. - 0, Do not print and rainfall data. - 1, Print <u>all</u> the data.	0
ISUM	Indicator for storm event summary printout. - 0, Do not print storm event summary, and - 1, Do print the storm event summary (1-2 pages per year).	0

Table 10-2 (continued). Rain Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	*** The following fields are not required if IDECID is 0 ***	
MIT	Minimum interevent time to separate storm events, number of hours (≥1). Only used if storm event statistics are printed. (See text.)	1
NPTS	NPTS highest events are printed in rainfall analysis tables. If zero, all events are printed.	0
IFILE	Indicator for storm event formatted file creation. = 0, Do not save storm event data on a file, and = 1, Save the storm event data on a formatted NSCRAT(1). User must insure that this file will be permanently saved by appropriate JCL or by using the @ function as described in Section 2.	0
A	Plotting position parameter (see text for explanation).	0.0
NOSTAT	Indicator for storm event statistics printout.	0

NOSTAT controls the printing of the event tables for volume, average intensity, storm duration, and interevent duration. In all cases, No = 0, Yes = 1. The control information is entered as a four digit integer number with each column controlling a different table.

First column - table of storm volume by return period.
Second column - table of average intensity by return period.
Third column - table of storm duration by return period.
Fourth column - table of interevent duration by return period.

For example, enter 1111 to print all four tables, 1000 to print the first table only, 1100 to print the first two tables, and 0000 or 0 to bypass all table printing. In all cases only the top NPTS events are printed.

User-Defined Rainfall Time Series

Required only if IFORM = 3 on data group B1.

A maximum of 3000 precipitation values per year may be input in file JIN (no limit on number of years), one value per line, each value with a date and time (and optional station ID).

B2	Group identifier	0
THISTO	Rainfall time interval, minutes.	60.0

Table 10-2 (continued). Rain Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
METRIC	Metric input/output. = 0, Use U.S. customary units. = 1, Use metric units, denoted by brackets [ ].	0
KUNIT	Standard rainfall units. = 0, intensity, in./hr [mm/hr], or = 1, volume, in. [mm]. (Note: other units, e.g., hundredths of an inch, may be used by using CONV below.)	0
FIRMAT	Rainfall format (character data). Should include integer fields for station number, year, month, day, hour, minute and an F, E or G field for rainfall. Rainfall may not be read as integer (I-format).	'None'
CONV	Multiply by CONV to convert non-standard rainfall units to in./hr [mm/hr] (KUNIT = 0) or in. [mm] (KUNIT = 1). (Conversion is to mm if METRIC = 1.)	1.0
F1	Field position for station number. If F1 is zero a station number will not be read.	0
F2	Field position for year. Required.	0
F3	Field position for month. Required.	0
F4	Field position for day. Required.	0
F5	Field position for hour. Required.	0
F6	Field position for minute. Required.	0
F7	Field position for precipitation. Required. Rainfall must be either first (1) or last (6 or 7) field. SWMM considers positive numbers to be rainfall and negative numbers to be snowfall.	0

End of Rain Block Data

At this point the program seeks new input from the Executive Block.

SECTION 11

TEMP BLOCK

BLOCK DESCRIPTION

Introduction

The purpose of the Temp Block is to input temperature, evaporation, and wind speed data and make a file accessible to the Runoff Block of SWMM.

The Temp Block replaces Subroutine CTRAIN in SWMM 3 (Huber et al., 1981b). It is able to read the NWS temperature, evaporation, and wind speed input formats and a simple user-generated precipitation time series.

Program Operation

The Temp Block consists of a single FORTRAN subroutine (TEMP). TEMP reads the input data, translates the temperature, evaporation, and/or wind speed data into the required SWMM format, and prints raw data or summary tables.

Input Options

The program is designed to read the National Weather Service (NWS) TD-3200 "Summary of Day Co-Operative" containing daily maximum and minimum temperatures, pan evaporation, and daily wind movement, among other variables. A simple user-defined time series can also be input. These data may be purchased from the National Climatic Data Center in Asheville, North Carolina. This program does not read the NWS format used by SWMM 3 ("Card Deck 345"). Hopefully, this will not inconvenience SWMM 4 users.

Output Options

The output of the Temp Block consists of a SWMM interface file containing daily maximum and minimum temperatures, evaporation estimates, and wind speed, either singly or in combination. The raw data, summary statistics, or both may be printed by the Temp Block depending on the value of IYEAR on data group B1.

INPUT AND OUTPUT FILES

File Identification

The Temp Block uses the JIN series (specified in the Executive Block) as

the temperature, evaporation and wind speed input file. This applies to both the NWS data and the user-created data. The JOUT file will contain the temperature, evaporation and wind speed interface file for the Runoff Block.

The JOUT file may be an existing file from a previous run of the Temp Block. A user who wants to create an interface file containing non-NWS temperature, evaporation and wind speed will have to run the Temp Block three times. During the first run, for example, only temperature data will be on the interface file. The second run will add evaporation data to the already existing interface file containing temperature data. The third run will add wind speed data to the temperature and evaporation data. Only one interface file will be read by the Runoff Block. This also applies to users who want to mix temperature, evaporation, and wind speed data from more than one NWS station. If the NWS station contains all forms of data, however, only one run of the Temp Block is required.

JIN and JOUT values are always required by the Temp Block. An NSCRAT(1) scratch file is required when evaporation or wind speed data are added to temperature data during multiple runs of the Temp Block.

Special Considerations

Long time series records are subject to periods of invalid data (for any reason, including broken gages). The NWS has special codes for invalid or suspect data. These suspect data are summarized by the Temp Block and not placed on the interface file. An interpolation scheme is used to replace invalid or missing data in the time series for use in the Runoff Block. The interpolation scheme will not be activated, however, for missing data periods longer than two weeks. In such an instance, the interface file will contain a gap of data that the Runoff Block will skip over and not simulate. For example, if snowmelt is simulated in the Runoff Block and there are no temperature data for January, January will not be simulated. The simulation period will resume when the temperature time series resumes.

Data Interval

The NWS data potentially utilized consist of daily maximum and minimum temperature, pan evaporation, and wind movement. Longer (but not shorter) periods may be input by the user by specifying the time unit parameter TUNIT on data group B2. For example, monthly estimates of evaporation for a multiple-year simulation may be entered using the user-defined time series option. Summaries of monthly pan evaporation for many U.S. stations are provided by Farnsworth and Thompson (1982).

PREPARATION OF INPUT DATA

Extent of Data

There are only three data groups in the input of the Temp Block. Table 11-1 presents the general structure of the input data. The input formats for the Temp Block are shown in Table 11-2 at the end of this section.

Table 11-1. Temp Block Input Data Sequence

Data Group	Description
$TEMP	Calls the Temp Block
A1	Two Title Lines
B1	General Control Data
B2	General Data for User-Defined Time Series

Data Group A1

Data group A1 consists of two 80-column lines of character data. These descriptive titles will be printed at the top of each page of output.

Data Group B1

Data group B1 contains information on program control. The parameters of data group B1 are:

Data Format --

Parameter IFORM specifies the format of the input data on the JIN file. This is restricted to NWS Tape Deck 3200 fixed-length or variable-length records, or a fixed-length user-defined format. The authors recommend that the SWMM user purchase NWS fixed-length data tapes.

Station Number --

ISTA is the station number of the principal climatological station operated by the NWS. These 8-digit numbers identify one of the 9000 stations currently being processed by the NWS, or one of the 23000 stations with recorded observations since 1945. The primary emphasis is on the recording of daily rainfall but 55 percent of the stations also record maximum and minimum temperature.

Type of Time Series Data --

Parameter KTYPE defines the type of data input. Daily maximum and minimum temperatures, daily pan evaporation, and daily wind speed may be input either singly or in combination to the Temp Block -- if the NWS data tapes are being used. A user-defined time series must consist of a single input parameter (maximum and minimum temperatures are herewith defined as a single input parameter).

Starting Date --

Parameter IYBEG is the starting date to begin reading the data. This is a six-digit number in format of YR/MO/DY. If this number is 0 then the

program will start at the first record of station ISTA.

Ending Date --

Parameter IYEND is the ending date to stop reading the data. This is a six-digit number in format of YR/MO/DY. If this number is 0 then the program will stop at the last record of station ISTA.

Echo Print of the Input Data --

Parameter IYEAR determines the extent to which the input data will be echoed back on the output file. Setting IYEAR equal to 0 will eliminate the echo of the raw data input and the summary tables. Setting IYEAR equal to 1 will result in a voluminous output containing all the input data and the summary tables. It is recommended that the user set IYEAR = 2 to print only the monthly/yearly summary tables. These tables will contain the minimum, mean, and maximum values read by month and/or year.

Pan Evaporation Coefficients --

If pan evaporation data are read by the Temp Block, then pan coefficients are required to convert the pan evaporation estimates to free-water-surface evaporation estimates used by the Runoff Block. (The pan data are multiplied by the pan coefficients to obtain the free-water-surface estimates.) Twelve monthly coefficients must be entered only if evaporation data are read, otherwise leave blank. Pan coefficient summaries may be found in hydrology textbooks (e.g., Linsley et al., 1983).

Data Group B2

File Identification --

The Temp Block has a rudimentary ability to read a user-generated data file. It reads only files that are similar to the fixed-format NWS Tape Deck 3200. The input file is always the JIN interface file.

Data Units --

The type and units of data are defined by parameters METRIC, KUNIT and CONV on data group B2.

Input Format and Date Positions --

FIRMAT is the format of the input data. Enough fields should be included to account for the site, date and meteorological variables. Example formats are:

'(I6,3I2,F10.0)'	-- I6 field for the site ID, 3I2 for yr/mo/dy, and F10.0 for evaporation
'(3I3,F10.0,I6)'	-- 3I3 for yr/mo/dy, F10.0 for evaporation, and I6 for the site ID

The exact position of each field is user-defined. The parameters F1-F6 on data group B2 communicate the correct field position for year, month, day and either: (1) evaporation; (2) temperature, or (3) wind speed. For example, for the second format listed just above, required parameters F1 - F5 would be 5, 1, 2, 3, 4, respectively. See the above section on "Input and Output Files" for the procedure used for mixing the various types of data. The year may be entered either as a four-digit number (e.g., 1971) or two-digit number (e.g., 71). The program will determine which form is being used.

The program adopts the following convention for missing data, or data intentionally left missing. Temperature data are always interpolated by the Runoff Block using a polynomial method. The interpolation scheme will not be activated, however, for missing data periods longer than two weeks. Evaporation and wind speed data are not interpolated. The last value read is assumed to be the constant evaporation rate or wind speed until a new evaporation rate or wind speed is read. This allows the user to create, for example, a monthly time series of evaporation rates for continuous simulation by specifying a new evaporation rate for the first day of every month for every year simulated.

Table 11-2. Temp Block Input Data

SWMM INPUT GUIDELINES

There have been many changes made to the input format of SWMM. Following is a short list of the major changes along with explanations and guidelines.

1. Free format input. Input is no longer restricted to fixed columns. Free format has the requirement, however, that at least one space separate each data field. Free format input also has the following strictures on real, integer, and character data.

a. No decimal points are allowed in integer fields. A variable is integer if it has a 0 in the default column. A variable is real if it has a 0.0 in the default column.

b. Character data must be enclosed by single quotation marks, including both of the two title lines.

2. Data group identifiers are a requirement and <u>must</u> be entered in columns 1 and 2. These aid the program in line and input error identification and are an aid to the SWMM user. Also blank lines no longer are required to signal the end of sets of data group lines; the data group identifiers are used to identify one data group from another.

3. The data lines may be up to 230 columns long.

4. Input lines can wrap around. For example, a line that requires 10 numbers may have 6 on the first line and 4 on the second line. The FORTRAN READ statement will continue reading until it finds 10 numbers, e.g.,

```
Z1   1  2   3  4  5  6
     7  8   9 10
```

Notice that the line identifier is <u>not</u> used on the second line.

5. An entry must be made for <u>every</u> parameter in a data group, even if it is not used or zero and even if it is the last required field on a line. Trailing blanks are not assumed to be zero. Rather, the program will continue to search on subsequent lines for the "last" required parameter. Zeros can be used to enter and "mark" unused parameters on a line. This requirement also applies to character data. A set of quotes must be found for each character entry field. For instance, if the two run title lines (data group A1) are to consist of one line followed by a blank line, the entry would be:

```
A1 'This is line 1.'
A1 ''
```

6. See Section 2 for use of comment lines (indicated by an asterisk in column 1) and additional information.

Table 11-2 (continued). Temp Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	Two Title Lines	
A1	Group Identifier	None
SITE	Two 80 column descriptive titles.	'Title'
	Control Information	
B1	Group Identifier	None
IFORM	Format of data, = 0, NWS Tape Deck 3200, fixed length records, = 1, NWS Tape Deck 3200, variable length records, = 2, User defined format.	0
ISTA	NWS Station Number, or alternatively for user-defined data, an arbitrary station number.	0
KTYPE	Type of time series data. = 0, Daily maximum and minimum temperature. = 1, Daily evaporation. = 2, Daily wind speed. = 3, Daily temperature and evaporation. = 4, Daily temperature and wind speed. = 5, Daily evaporation and wind speed. = 6. Daily temperature, evaporation and wind speed.	0
IYBEG	Starting date (six digits). If zero the program searches for beginning year.	0
IYEND	Ending date (six digits). If zero the program reads all the station data.	0
IYEAR	Echo print of the KTYPE values read. = 0, Do not print raw data or summary tables, = 1, Print <u>all</u> the data and summary tables, and = 2, Print only monthly/yearly summary tables.	0
PAN(1) . . PAN(12)	January pan evaporation coefficient. Required only if evaporation data are read by the Temp Block. . . December pan evaporation coefficient. Required only if evaporation data are read by the Temp Block.	0.7 0.7

Table 11-2 (continued). Temp Block Input Data

VARIABLE	DESCRIPTION	DEFAULT
	User-defined temperature/evaporation/wind speed time series	
	Required only if IFORM = 2 on data group B1.	
B2	Group Identifier	0
FIRMAT	Format (character data). Should include a field for station number, year, month, day, and daily max-min temperature, evaporation, or wind speed.	'None'
METRIC	Metric input-output. = 0, Use U.S. customary units. = 1, Use metric units.	0
KUNIT	Units of temperature. Required field. = 0, Degrees F. = 1, Degrees C.	0
CONV	Conversion factor used to convert input units to internal SWMM units for evaporation (in./day or mm/day) and wind speed (miles/hr or km/hr), depending on the value of METRIC.	1.0
F1	Field position for station number. If F1 is zero a station number will not be read.	0
F2	Field position for year. Required.	0
F3	Field position for month. Required.	0
F4	Field position for day. Required.	0
F5	Field position for daily maximum temperature, or Field position for daily evaporation estimate, or Field position for wind speed.	0
F6	Field position for daily minimum temperature.	0

End of Temp Block Data

At this point the program seeks new input from the Executive Block.

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APPENDIX I

CONTINUOUS SIMULATION

CONTINUOUS AND SINGLE EVENT SIMULATION

The original (1971 and 1975 versions) Storm Water Management Model was designed for single-event simulation, and produced detailed (i.e., short time increment) hydrographs and pollutographs for individual storm events. SWMM may also be run for an unlimited number of time steps, for multiple events. In this mode an overall assessment of urban runoff problems and estimates of the effectiveness and costs of abatement procedures can be performed. Trade-offs among various control options, such as storage, treatment and street sweeping, may be evaluated. Complex interactions between the meteorology, e.g., precipitation patterns, and the hydrology of an area may be simulated without resorting to average values or very simplified methods. In this manner, critical events from the long period of simulation may be selected for detailed analysis. In addition, return periods for intensity, duration and volume (mass) of runoff (pollutant loads) may be assigned on the basis of the simulated record using the SWMM Statistics Block. In this manner, the critical events chosen for study may be substituted for synthetic design storms (e.g., "SCS Type-II") the latter often being synthesized from intensity-duration-frequency curves on the basis of questionable statistical assumptions (Huber et al., 1986). Linsley and Crawford (1974) present a useful discussion of continuous simulation in urban hydrology.

Several continuous simulation models are available for urban runoff analysis. Among the earliest was the Stanford Watershed Model (Crawford and Linsley, 1966), out of which evolved the HSPF Model (Johanson et al., 1980), a versatile program for natural and agricultural as well as urban areas. It uses a 15 minute time step whereas a 5 minute time step is used by the Dorsch QQS model (Geiger et al., 1974; Geiger and Dorsch, 1980). A widely-used continuous simulation model for urban areas is STORM (Hydrologic Engineering Center, 1977; Roesner et al., 1974), developed by Water Resources Engineers, the City of San Francisco and the Hydrologic Engineering Center of the Corps of Engineers. It utilizes one hour time steps coupled with simplified runoff and pollutant estimation procedures and has been extensively used for planning (Roesner et al., 1974) and overall urban runoff evaluation (Heaney et al., 1977). A similar, but even simpler model, still producing useful statistics of long-term urban runoff, is the Simplified Storm Water Management Model developed by Metcalf and Eddy, Inc. (Lager et al., 1976). Finally, several "first cut" procedures have been developed, based in part upon continuous simulation, but avoiding any computer usage at all (Hydroscience, Inc., 1976; Howard, 1976; Heaney et al., 1976; Chan and Bras, 1979).

CONTINUOUS SWMM OVERVIEW

SWMM may be run continuously using any (or all) of the blocks, although the most convenient output summaries are in the Runoff and Storage/Treatment Blocks. The Statistics Block is almost always used to analyze the continuous time series produced during a continuous simulation. A "Level III" receiving water model that will couple with either SWMM or STORM has been developed based upon earlier work (Heaney et al., 1977) and is documented (Medina, 1979). There is no functional distinction between single-event and continuous simulation. In general, any time step and any number of time steps may be used for any simulation.

INPUT DATA

Continuous SWMM requires the same data entries as for the event mode. A coarse schematization greatly reduces the amount of entries required for subcatchments and channels (see below). The key data need is a long-term precipitation record for the area. SWMM is keyed to the use of magnetic tapes available from the National Climatic Data Center of the NWS at Asheville, North Carolina. These tapes contain at least 25 years of hourly data for most stations and cost up to a few hundred dollars depending on the amount of processing required. A tape will ordinarily contain data for all the stations in one or more states. (Similar tapes are supplied in Canada by the Atmospheric Environment Service.) When snowmelt is simulated, a record of daily temperature data is also required; see the snowmelt documentation in Appendix II and Chapter 4. These data are processed in by the Rain and Temp Blocks for later use by the other blocks. Optionally, the processed data, including a tabulation of the 50 highest values, may be examined prior to proceeding with the remainder of the simulation. When snowmelt is simulated, rainfall or snowfall is determined from hourly air temperatures synthesized from the daily max-min values for the station. Snowfall values are keyed as negative precipitation for internal use in the program. Other input data unique to continuous simulation consist mainly of dates for starting and stopping, printing, etc.

CATCHMENT SCHEMATIZATION

Guidelines for subcatchment "lumping" or aggregation as described by Smith (1975) and Proctor and Redfern, Ltd. and James F. MacLaren, Ltd. (1976a, 1976b) are given in Section 4. In general, almost identical outlet hydrographs may be produced using only one subcatchment and one or no channel/pipes as for a detailed schematization, using several subcatchments and channel/pipes. A key parameter to be adjusted is the subcatchment width. Quality comparisons may be more variable depending upon how the several land uses and/or pollutant loading rates are aggregated.

OUTPUT

Runoff Block

Output from single-event simulation consists basically of hydrographs and

pollutographs printed over the whole event at a specified interval of time steps (e.g., every time step). Continuous SWMM retains this option for up to five user-specified date intervals. In addition, daily, monthly, annual and grand total values for runoff, precipitation and pollutant loads are provided. Daily totals are printed whenever there is runoff and/or precipitation.

In addition, the 50 highest hourly totals are listed, by both runoff volume and BOD load. These may be compared to the 50 highest hourly rainfall depths and used in selecting critical time periods for more detailed study. For example, a two-year simulation of a 312 ac (126 ha) catchment tributary to Lake Calhoun in Minneapolis was made, and the ten highest rainfall, runoff and BOD loads (from the output of the 50 highest) are shown in Table I-1. The comparisons indicate that the rankings differ according to the antecedent conditions, etc. affecting each parameter. For example, the highest rainfall depth corresponds to the third highest runoff depth and second highest BOD load. The table adds further justification to the contention that it is necessary to treat rainfall, runoff and pollutant loads separately in terms of statistical analyses.

Statistics Block

The most useful review of continuous SWMM output is probably accomplished using the Statistics Block where a frequency analysis of many storm quantity and quality parameters (e.g., depth, duration, interevent time, load, peak concentration, etc.) may be performed. Output is available in both tabular and graphical forms. Analysis by the Statistics Block may follow any other block whether or not a long-term (continuous) simulation was run.

Other Blocks

There is no distinction made between output for a single-event or continuous simulation in the Transport, Extran or Storage/Treatment Blocks.

DRY-PERIOD REGENERATION

Quantity

Infiltration capacity is regenerated during dry periods assuming an exponential "drying curve" analogous to the "wetting curve" of Horton's equation (see Appendix V). Monthly evaporation totals are used to regenerate depression storage on both pervious and impervious areas and are also considered an initial "loss" for each time step with rainfall. Computations are bypassed during dry periods if infiltration and depression storage regeneration is complete.

Quality

Pollutant loadings on the subcatchment surfaces are generated during dry time steps (i.e., no runoff) depending upon how they are input initially. Linear or non-linear buildup may be used, with or without an upper limit. If

Table I-1. Hourly Event Ranking by Rain Flow and BOD for Two Year Simulation of Lake Calhoun Catchment, Minneapolis.

Ten highest values are taken from the tabulated output of 50 highest given by SWMM.

Rank	Date	Hr	Rain (in./hr)	Date	Hr	Flow (in./hr)	Date	Hr	BOD (lb/min)
1	7/20/51	22	0.98	7/21/51	2	0.543	5/15/51	22	16.78
2	7/21/51	1	0.80	7/20/51	23	0.429	7/20/51	22	12.88
3	7/22/50	15	0.79	7/20/51	22	0.392	7/16/51	2	9.62
4	7/30/51	8	0.65	5/15/51	22	0.383	7/20/51	23	7.64
5	5/15/51	21	0.63	7/21/51	1	0.320	5/15/51	21	6.19
6	7/21/51	2	0.56	7/30/51	8	0.295	9/08/51	20	5.70
7	9/11/51	23	0.55	7/16/51	2	0.254	7/22/51	15	5.43
8	8/07/51	18	0.54	7/22/51	16	0.253	7/30/51	8	5.42
9	5/05/50	10	0.49	5/18/51	16	0.238	5/05/50	10	5.25
10	6/25/51	24	0.49	7/22/50	15	0.221	7/22/50	16	5.11

desired, a rating curve (load versus flow) may be used instead of a washoff equation.

Street sweeping occurs at intervals specified for each land use. The intervals are computed on the basis of intervening dry time steps. A dry time step is one in which the subcatchment receives no precipitation and has no water remaining in impervious area depression storage or as snow. When snowmelt is simulated, street sweeping may be bypassed for a specified interval of the year (e.g., the winter months). Runoff simulates any ten quality parameters with arbitrary units, plus, optionally, erosion using the Universal Soil Loss Equation. As a user option, regeneration of selected constituents (e.g., chlorides) during dry periods will occur only when snow is present.

CONTINUOUS SWMM COMPARED TO STORM

Comparisons of SWMM and STORM, without S/T simulation, indicate that the two outputs are comparable and STORM is approximately 50 percent faster. Why, then, might SWMM be used over STORM or other existing continuous models? When just the Runoff Block is required, STORM could be the choice because of its simplicity, good documentation, useful output or inclusion of the SCS method for rural runoff generation. SWMM might be preferred if smaller time-steps than one hour were needed, or if flow routing in channel/pipes were desired, or if particular features of runoff or quality generation were needed. In addition, SWMM couples both the single-event and continuous simulation capability into one model. Finally, the Statistics Block of SWMM is a very flexible routine for a large variety of post-processing of continuous time series, including separation into independent events and frequency analysis.

APPENDIX II

SWMM SNOWMELT ROUTINES

INTRODUCTION

Snowmelt is an additional mechanism by which urban runoff may be generated. Although flow rates are typically low, they may be sustained over several days and remove a significant fraction of pollutants deposited during the winter. Rainfall events superimposed upon snowmelt baseflow may produce higher runoff peaks and volumes as well as add to the melt rate of the snow.

In the context of long term continuous simulation, runoff and pollutant loads are distributed quite differently in time between the cases when snowmelt is and is not simulated. The water and pollutant storage that occurs during winter months in colder estimates cannot be simulated without including snowmelt.

Several hydrologic models include snowmelt computations, e.g., Stanford Watershed Model (Crawford and Linsley, 1966), HSPF (Johanson et al., 1980), NWS (Anderson, 1973, 1976), STORM (Hydrologic Engineering Center, 1977; Roesner et al., 1974) and SSARR (Corps of Engineers, 1971). Of these examples, only HSPF and STORM include pollutant routing options. Useful summaries of snowmelt modeling techniques are available in texts by Fleming (1975), Eagleson (1970), Linsley et al. (1975), Viessman et al. (1977), and Gray (1970). All of these draw upon the classic work, Snow Hydrology, of the Corps of Engineers (1956).

As part of a broad program of testing and adaptation to Canadian conditions, a snowmelt routine was placed in SWMM for single event simulation by Proctor and Redfern, Ltd. and James F. MacLaren, Ltd., abbreviated PR-JFM (1976a, 1976b, 1977), during 1974-1976. The basic melt computations were based on routines developed by the U.S. National Weather Service, NWS (Anderson, 1973). The work herein has utilized the Canadian SWMM snowmelt routines as a starting point and has considerably augmented their capabilities as well as added the facility for snowmelt computations while running continuous SWMM. In addition, features have been added which aid in adapting the snowmelt process to urban conditions since most efforts in the past, except for STORM, have been aimed at simulation of spring melt in large river basins. The work of the National Weather Service (Anderson, 1973) has also been heavily utilized, especially for the extension to continuous simulation and the resulting inclusion of cold content, variable melt coefficients and areal depletion.

The following sections describe the methodology presently programmed in the SWMM Runoff Block. It is intended to aid in understanding the various input parameters required, computations performed, and the output produced.

OVERVIEW

Snow Depth

Throughout the program, all snow depths are treated as "depth of water equivalent" to avoid specification of the specific gravity of the snow pack which is highly variable with time. The specific gravity of new snow is of the order of 0.09; an 11:1 or 10:1 ratio of snow pack depth to water equivalent depth is often used as a rule of thumb. With time, the pack compresses until the specific gravity can be considerably greater, to 0.5 and above. In urban areas, lingering snow piles may resemble ice more than snow with specific gravities approaching 1.0. Although snow pack heat conduction and storage depend on specific gravity, sufficient accuracy may be obtained without using it. It is adequate to maintain continuity through the use of depth of water equivalent.

Most input parameters are in units of inches of water equivalent (in. w.e.). For all computations, conversions are made to feet of water equivalent.

Single Event Simulation

For most SWMM calculations, there is no functional distinction between single event and continuous simulation. However, for snowmelt calculations, the user can specify (through parameter ISNOW in Runoff Block data group B1) whether melt is to be treated in a single event or continuous form. For single event simulation, it is unnecessary to generate a long record of precipitation and temperature data. Snow quantities are input as initial depths (water equivalent) on subcatchments and as negative rainfall intensities on rainfall input data groups. Snowfall is generally keyed as negative precipitation on input files. Temperature data are read for each time step from line input. The air temperature time step is defined by parameter DTAIR on data group C5. (Other parameters are explained subsequently.)

During the simulation, melt is generated at each time step using a degree-day type equation during dry weather and Anderson's NWS equation (1973) during rainfall periods. Specified, constant areas of each subcatchment are designated as snow covered. Melt, after routing through the remaining snow pack, is combined with rainfall to form the spatially weighted "effective rainfall" for overland flow routing.

Continuous Simulation

For continuous simulation, hourly precipitation depths from NWS magnetic tapes are utilized along with daily max-min temperatures from other NWS tapes. The latter are interpolated sinusoidally to produce the temperature value at the beginning of a time step, as explained in detail in the next subsection. If temperatures are below a dividing value (e.g., 32°F), precipitation values are treated as snow and keyed with a negative sign. The interpolated temperatures are also used in the melt computations.

Melt is again generated using a degree-day type equation during dry

weather and Anderson's NWS equation during rainfall periods. In addition, a record of the cold content of the snow is maintained. Thus, before melt can occur, the pack must be "ripened," that is, heated to a specified base temperature.

One partition of the urban subcatchment is the "normally bare impervious area." This is intended to represent surfaces such as streets, parking lots and sidewalks which are subject to plowing or snow "redistribution". The program includes this feature.

Following the practice of melt computations in natural basins, "areal depletion curves" describe the spatial extent of snow cover as the pack melts. For instance, shaded areas would be expected to retain a snow cover longer than exposed areas. Thus, the snow covered area of each subcatchment changes with time during continuous simulation.

Melt computations themselves proceed as in the single event simulation, except that the degree-day melt coefficients vary sinusoidally, from a maximum on June 21 to a minimum on December 21.

Pollutant Simulation

Pollutant washoff is simulated using combined runoff from snowmelt and/or rainfall. For continuous SWMM, regeneration of any pollutant may depend upon whether snow cover is present if, for example, chlorides are to be simulated.

SNOW AND TEMPERATURE GENERATION FROM NWS TAPES

National Weather Service (NWS) Data

Continuous SWMM utilizes long-term precipitation and temperature data obtained from the National Climatic Data Center (NCDC) at Asheville, North Carolina for the nearest NWS or airport weather station of record. (Similar data, but with a different format, are available in Canada from the Atmospheric Environment Service). If snowmelt is not simulated only the precipitation tape is needed; hourly precipitation totals are included on it for every day with measurable precipitation. For continuous SWMM without snowmelt, all such hourly values are treated as rainfall.

Maximum and minimum temperatures as well as several other meteorological parameters are given for every day of the year on the NCDC's "Surface Land Daily Cooperative, Summary of Day, TD-3200." For snowmelt, only the ID number, date and max-min temperatures are used although other data (e.g., evaporation) may be used for other purposes. Note that the ID number for TD-3200 is not necessarily the same as for the hourly precipitation data. The data are accessed in the Rain and Temp Blocks, usually directly from the magnetic tape. The unit number of the tape is input in the Executive Block as NSCRAT(1). As explained in the description of continuous SWMM, a magnetic tape containing card images of hourly precipitation values is accessed similarly using unit number JIN(1).

Temperature data are input and processed for every day of the year, in-

cluding summer months. Should an entry (date) be missing, the max-min values for the previous day are used.

Creation of Hourly Temperatures

The "Summary of Day" or temperature tape does not list the time of day at which the minimum and maximum temperatures occur. Hence, the minimum temperature is assumed to occur at sunrise each day, and the maximum is assumed to occur three hours prior to sunset. All times are rounded to the nearest hour. This scheme obviously cannot account for many meteorological phenomena that would create other temperature-time distributions but is apparently the most appropriate one under the circumstances. Given the max-min temperatures and their assumed hours of occurrence, the other 22 hourly temperatures are readily created by sinusoidal interpolation, as sketched in Figure II-1. The interpolation is performed, using three different periods: 1) between the maximum of the previous day and the minimum of the present, 2) between the minimum and maximum of the present, and 3) between the maximum of the present and minimum of the following.

The time of day of sunrise and sunset are easily obtained as a function of latitude and longitude of the catchment and the date. Techniques for these computations are explained, for example, by List (1966) and by the TVA (1972). The Runoff Block utilizes approximate (but sufficiently accurate) formulas given in the latter reference. Their use is explained briefly below.

The hour angle of the sun, h, is the angular distance between the instantaneous meridian of the sun (i.e., the meridian through which passes a line from the center of the earth to the sun) and the meridian of the observer (i.e., the meridian of the catchment). It may be measured in degrees or radians or readily converted to hours, since 24 hours is equivalent to 360 degrees or 2 pi radians. The hour angle is a function of latitude, declination of the earth and time of day and is zero at noon, true solar time, and positive in the afternoon. However, at sunrise and sunset, the solar altitude of the sun (vertical angle of the sun measured from the earth's surface) is zero, and the hour angle is computed only as a function of latitude and declination,

$$\cos h = - \tan \delta \cdot \tan \phi \qquad \text{(II-1)}$$

where h = hour angle, radians,
δ = earth's declination, a function of season (date), radians, and
ϕ = latitude of observer, radians.

The earth's declination is provided in tables (e.g., List, 1966), but for programming purposes an approximate formula is used (TVA, 1972):

$$\delta = \left(\frac{23.45 \text{ pi}}{180}\right) \cos \left[\frac{2 \text{ pi}}{365} (172 - D)\right] \qquad \text{(II-2)}$$

where D is number of the day of the year (no leap year correction is warranted) and d is in radians. Having the latitude as an input parameter, the

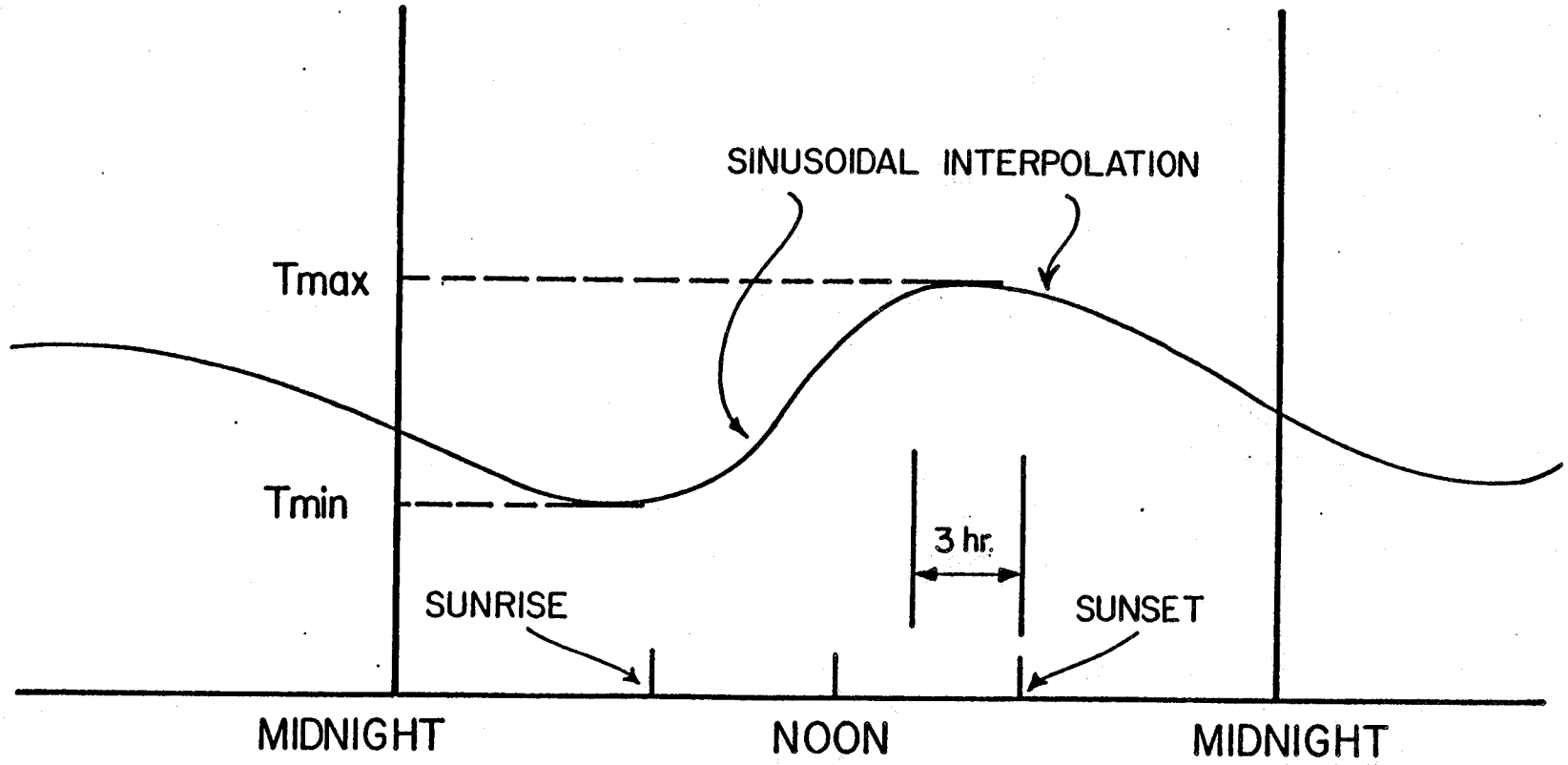


Figure II-1. Sinusoidal Interpolation of Hourly Temperatures.

hour angle is thus computed in hours, positive for sunset, negative for sunrise, as

$$h = (12/pi) \cos^{-1} (-\tan \delta \cdot \tan \phi) \qquad \text{(II-3)}$$

The computation is valid for any latitude between the arctic and antarctic circles, and no correction is made for obstruction of the horizon.

The hour of sunrise and sunset is symmetric about noon, true solar time. True solar noon occurs when the sun is at its highest elevation for the day. It differs from standard zone time, i.e., the time on clocks) because of a longitude effect and because of the "equation of time". The latter is of astronomical origin and causes a correction that varies seasonally between approximately +/- 15 minutes.; it is neglected here. The longitude correction accounts for the time difference due to the separation of the meridian of the observer and the meridian of the standard time zone. These are listed in Table II-1. It is readily computed as

$$DTLONG = 4 \frac{\text{minutes}}{\text{degree}} \times (\Theta - SM) \qquad \text{(II-4)}$$

where DTLONG = longitude correction, minutes (of time),
Θ = longitude of the observer, degrees, and
SM = standard meridian of the time zone, degrees, from Table II-1.

Note that DTLONG can be either positive or negative, and the sign should be retained. For instance, Boston at approximately 71°W has DTLONG = -16 minutes, meaning that mean solar noon precedes EST noon by 16 minutes. (Mean solar time differs from true solar time by the neglected "equation of time.")

The time of day of sunrise is then

$$HSR = 12 - h + DTLONG/60 \qquad \text{(II-5)}$$

and the time of day of sunset is

$$HSS = 12 + h + DTLONG/60 \qquad \text{(II-6)}$$

These times are rounded to the nearest hour for use in continuous SWMM. As stated earlier, the maximum temperature is assumed to occur at hour HSS - 3.

Standard time is used in all calculations and in NWS tapes. There is no input or output that includes allowance for daylight savings time.

Generation of Snowfall Intensities

The estimated hourly temperatures, T, in °F, are compared to a dividing temperature, SNOTMP, for each hour with precipitation. Then if

$$T > SNOTMP, \text{ precipitation = rain;}$$
$$T \geq SNOTMP, \text{ precipitation = snow.} \qquad \text{(II-7)}$$

Snowfall depths are tagged as negative quantities for identification by later components of the program.

Table II-1. Time Zones and Standard Meridians

Time Zone	Example Cities	Standard Meridian
Newfoundland Std. Time	St. Johns's, Newfoundland	52.5[a]
Atlantic Std. Time	Halifax, Nova Scotia San Juan, Puerto Rico	60
Eastern Std. Time	New York, New York	75
Central Std. Time	Chicago, Illinois	90
Mountain Std. Time	Denver, Colorado	105
Pacific Std. Time	San Francisco, California	120
Yukon Std. Time	Yakutat, Alaska[b]	135
Alaska Std. Time Hawaiian Std. Time	Anchorage, Alaska Honolulu, Hawaii	150
Bering Std. Time	Nome, Alaska	165

[a]The time zone of the island of Newfoundland is offset one half hour from other zones.
[b]All of the Yukon Territory is on Pacific Standard Time.

Gage Catch Deficiency Correction

Precipitation gages tend to produce inaccurate snowfall measurements because of the complicated aerodynamics of snow flakes falling into the gage. Snowfall totals are generally underestimated as a result, by a factor that varies considerably depending upon gage exposure, wind velocity and whether or not the gage has a wind shield. The program includes a parameter, SCF, which multiplies snow depths only.

Although it will vary considerable from storm to storm, SCF acts as a mean correction factor over a season in the model. Anderson (1973) provides typical values of SCF as a function of wind speed, as shown in Figure II-2, that may be helpful in establishing an initial estimate. The value of SCF can also be used to account for other factors, such as losses of snow due to interception and sublimation not accounted for in the model. Anderson (1973) states that both losses are usually small compared to the gage catch deficiency.

Structure of Precipitation - Temperature Data Set

The Rain and Temp Blocks create output files from the NWS precipitation and temperature data tapes that are subsequently read as input by the Runoff Block. The interested user can find descriptions of the output file format used by the Rain and Temp Blocks in Sections 10 and 11, respectively.

Single Event SWMM

NWS tapes are not used in single event simulation. Precipitation is entered on Runoff Block data group E1-E3. However, snowfall can be included, if desired, as a negative precipitation value at any time step.

SUBCATCHMENT SCHEMATIZATION

Land Surface - Snow Cover Combinations

In order to have flexibility in treating different combinations of snow cover and ground surface types, four such combinations are provided, as described in Table II-2 and illustrated in Figure II-3. When snowmelt is not simulated, only the first three are used, as in the past. (Type 3, impervious area with no depression storage, is specified in Runoff by the parameter PCTZER, percent of impervious area with immediate runoff.) Snow cover is treated identically on types 1 and 3 since these surfaces are likely to be of similar nature, e.g., streets, sidewalks, parking lots, etc. For continuous simulations, these surfaces are considered "normally bare" because of probable plowing, salting or other rapid snow removal, but are subject to snow cover also, as described subsequently. For single event simulation, these surfaces are always bare; all snow on impervious areas is handled in type 4.

In Runoff, especially subroutine WSHED, the "types" are subscripts for the parameter WDEPTH, the water depth on each surface type. Since snow cover is the same for types 1 and 3, snow depths, WSNOW, are only triply subscripted.

For single event simulation, the fraction of snow-covered pervious area is constant; for continuous simulation the fraction varies according to an areal depletion curve (as for type 4 impervious). The depletion curves are explained later.

Apportionment of impervious area is different when simulating with and without snowmelt. For the latter situation, the area with zero depression storage (type 3) is taken to be a percentage, PCTZER, of the total impervious area. For the former situation (with snowmelt), it is taken as a percentage, the "normally bare" impervious area (continuous simulation). Thus, the type 3 area will vary according to whether snowmelt is simulated or not, as shown in Figure II-3. The effect on outflow is very minor. The fraction of impervious area with 100 percent snow cover (single event) or subject to an areal depletion curve (continuous) is an input parameter, SNN1, for each subcatchment.

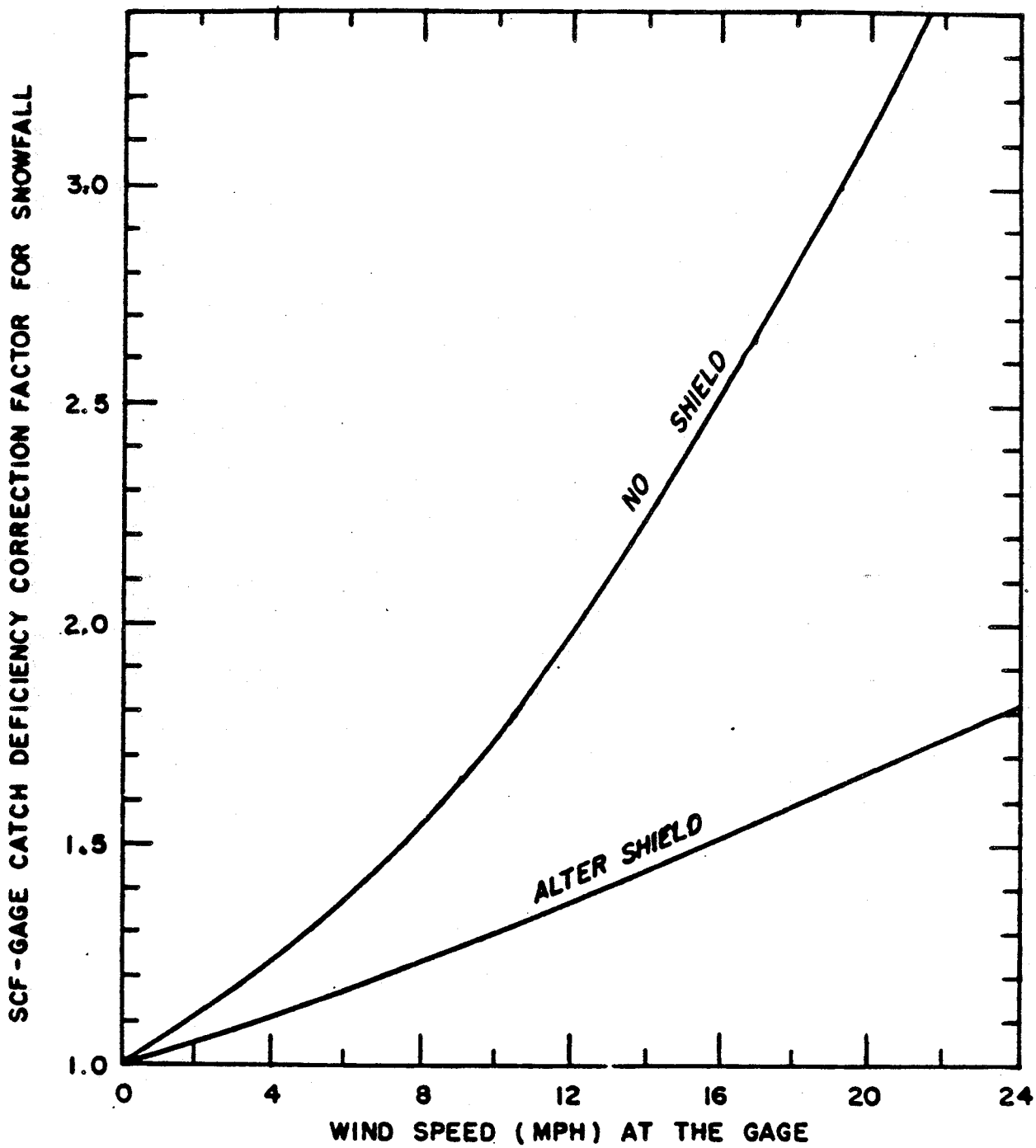


Figure II-2. Typical Gage Catch Deficiency Correction (Anderson, 1973, p. 5-20).

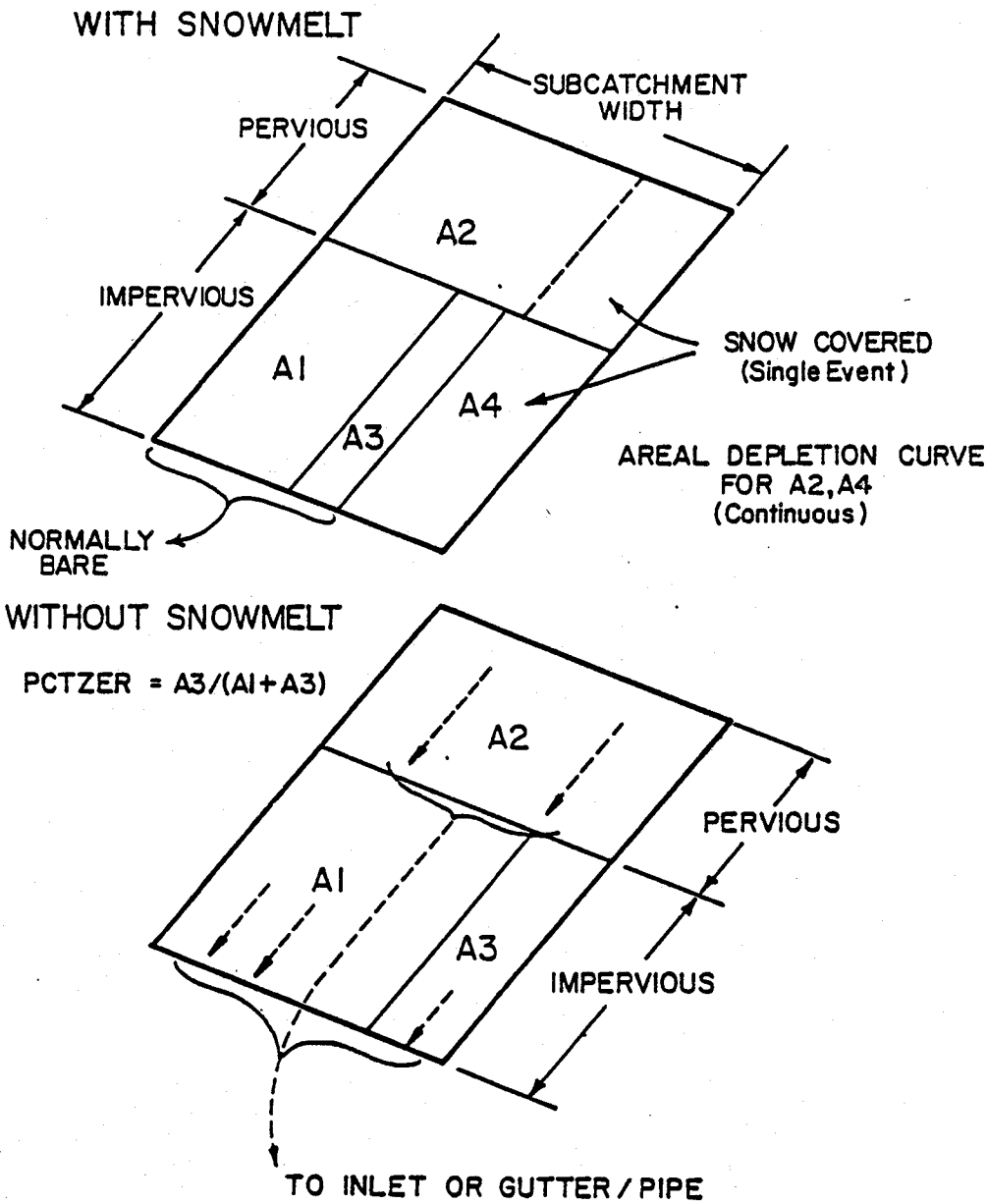


Figure II-3. Subcatchment Schematization With and Without Snowmelt Simulation. See also Table II-2.

Table II-2. Subcatchment Surface Classification

Type	Perviousness	Depression Storage	Snow Cover and Extent: Single Event*	Snow Cover and Extent: Continuous*
1	Impervious	Yes	Bare	Normally bare, but may have snow cover over 100% of type 1 plus type 3 area.
2	Pervious	Yes	Constant fraction, SNCP, of area is snow covered.	Snow covered subject to areal depletion curve.
3	Impervious	No	Bare	Same as type 1.
4	Impervious	Yes	100% covered.	Snow covered subject to areal depletion curve.

*Single event or continuous is determined by parameter ISNOW in Runoff Block input.

Redistribution and Simulation of Snow Removal

Snow removal practices form a major difference between the snow hydrology of urban and rural areas. Much of the snow cover may be completely removed from heavily urbanized areas, or plowed into windrows or piles, with melt characteristics that differ markedly from those of undisturbed snow. Management practices in cities vary according to location, climate, topography and the storm itself; they are summarized in a study by APWA (1974). It is probably not possible to treat them all in a simulation model. See Table R-20. However, in continuous SWMM, provision is made to approximate simulation of some practices.

It is assumed that all snow subject to "redistribution", (e.g. plowing) resides on the "normally bare" category, type 1 plus 3 above, (see Figure II-3), that might consist of streets, sidewalks, parking lots, etc. (The desired degree of definition may be obtained by using several subcatchments, although a coarse schematization, e.g., one or two subcatchments, may be sufficient for some continuous simulations.) For each subcatchment, a depth of snow, WEPLOW, is input for this area, above which redistribution occurs as indicated in Figure II-4. All snow in excess of this depth, say 0.1 - 0.2 in. water equivalent (2.5 - 5.1 mm), is redistributed to other areas according to five fractions, SFRAC, input for each subcatchment. These are described on Figure II-4. For instance, if snow is usually windrowed onto adjacent impervious or pervious areas, SFRAC(1) or SFRAC(2) may be used. If it is trucked to another subcatchment (the last one input is used for this purpose), a fraction

A1 = IMPERVIOUS AREA WITH DEPRESSION STORAGE
A2 = PERVIOUS AREA
A3 = IMPERVIOUS AREA WITH ZERO DEPRESSION STORAGE
A4 = SNOW COVERED IMPERVIOUS AREA

A1 + A3 = NORMALLY BARE

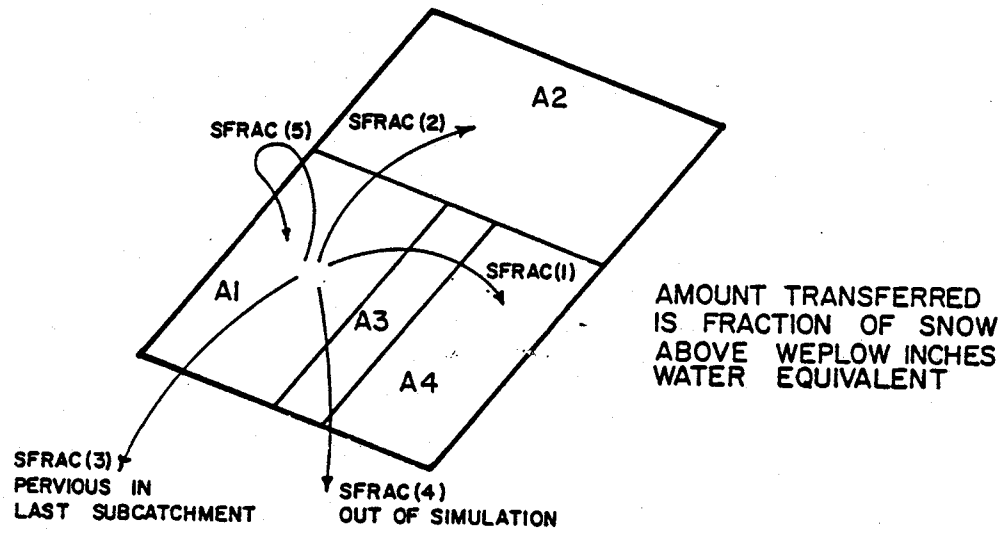


Figure II-4. Redistribution of Snow During Continuous Simulation.

SFRAC(3) will so indicate, or SFRAC(4) if the snow is removed entirely from the simulated watershed. In the latter case, such removals are tabulated and included in the final continuity check. Finally, excess snow may be immediately "melted" (i.e., treated as rainfall), using SFRAC(5). The transfers are area weighted, of course, and the five fractions should sum to 1.0. A depth of snow WEPLOW remains on the normally bare area and is subject to melting as on the other areas. See Table II-3 for guidelines as to typical levels of service for snow and ice control (Richardson et al, 1974).

No pollutants are transferred with the snow. The transfers are assumed to have no effect on pollutant washoff and regeneration. In addition, all the parameters of this process remain constant throughout the simulation and can only represent averages over a snow season.

The redistribution simulation does not account for snow management practices using chemicals, e.g., roadway salting. This is handled using the melt equations, as described subsequently.

Array Restrictions

Continuous snowmelt and single event snowmelt are limited to the number of subcatchments defined by the variable NOW in the parameter statement of the /Tapes/ Common. The NOW parameter is 100 in the default version of SWMM. This should be more than adequate for continuous simulation, with or without snowmelt, since only a coarse catchment discretization should be sufficient.

MELT CALCULATIONS

Theory of Snowmelt

Introduction --

Excellent descriptions of the processes of snowmelt and accumulation are available in several texts and simulation model reports and in the well known 1956 Snow Hydrology report by the Corps of Engineers (1956). The important heat budget and melt components are first mentioned briefly here; any of the above sources may be consulted for detailed explanations. A brief justification for the techniques adopted for snowmelt calculations in SWMM is presented below.

Snowpack Heat Budget --

Heat may be added or removed from a snowpack by the following processes:

1. Absorbed solar radiation (addition).

2. Net longwave radiation exchange with the surrounding environment (addition or removal).

3. Convective transfer of sensible heat from air (addition or removal).

Table II-3. Guidelines for Levels of Service in Snow and Ice Control (Richardson et al., 1974).

Road Classification	Level of Service	Snow Depth to Start Plowing (Inches)	Max. Snow Depth on Pavement (Inches)	Full Pavement Clear of Snow After Storm (Hours)	Full Pavement Clear of Ice After Storm Hours
1. Low-Speed Multilane Urban Expressway	• Roadway routinely patrolled during storms • All traffic lanes treated with chemicals • All lanes (including breakdown lanes) operable at all times but at reduced speeds • Occasional patches of well-sanded snow pack • Roadway repeatedly cleared by echelons of plows to minimize traffic disruption • Clear pavement obtained as soon as possible	0.5 to 1	1	1	12
2. High-Speed 4-Lane Divided Highways Interstate System ADT greater than 10,000[a]	• Roadway routinely patrolled during storms • Driving and passing lanes treated with chemicals • Driving lane operable at all times at reduced speeds • Passing lane operable depending on equipment availability • Clear pavement obtained as soon as possible	1	2	1.5	12
3. Primary Highways Undivided 2 and 3 lanes ADT 500 -- 5000[a]	• Roadway is routinely patrolled during storms • Mostly clear pavement after storm stops • Hazardous areas receive treatment of chemicals or abrasive • Remaining snow and ice removed when thawing occurs	1	2.5	2	24
4. Secondary Roads ADT less than 500[a]	• Roadway is patrolled at least once during a storm • Bare left-wheel track with intermittent snow cover • Hazardous areas are plowed and treated with chemicals or abrasives as a first order of work • Full width of road is cleared as equipment becomes available	2	3	3	48

[a] ADT - average daily traffic

4. Release of latent heat of vaporization by condensate (addition) or, the opposite, its removal by sublimation (removing the latent heat of vaporization plus the latent heat of fusion).

5. Advection of heat by rain (addition) plus addition of the heat of fusion if the rain freezes.

6. Conduction of heat from underlying ground (removal or addition).

The terms may be summed, with appropriate signs, and equated to the change of heat stored in the snowpack to form a conservation of heat equation. All of the processes listed above vary in relative importance with topography, season, climate, local meteorological conditions, etc., but items 1-4 are the most important. Item 5 is of less importance on a seasonal basis, and item 6 is often neglected.

A snow pack is termed "ripe" when any additional heat will produce liquid runoff. Rainfall (item 5) will rapidly ripen a snowpack by release of its latent heat of fusion as it freezes in subfreezing snow, followed by quickly filling the free water holding capacity of the snow.

Melt Prediction Techniques --

Prediction of melt follows from prediction of the heat storage of the snow pack. Energy budget techniques are the most exact formulation since they evaluate each of the heat budget terms individually, requiring as meteorologic input quantities such as solar radiation, air temperature, dew point or relative humidity, wind speed, and precipitation. Assumptions must be made about the density, surface roughness and heat and water storage (mass balance) of the snow pack as well as on related topographical and vegetative parameters. Further complications arise in dealing with heat conduction and roughness of the underlying ground and whether or not it is permeable.

Several models individually treat some or all of these effects. One of the more recent was developed for the NWS river forecast system by Anderson (1976). Interestingly, under many conditions he found that results obtained using his energy balance model were not significantly better than those obtained using simpler (e.g., degree-day or temperature-index) techniques in his earlier model (1973). The more open and variable the conditions, the better is the energy balance technique. Closest agreement between his two models was for heavily forested watersheds.

Minimal data needed to apply an energy balance model are a good estimate of incoming solar radiation, plus measurements of air temperature, vapor pressure (or dew point or relative humidity) and wind speed. All of these data, except possibly solar radiation, are available at at least one location (e.g., the airport) for almost all reasonably sized cities. Even solar radiation measurements are taken at several locations in most states. Predictive techniques are also available, for solar radiation and other parameters, based on available measurements (TVA, 1972; Franz, 1974).

Choice of Predictive Method --

Two major reasons suggest that simpler, e.g., temperature-index, techniques should be used for simulation of snowmelt and accumulation in urban areas. First, even though required meteorologic data for energy balance models are likely to be available, there is a large local variation in the magnitude of these parameters due to the urbanization itself. For example, radiation melt will be influenced heavily by shading of buildings and albedo reduced by urban pollutants. In view of the many unknown properties of the snowpack itself in urban areas, it may be overly ambitious to attempt to predict melt at all! But at the least, simpler techniques are probably all that are warranted. They have the added advantage of considerably reducing the already extensive input data to a model such as SWMM.

Second, the objective of the modeling should be examined. Although it may contribute, snowmelt seldom causes flooding or hydrologic extremes in an urban area itself. Hence, exact prediction of flow magnitudes does not assume nearly the importance it has in the models of, say, the NWS, in which river flood forecasting for large mountainous catchments is of paramount importance. For planning purposes in urban areas, exact quantity (or quality) prediction is not the objective in any event; rather, these efforts produce a statistical evaluation of a complex system and help identify critical time periods for more detailed analysis.

For these and other reasons, simple snowmelt prediction techniques have been incorporated into SWMM. Anderson's NWS (1973) temperature-index method is also well documented and tested, and has been incorporated into SWMM. As described subsequently, the snowmelt modeling follows Anderson's work in several areas, not just in the melt equations. The energy budget technique is illustrated later to show how it reduces to a temperature-index equation under certain assumptions. It may be noted that the STORM model (Hydrologic Engineering Center, 1977; Roesner et al., 1974) also uses the temperature-index method for snowmelt prediction, in a considerably less complex manner than is now programmed in SWMM.

SWMM Melt Equations

Anderson's NWS model (1973) treats two different melt situations: with and without rainfall. When there is rainfall (greater than 0.1 in./6 hr or 2.5 mm/6 hr in the NWS model; greater than 0.02 in./hr or 0.51 mm/hr in SWMM), accurate assumptions may be made about several energy budget terms. These are: zero solar radiation, incoming longwave radiation equals blackbody radiation at the ambient air temperature, the snow surface temperature is 32°F (0°C), and the dew point and rain water temperatures equal the ambient air temperature. Anderson combines the appropriate terms for each heat budget component into one equation for the melt rate. As used in subroutine MELT in SWMM, it is:

$$\text{SMELT} = (\text{TA} - 32)\cdot(0.001167 + \text{SGAMMA}\cdot\text{UADJ} + 0.007\cdot\text{PREC}) + 8.5\cdot\text{UADJ}\cdot(\text{EA} - 0.18) \qquad \text{(II-8)}$$

where SMELT = melt rate, in./hr,

TA = air temperature, ^{o}F,
SGAMMA = 7.5·GAMMA, in. Hg/^{o}F,
GAMMA = psychometric constant, in. Hg/^{o}F,
UADJ = wind speed function, in. /in. Hg - hr,
PREC = rainfall intensity, in./hr, and
EA = saturation vapor pressure at air temperature, in. Hg.

The psychometric constant, GAMMA, is calculated as:

$$GAMMA = 0.000359 \cdot PA \qquad \text{(II-9)}$$

where PA = atmospheric pressure, in. Hg.

Average atmospheric pressure is in turn calculated as a function of elevation, z:

$$PA = 29.9 - 1.02\ (z/1000) + 0.0032 \cdot (z/1000)^{2.4} \qquad \text{(II-10)}$$

where z = average catchment elevation, ft.

The elevation, z, is an input parameter, ELEV. The wind function, UADJ, accounts for turbulent transport of sensible heat and water vapor. Anderson (1973) gives:

$$UADJ = 0.006 \cdot u \qquad \text{(II-11)}$$

where UADJ = wind speed function, in./in. Hg - hr, and
u = average wind speed 1.64 ft (0.5 m) above the snow surface, mi/hr.

In practice, available wind data are used and are seldom corrected for the actual elevation of the anemometer. For SWMM, average wind speeds are input for each month. Finally, the saturation vapor pressure, EA, is given accurately by the convenient exponential approximation,

$$EA = 8.1175 \times 10^{6} \exp[-7701.544/(TA + 405.0265)] \qquad \text{(II-12)}$$

where EA = saturation vapor pressure, in. Hg, and
TA = air temperature, ^{o}F.

The origin of numerical constants found in equation II-8 for SMELT is given by Anderson (1973), and reflects units conversions as well as U.S. customary units for physical properties. Note that equation II-13 of Appendix III may be reduced to equation II-8.

During non-rain periods, melt is calculated as a linear function of the difference between the air temperature, TA, and a base temperature, TBASE, using a degree-day or temperature-index type equation:

$$SMELT = DHM \cdot (TA - TBASE) \qquad \text{(II-13)}$$

where SMELT = snowmelt, in./hr (internally as ft/sec,)

TA = air temperature, ^{o}F,
TBASE = base melt temperature, ^{o}F, and
DHM = melt factor, in./hr-^{o}F (internally ft/sec-^{o}F).

Different values of TBASE and DHM may be input for three area classifications for each subcatchment (see Table II-2 and Figure II-3). For instance, these parameters may be used to account for street salting which lowers the base melt temperature. If desired, rooftops could be simulated as a separate subcatchment using a lower value of TBASE to reflect heat transfer vertically through the roof. Values of TBASE will probably range between 25 and 32 ^{o}F (-4 and 0 ^{o}C). Unfortunately, few urban area data exist to define adequately appropriate modified values for TBASE and DHM, and they may be considered calibration parameters.

In rural areas, the melt coefficient ranges from 0.03 - 0.15 in./day-^{o}F (1.4 - 6.9 mm/day-^{o}C) or from 0.001 - 0.006 in./hr-^{o}F (0.057 - 0.29 mm/hr-^{o}C). In urban areas, values may tend toward the higher part of the range due to compression of the pack by vehicles, pedestrians, etc. Again there appear to be few data available to produce accurate estimates. However, Bengtsson (1981) and Westerstrom (1981) do describe preliminary results of urban snowmelt studies in Sweden, including degree-day coefficients which range from 3 to 8 mm/^{o}C-day (0.07 - 0.17 in./^{o}F-day). Additional data for snowmelt on an asphalt surface (Westerstrom, 1984) gave degree-day coefficients of 1.7 - 6.5 mm/^{o}C-day (0.04 - 0.14 in./^{o}F-day).

It is important to realize that a degree-day equation may be derived from the complete energy budget equation if parameters other than air temperature are held constant. The equation is simply linearized about a desired air temperature range, and numerical values for DHM and TBASE computed. The values are accurate for the assumed values of other parameters, but may not appear to make sense physically, e.g., it is not difficult to use parameters that produce negative values of TBASE. An example of this procedure is given in Appendix III. It also serves to illustrate the energy budget computation method.

For single event SWMM, parameters DHM and TBASE are constant throughout the simulation. For continuous SWMM, TBASE remains constant, but DHM is allowed a seasonal variation, as illustrated in Figure II-5. Following Anderson (1973), the minimum melt coefficient is assumed to occur on December 21 and the maximum of June 21. Parameters DHMIN and DHMAX are input for the three areas of each subcatchment, and sinusoidal interpolation is used to produce a value of DHM, constant over each day,

$$DHM = (DHMAX + DHMIN)/2 + (DHMAX - DHMIN)/2 \cdot \sin\left[\frac{pi}{182}(D-81)\right] \qquad \text{(II-14)}$$

where DHMIN = minimum melt coefficient, occurring Dec. 21, in./hr-^{o}F,
DHMAX = maximum melt coefficient, occurring June 21, in./hr-^{o}F, and
D = number of the day of the year.

No special allowance is made for leap year. However, the correct date (and day number, D) is maintained.

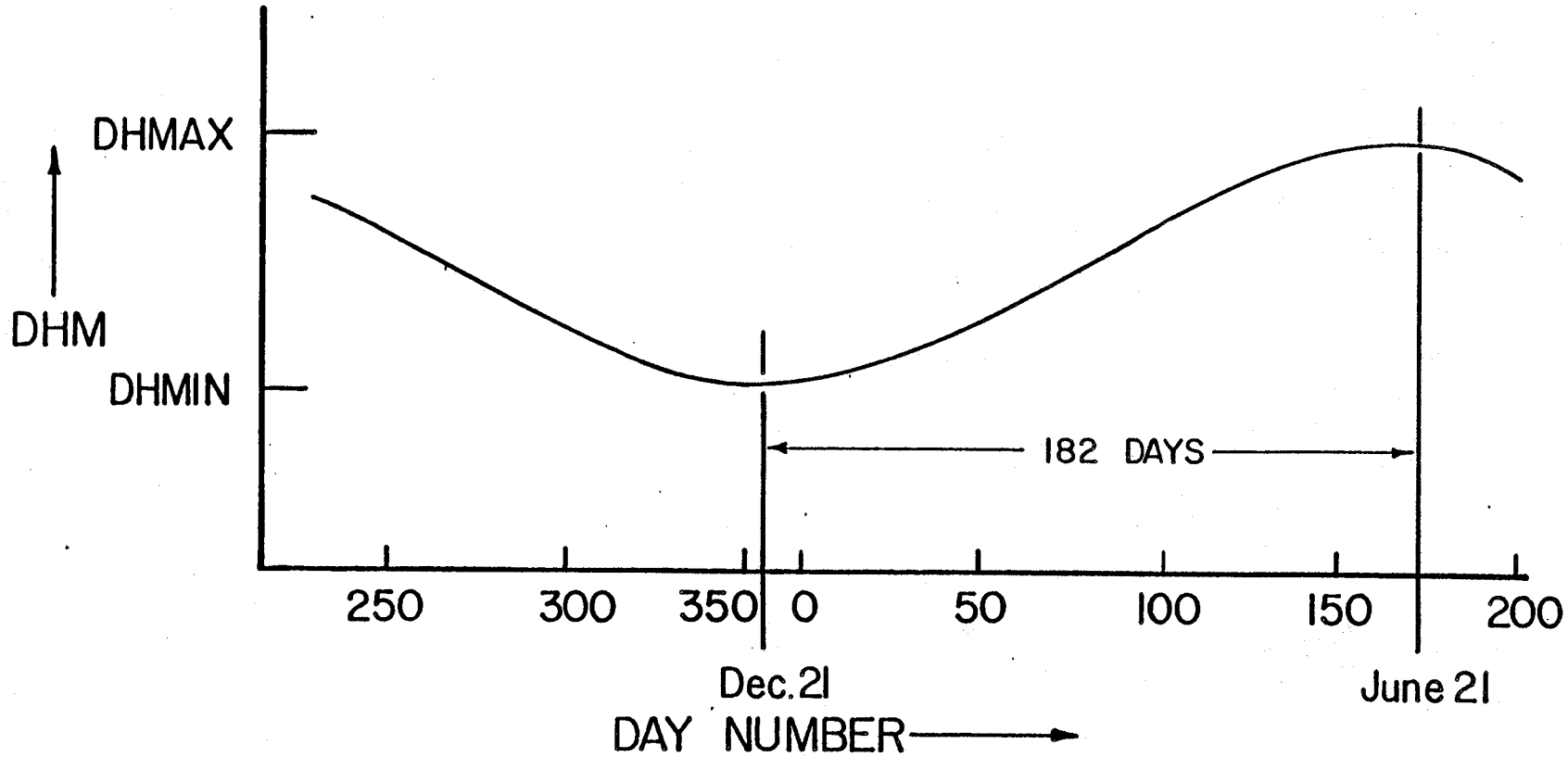


Figure II-5. Seasonal Variation of Melt Coefficients.

Heat Exchange During Non-Melt Periods

During subfreezing weather, the snow pack does not melt, and heat exchange with the atmosphere can either warm or cool the pack. The difference between the heat content of the subfreezing pack and the (higher) base melt temperature is taken as positive and termed the "cold content" of the pack. No melt will occur until this quantity, COLDC, is reduced to zero. It is maintained in inches (or feet) of water equivalent. That is, a cold content of 0.1 in. (2.5 mm) is equivalent to the heat required to melt 0.1 in. (2.5 m) of snow. Following Anderson (1973), the heat exchange altering the cold content is proportional to the difference between the air temperature, TA, and an antecedent temperature index, ATI, indicative of the temperature of the surface layer of the snow pack. The revised value of ATI at time step 2 is calculated as

$$ATI_2 = ATI_1 + TIPM \cdot (TA_2 - ATI_1) \qquad \text{(II-15)}$$

where ATI = antecedent temperature index, ^{o}F,
TA = air temperature, ^{o}F,
TIPM = antecedent temperature index parameter, $0 \leq TIPM \leq 1.0$, and
subscripts 1 and 2 refer to time steps 1 and 2, respectively. The value of ATI is not allowed to exceed TBASE, and when snowfall is occurring, ATI takes on the current air temperature.

The weighting factor, TIPM, is an indication of the thickness of the "surface" layer of snow. Values of TIPM less than 0.1 give significant weight to temperatures over the past week or more and would thus indicate a deeper layer than TIPM values greater than, say, 0.5, which would essentially only give weight to temperatures during the past day. In other words, the pack will both warm and cool more slowly with low values of TIPM. Anderson states that TIPM = 0.5 has given reasonable results in natural watersheds, although there is some evidence that a lower value may be more appropriate. No calibration has been attempted on urban watersheds.

Following computation of the antecedent temperature index, the cold content is changed by an amount

$$DCOLDC = RNM \cdot DHM \cdot (ATI - TA) \cdot DELT \qquad \text{(II-16)}$$

where DCOLDC = change in cold content, ft water equivalent,
RNM = ratio of negative melt coefficient to melt coefficient,
DHM = melt coefficient, ft/sec-^{o}F,
TA = air temperature, ^{o}F,
ATI = antecedent temperature index, ^{o}F, and
DELT = time step, sec.

Note that the cold content is increased, (DCOLDC is positive) when the air temperature is less (colder) than the antecedent temperature index. Since heat transfer during non-melt periods is less than during melt periods, Anderson uses a "negative melt coefficient" in the heat exchange computation. SWMM computes this simply as a fraction, RNM, of the melt coefficient, DHM. Hence,

the negative melt coefficient, i.e., the product RNM x DHM, also varies seasonally. A typical value of RNM is 0.6.

When heat is added to a snow pack with zero cold content, liquid melt is produced, but runoff does not occur, until the "free water holding capacity" of the snow pack is filled. This is discussed subsequently. For single event SWMM no cold content calculations are performed; values of COLDC are assumed to equal zero throughout the simulation. The value of COLDC is in units of feet of water equivalent over the area in question. The cold content "volume," equivalent to calories or BTUs, is obtained by multiplying by the area. Finally, an adjustment is made to equation II-16 depending on the areal extent of snow cover. This is discussed below.

Areal Extent of Snow Cover

Introduction --

The snow pack on a catchment rarely melts uniformly over the total area. Rather, due to shading, drifting, topography, etc., certain portions of the catchment will become bare before others, and only a fraction, ASC, will be snow covered. This fraction must be known in order to compute the snow covered area available for heat exchange and melt, and to know how much rain falls on bare ground. Because of year to year similarities in topography, vegetation, drift patterns, etc., the fraction, ASC, is primarily only a function of the amount of snow on the catchment at a given time; this function, called an "areal depletion curve", is discussed below. These functions are used only for continuous SWMM to describe the seasonal growth and recession of the snow pack. For single event simulation, fractions of snow covered area are fixed for the pervious and impervious areas of each subcatchment.

Areal Depletion Curves --

As used in most snowmelt models, it is assumed that there is a depth, SI, above which there will always be 100 percent cover. In some models, the value of SI is adjusted during the simulation; in SWMM it remains constant. The amount of snow present at any time is indicated by the parameter WSNOW, which is the depth (water equivalent) over each of the three possible snow covered areas of each subcatchment (see Figure II-3). This depth is nondimensionalized by SI for use in calculating ASC. Thus, an areal depletion curve is a plot of WSNOW/SI versus ASC; a typical ADC for a natural catchment is shown in Figure II-6. For values of the ratio AWESI = WSNOW/SI greater than 1.0, ASC = 1.0, that is, the area is 100 percent snow covered.

Some of the implications of different functional forms of the ADC may be seen in Figure II-7. Since the program maintains snow quantities, WSNOW, as the depth over the total area, AT, the actual snow depth, WS, and actual area covered, AS, are related by continuity:

$$WSNOW \cdot AT = WS \cdot AS \qquad \text{(II-17)}$$

where WSNOW = depth of snow over total area AT, ft water equivalent,
AT = total area, ft^2

WS = actual snow depth, ft water equivalent, and
AS = snow covered area, ft^2.

In terms of parameters shown on the ADC, this equation may be rearranged to read

$$AWESI = WSNOW/SI = (WS/SI) \cdot (AS/AT) = (WS/SI) \cdot ASC \qquad (II\text{-}18)$$

This equation can be used to compute the actual snow depth, WS, from known ADC parameters, if desired. It is unnecessary to do this in the program, but it is helpful in understanding the curves of Figure II-7. Thus:

$$WS = (AWESI/ASC) \cdot SI \qquad (II\text{-}19)$$

Consider the three ADC curves B, C and D. For curve B, AWESI is always less than ASC; hence WS is always less than SI as shown in Figure II-7d. For curve C, AWESI = ASC, hence WS = SI, as shown in Figure II-7e. Finally, for curve D, AWESI is always greater than ASC; hence, WS is always greater than SI, as shown in Figure II-7f. Constant values of ASC at 100 percent cover and 40 percent cover are illustrated in Figure II-7c, curve A, and Figure II-7g, curve E, respectively. At a given time (e.g., t_1 in Figure II-7), the area of each snow depth versus area curve is the same and equal to AWESI · SI, (e.g., 0.8 SI for time t_1).

Curve B on Figure II-7a is the most common type of ADC occurring in nature, as shown in Figure II-6. The convex curve D requires some mechanism for raising snow levels above their original depth, SI. In nature, drifting might provide such a mechanism; in urban areas, plowing and windrowing could cause a similar effect. A complex curve could be generated to represent specific snow removal practices in a city. However, the program utilizes only on ADC curve for all impervious areas (e.g., area A4 of Figure II-3 for all subcatchments) and only one ADC curve for all pervious areas (e.g., area A2 of Figure II-3 for all subcatchments). This limitation should not hinder an adequate simulation since the effects of variations in individual locations are averaged out in the city-wide scope of most continuous simulations.

The two ADC curves for pervious and impervious areas are input by the user, as are values of SI for each subcatchment. The program does not require the ADC curves to pass through the origin, AWESI = ASC = 0; they may intersect the abscissa at a value of ASC > 0 in order to maintain some snow covered area up until the instant that all snow disappears (see Figure II-6). However, the curves may not intersect the ordinate, AWESI > 0 when ASC=0.

The preceding paragraphs have centered on the situation where a depth of snow greater than or equal to SI has fallen and is melting. (The ADC curves are not employed until WSNOW becomes less than SI.) The situation when there is new snow needs to be discussed, starting from both zero or non-zero initial cover. The SWMM procedure again follows Anderson's NWS method (1973).

When there is new snow and WSNOW is already greater than or equal to SI, them ASC remains unchanged at 1.0. However, when there is new snow on bare or partially bare ground, it is assumed that the total area is 100 percent cov-

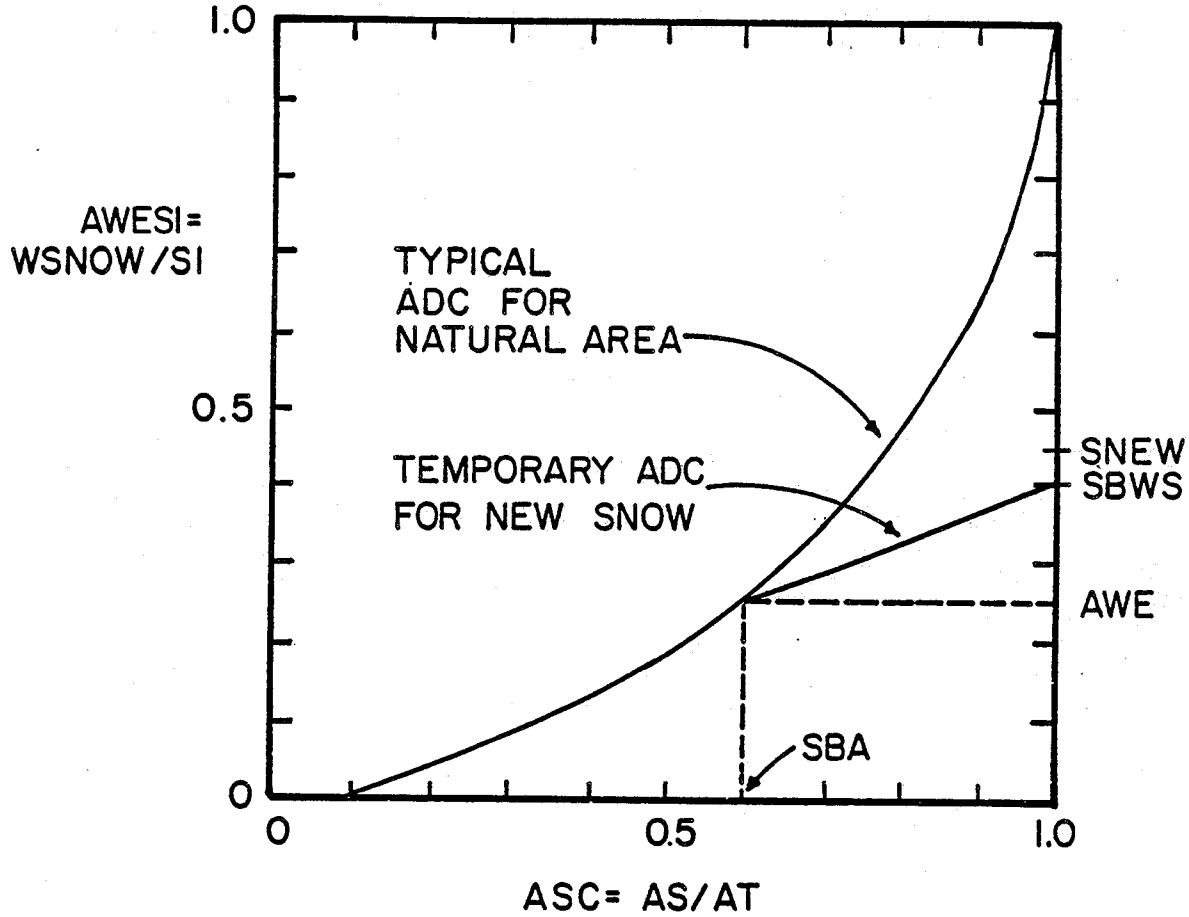


Figure II-6. Typical Areal Depletion Curve for Natural Area (Anderson, 1973, P. 3-15) and Temporary Curve for New Snow.

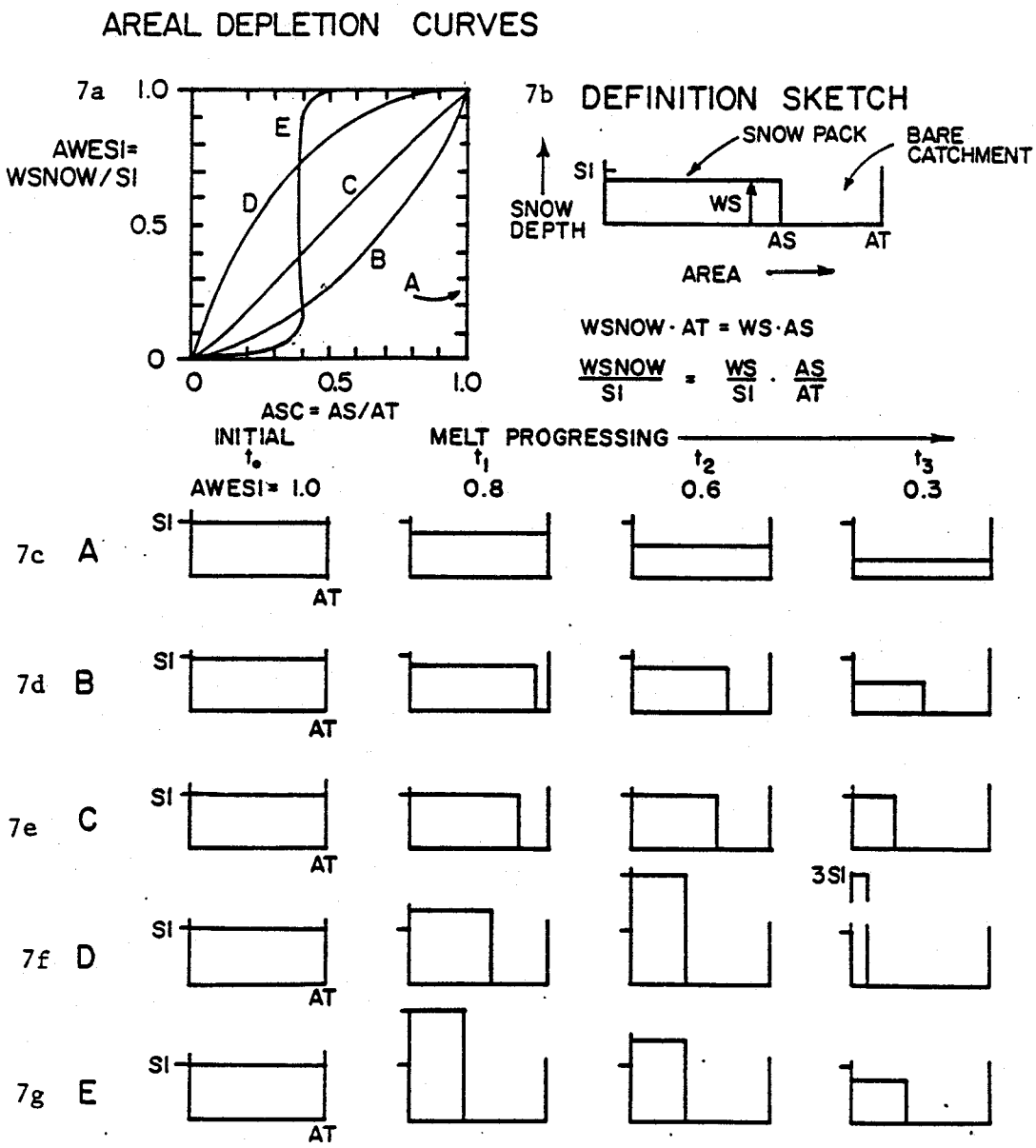


Figure II-7. Effect on Snow Cover on Areal Depletion Curves.

ered for a period of time, and a "temporary" ADC is established as shown in Figure II-6. This temporary curve returns to the same point on the ADC as the snow melts. Let the depth of new snow be SNO, measured in equivalent feet of water. Then the value of AWESI will be changed from an initial value of AWE to a new value of SNEW by:

$$SNEW = AWE + SNO/SI \qquad \text{(II-20)}$$

It is assumed that the areal snow cover remains at 100 percent until 25 percent of the new snow melts. This defines the value of SBWS of Figure II-6 as:

$$SBWS = AWE + 0.75 \cdot SNO/SI \qquad \text{(II-21)}$$

Anderson (1973) reports low sensitivity of model results to the arbitrary 25 percent assumption. When melt produces a value of AWESI between SBWS and AWE, linear interpolation of the temporary curve is used to find ASC until the actual ADC curve is again reached. When new snow has fallen, the program thus maintains values of AWE, SBA and SBWS (Figure II-6).

The interactive nature of melt and fraction of snow cover is not accounted for <u>during</u> each time step. It is sufficient to use the value of ASC at the beginning of each time step, especially with a short (e.g., one-hour) time step for the simulation.

Use of Value of ASC --

The fraction of area that is snow covered, ASC, is used to adjust 1) the volume of melt that occurs, and 2) the "volume" of cold content change, since it is assumed that heat transfer occurs only over the snow covered area. The melt rate is computed from either of the two equations for SMELT. The snow depth is then reduced from its value at time step 1 to time step 2 as:

$$WSNOW_2 = WSNOW_1 - SMELT \cdot ASC \qquad \text{(II-22)}$$

with variables as defined previously and including appropriate continuity checks in the program to avoid melting more snow than is there, etc.

Cold content changes are also adjusted by the value of ASC. Thus, using a equation II-16, cold content at time step 2 is computed from the value at time step 1 by:

$$COLDC_2 = COLDC_1 + RNM \cdot DHM \cdot (ATI-TA) \cdot DELT \cdot ASC \qquad \text{(II-23)}$$

where variables are as previously defined. Again there are program checks for negative values of COLDC, etc.

<u>Liquid Water Routing in Snow Pack</u>

Production of melt does not necessarily mean that there will be liquid runoff at a given time step since a snow pack, acting as a porous medium with a "porosity," has a certain "free water holding capacity" at a given instant

in time. Following PR-JFM (1976a, 1976b), this capacity is taken to be a constant fraction, FWFRAC, of the variable snow depth, WSNOW, at each time step. This volume (depth) must be filled before runoff from the snow pack occurs. The program maintains the depth of free water, FW, ft of water, for use in these computations. When FW = FWFRAC x WSNOW, the snow pack is fully ripe. The procedure is sketched in Figure II-8.

The inclusion of the free water holding capacity via this simple reservoir-type routing delays and somewhat attenuates the appearance of liquid runoff. The value of FWFRAC will normally be less than 0.10 and usually between 0.02 - 0.05 for deep snow packs (SWNOW > 10 in. or 254 mm water equivalent). However, Anderson (1973) reports that a value of 0.25 is not unreasonable for shallow snow packs that may form a slush layer. When rainfall occurs, it is added to the melt rate entering storage as free water. No free water is released when melt does not occur, but remains in storage, available for release when the pack is again ripe. This re-frozen free water is not included in subsequent cold content or melt computations.

Net Runoff

Melt from snow covered areas and rainfall on bare surfaces are area weighted and combined to produce net runoff onto the surface as follows:

$$RI = ASC \cdot SMELT + (1.0 - ASC) \cdot RINE \qquad \text{(II-24)}$$

where RI = net runoff onto surface, ft/sec,
ASC = fraction of area that is snow covered,
SMELT = melt rate, including effect of attenuation due to free water holding capacity, ft/sec, and
RINE = rainfall intensity, ft/sec.

Thus, the net runoff acts just as rainfall would act alone in subsequent overland flow and infiltration calculations.

If immediate melt is produced through the use of the snow redistribution fraction SFRAC(5) (see Figure II-4), it is added to the last equation. Furthermore, all melt calculations are ended when the depth of snow water equivalent becomes less than 0.001 in. (0.025 mm), and remaining snow and free water are converted to immediate melt and added to equation II-24.

Effect of Snow on Infiltration and Surface Parameters

A snow pack tends to insulate the surface beneath it. If ground has frozen prior to snowfall, it will tend to remain so, even as the snow begins to melt. Conversely, unfrozen ground is generally not frozen by subsequent snowfall. The infiltration characteristics of frozen versus unfrozen ground are not well understood and depend upon the moisture content at the time of freezing. For these and other reasons, SWMM assumes that snow has no effect on infiltration or other parameters, such as surface roughness or detention storage (although the latter is altered in a sense through the use of the free water holding capacity of the snow). In addition, all heat transfer calculations cease when the water becomes "net runoff." Thus, water in temporary

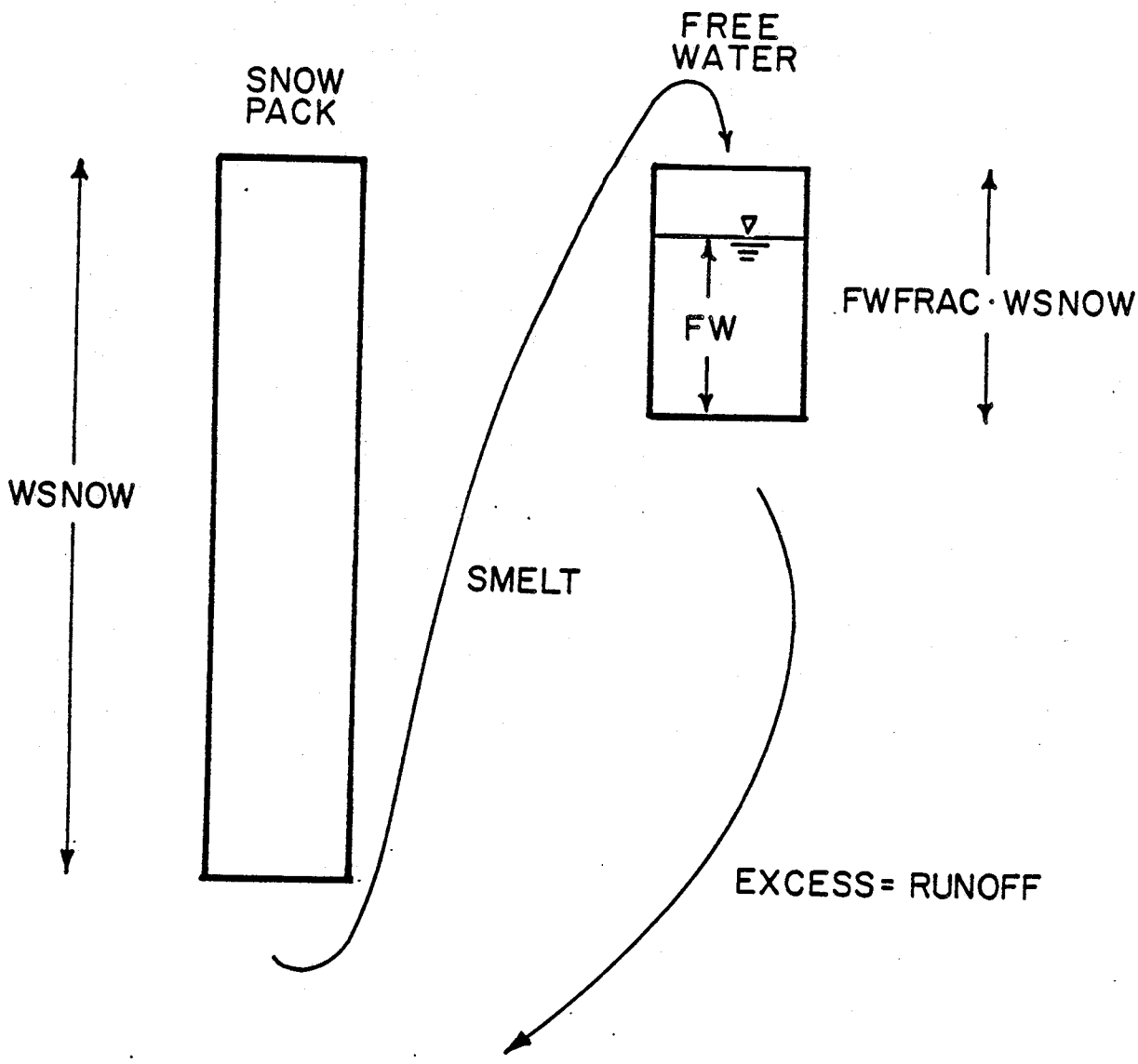


Figure II-3 . Schematic of Liquid Water Routing Through Snow Pack.

surface storage during the overland flow routing will not refreeze as the temperature drops and is also subject to evaporation beneath the snow pack.

QUALITY INTERACTIONS

Pollutant Accumulation

Snowmelt Quality --

A detailed review of literature related to snowmelt quality is given by PR-JFM (1976a, 1976b). Among the various contaminants found in deposited snow and melt water, chlorides and lead appear to be the most serious and potentially hazardous. Chloride concentrations in runoff along major highways can be higher than 20,000 mg/l, with typical values of from 1,000 to 10,000 mg/l. Several other studies also document chloride contamination and discuss street salting practices (Field et al., 1973; Richardson et al., 1974; Ontario Ministry of the Environment, 1974). Lead concentrations in snow windrows have been as high as 100 mg/l with typical values of from 1 to 10 mg/l. However, most deposited lead results from automobile combustion and is insoluble. Hence, melt runoff concentrations are lower than snow pack values and are mostly associated with suspended solids.

Pollutant Loadings --

Mechanisms and modeling alternatives for pollutant buildup and washoff are described extensively in Section 4 (Runoff Block). Any parameter related to snowmelt may be generated using linear or non-linear buildup, or else a rating curve (load proportional to flow). Specifically, street salting chemicals may be simulated, such as sodium chloride or calcium chloride.

Adjustments for Presence of Snow --

As a user option, regeneration of any quality constituent may be performed only when snow is present. This option is indicated by parameter LINKUP. Thus, if chlorides are simulated, for example, they will not be regenerated from bare ground, during the summer months for instance. However, regeneration when it does occur is a function only of snow presence, not the actual amount (depth).

Possible Loading Rates --

Pollutant loading rates are best determined from local data. The literature review of PR-JFM (1976a, 1976b) may also be consulted for tables that may be used to estimate loading rate parameters for snow-associated pollutants. Other references will also be useful (e.g., Field et al., 1973; Richardson et al., 1974; Ontario Ministry of the Environment, 1974).

Table II-4 (Richardson et al., 1974) lists recommended deicing chemical application rates for roadways. In general, PR-JFM show that observed loading rates are functions of population density with suburban rates lower than arterial highway rates, as indicated in Table II-5. This is also true for other pollutants.

Table II-4. Guidelines for Chemical Application Rates (Richardson et al., 1974).

WEATHER CONDITIONS			APPLICATION RATE (Pounds of material per mile of 2-lane road or 2-lanes of divided)			
Temperature	Pavement Conditions	Precipitation	Low-and High-Speed Multilane Divided	Two and Three-Lane Primary	Two-Lane Secondary	INSTRUCTIONS
30°F and above	Wet	Snow	300 salt	300 salt	300 salt	- wait at least 0.5 hour before plowing
		Sleet or Freezing Rain	200 salt	200 salt	200 salt	- reapply as necessary
25-30°F	Wet	Snow or Sleet	initial at 400 salt repeat at 200 salt	initial at 400 salt repeat at 200 salt	initial at 400 salt repeat at 200 salt	- wait at least 0.5 hour before plowing; repeat
		Freezing Rain	initial at 300 salt repeat at 200 salt	initial at 300 salt repeat at 200 salt	initial at 300 salt repeat at 200 salt	- repeat as necessary
20-25°F	Wet	Snow or Sleet	initial at 500 salt repeat at 250 salt	initial at 500 salt repeat at 250 salt	1200 of 5:1 Sand/Salt; repeat same	- wait about 0.75 hour before plowing; repeat
		Freezing Rain	initial at 400 salt repeat at 300 salt	initial at 400 salt repeat at 300 salt		- repeat as necessary
15-20°F	Dry	Dry Snow	plow	plow	plow	- treat hazardous areas with 1200 of 20:1 Sand/Salt
	Wet	Wet Snow or Sleet	500 of 3:1 Salt/ Calcium Chloride	500 of 3:1 Salt/ Calcium Chloride	1200 of 5:1 Sand	- wait about one hour before plowing; continue plowing until storm ends; then repeat application
below 15°F	Dry	Dry Snow	plow	plow	plow	- treat hazardous area with 1200 of 20:1 Sand/Salt

Street Sweeping

The effect of snow is included in two minor ways. First, beginning and ending dates, parameters KLNBGN and KLNEND respectively, may be input for continuous SWMM to indicate the interval during the year subject to street sweeping. If sweeping normally is not done between, say, December 1 and March 1, because of high snow volumes, this may be so indicated.

Table II-5. Salting Rates Used in Ontario
(Proctor and Redfern Ltd. and James F. MacLaren, Ltd., Vol. II, 1976b)

Population Density (person per sq mile)	Salting Rate per Application (lb per lane-mile)
Less than 1,000	75 - 800
1,000 to 5,000	350 - 1,800
More than 5,000	400 - 1,200

Second, the presence of snow can alter the street sweeping interval. These intervals are specified for each of the five land uses. Each subcatchment is swept when the number of dry time steps for that subcatchment exceeds the interval for the given land use. A dry time step, in subroutine QSHED, is one in which there is no precipitation and no water or snow on areas A1 and A3 (Figure II-3). Thus, subcatchments will not be swept until there is no snow or water on "normally bare" impervious areas.

Other Considerations

The snow itself is assumed to be "pure" and contain no pollutants. Thus, the redistribution or transfers of snow described earlier (Figure II-4) will not remove accumulated pollutants. This is partially justified on the basis of the assumption that such transfers would occur soon after fresh snow has fallen. They occur during the same time step in the model.

Although not well tested, it is assumed that the principal effect of inclusion of snowmelt upon runoff quality predictions of continuous SWMM will be to shift the season and magnitude of pollutant washoff. There will tend to be fewer periods of washoff during the winter. As snowmelt, equivalent melt rates are likely to be less than the usual magnitude of rainfall intensities experienced. Hence, concentrations may tend to be more uniform during the melt washoff events.

DATA REQUIREMENTS

Input Parameters

For single event simulation, input parameters include watershed elevation, free water holding capacities, air temperatures and wind speeds, and for each subcatchment, snow covered fractions, initial snow and free water, melt coefficients and base temperatures. Continuous simulation requires the same data as above, except that air temperatures are computed using other input parameters. In addition, it requires the snow gage correction factor, negative heat exchange parameter, areal depletion curves, and, for each subcatchment, the redistribution parameters. Of course, for continuous simulation, the required parameters can be kept to a minimum by keeping the number of subcatchments used to a minimum. Also required are pollutant loading data that may or may not be related to snow.

Sensitivity

The melt routines have not been sufficiently tested to date to quantify the sensitivity of results to various input parameters. It is expected that melt volumes will be most related to the precipitation record, of course, and to the gage correction factor, which influences the amount of snow that falls. Melt rates will be influenced by the melt coefficients and base temperatures, and, to some degree, by the areal depletion curves which simulate the relative "piling" or "stacking" of the snow.

OUTPUT

Temperature and Snowfall Generation

Output consists of temperatures synthesized from daily max-min values, and hourly precipitation totals, in which snowfall is tagged as a negative value.

Runoff Simulation Output

Snowmelt events are not indicated in a special manner for output by either continuous or single event SWMM. If daily output is used, snowmelt may be discerned to some degree by observing whether precipitation accompanies the runoff for that day. Snowfall and initial snow depths are identified as separate items in the final continuity check for the total watershed.

APPENDIX III

REDUCTION OF ENERGY BALANCE EQUATION TO DEGREE-DAY EQUATION

PURPOSE

This appendix presents equations that can be used for each term in the energy balance equation discussed in Appendix II. The equation is then linearized and typical numerical values are used to reduce it to a degree-day or temperature-index type equation. The energy budget method will thus be better understood, and a physical basis for the simple prediction equations will be seen. Notation and equations used will follow Eagleson (1970), although an identical development could be based on several other references.

ENERGY BUDGET

The energy budget given in Appendix II is repeated and symbols are assigned to each term. Units for each energy budget term will be energy/area-time, e.g., ly/day (one langley = one cal/cm^2). However, within this scope, there will be mixtures of units used as convenient, e.g., minutes and days, °C and °F. The equation will ultimately be converted to U.S. customary units.

The snow pack energy budget is (e.g., units of ly/day)

$$\Delta H = H_{rs} + H_g + H_{rl} + H_c + H_e + H_p \qquad \text{(III-1)}$$

where ΔH = change in heat storage in snow pack,
H_{rs} = net short wave radiation entering the snow pack,
H_g = conduction of heat to snow pack from underlying ground,
H_{rl} = net (incoming minus outgoing) long wave radiation entering the snow pack,
H_c = convective transport of sensible heat from air to snow pack,
H_e = release of latent heat of vaporization by condensation of atmospheric water vapor, and
H_p = advection of heat to snow pack by rain.

All terms can be positive or negative except for H_e (sublimation will not be considered since it also involves the heat of fusion), H_{rs} and H_p (heat cannot be removed by rain).

It will be assumed that the snow pack is ripe, and all heat added will product liquid melt. Since inches of melt are desired, and it requires

about 80 cal to melt one gram of water (the latent heat of fusion) or 80 ly per cm, it requires 2.54 cm/in. x 80 ly/cm = 203.2 ly per inch of melt. Thus, equation III-1 will eventually be linearized and put in the form of equation II-13 in Appendix II,

$$SMELT = \Delta H/203.2 = DHM \cdot (T_a - T_b) \qquad \text{(III-2)}$$

where SMELT = melt rate, in./day,
ΔH = change in heat storage, ly/day,
DHM = melt coefficient, in./day-°F,
T_a = air temperature, °F, and
T_b = base melt temperature, °F.

Other terms will be defined where introduced. Caution should be used to insure that all terms eventually have the same units.

SHORT WAVE RADIATION, H_{rs}

Measured values from NWS stations are ordinarily used. The albedo (reflection coefficient) of new snow can be as high as 0.80 and is seldom lower than 0.4 in natural areas. Albedos of dirty urban snow surfaces are not documented, but probably lower than 0.4. Net shortwave radiation, H_{rs}, is incoming minus reflected. If measurements of incoming radiation are unavailable, predictive techniques may be used (TVA, 1972, Franz, 1974).

HEAT CONDUCTION THROUGH GROUND, H_g

Few data are available to quantify this term, and it is often determined as a residual in the energy budget equation. For urban areas, the intriguing possibility exists of predicting heat transfer through roofs based upon assumed temperature differences across the roof surface and thermal properties of the roofing material. In most cases, however, such calculations will be inaccurate and/or infeasible. Hence, this term is usually neglected.

NET LONG WAVE RADIATION, H_{rl}

Incoming minus outgoing long wave radiation is given by the Stefan-Boltzman law,

$$H_{rl} = 0.97 \cdot \varepsilon_a \cdot \sigma \cdot T_a^4 - 0.97 \cdot \sigma \cdot T_s^4 \qquad \text{(III-3)}$$

where ε_a = atmospheric emissivity, a function of water vapor content,
σ = Stefan-Boltzman constant = 0.826×10^{-10} ly/min-°K^4,
T_a = air temperature at specified elevation, °K,
T_s = snow surface temperature, °K.

The first factor of 0.97 accounts for three percent reflection of incoming long wave radiation, and the second factor of 0.97 is the emissivity of the snow surface.

The key unknown is the atmospheric emissivity, for which several empirical formulas are available and in which the effect of clouds may also be included (TVA, 1972). For example, a simple formula due to Anderson (1954) for clear skies is

$$\varepsilon_a = 0.74 + 0.0049e \qquad \text{(III-4)}$$

where e = ground level atmospheric vapor pressure, mb.

Clouds may be assumed to radiate with an emissivity of 0.97 at the cloud base temperature, if known.

The snow surface temperature may be taken as 0°C. Hence, it is necessary to linearize only the air temperature term. This may be done by means of a Taylor series, under the assumption

$$T_a = T_o + \Delta T \qquad \text{(III-5)}$$

The fourth-power term is then linearized about the reference temperature, T_o,

$$T_a^4 = (T_o + \Delta T)^4 = T_o^4 + \Delta T \cdot 4 \cdot T_o^3 + \ldots = T_o^3\,(4T_a - 3T_o) \qquad \text{(III-6)}$$

The reference temperature, T_o, will be a constant in the equation and is chosen near the midpoint of the expected temperature range at the time of evaluation of the heat budget. Equation III-6 may be substituted into equation III-3,

$$H_{rl} = 0.97 \cdot \varepsilon_a \cdot \sigma \cdot T_o^3\,(4T_a - 3T_o) \;-\; 0.97 \cdot \sigma \cdot T_s^4 \qquad \text{(III-7)}$$

Which is linear in T_a, in °K. Later, temperatures must be converted to °F for consistency.

CONVECTIVE HEAT TRANSFER, H_c

Equations for this process (and for condensation melt) vary according to the asumptions made about surface roughness, wind speed profiles and turbulent transfer coefficients. A common equation is (Eagleson, 1970)

$$H_c = 203.2 \cdot k_c \cdot p_s/p_o \cdot (z_a \cdot z_b)^{-1/6} \cdot \bar{u}_b \cdot (T_a - T_s) \qquad \text{(III-8)}$$

where p_s = surface atmospheric pressure (consistent units with p_o),
p_o = sea level atmospheric pressure (consistent units with p_s),
z_a = height above surface of air temperature (and humidity) measurement, ft,

z_b = height above surface of wind speed measurement, ft,
$\bar{u}_b$ = wind speed at height z_b, mph,
T_a = air temperature, °F,
T_s = snow surface temperature, °F, and
H_c = heat transfer in ly/day.

The factor 203.2 converts inches to langleys and the coefficient k_c has been measured for the Sierra Nevada mountains as

$$k_c = 0.00629 \text{ in. ft}^{1/3} \text{ hr/day-°F-mi} \qquad \text{(III-9)}$$

CONDENSATION HEAT TRANSFER, H_e

Since both this and convective heat transfer are diffusive type processes, the same introductory remarks hold as for the latter. A common equation is (Eagleson, 1970)

$$H_e = 203.2 \cdot 8.5 \cdot k_e \cdot (z_a \cdot z_b)^{-1/6} \cdot \bar{u}_b \cdot (e_a - e_s) \qquad \text{(III-10)}$$

where e_a = vapor pressure of atmosphere at temperature and relative humidity at height z_a, mb,

e_s = saturation vapor pressure at the snow surface temperature, mb,

and other variables are defined as for equation III-8. The coefficient k_e has been measured for the Sierras as

$$k_e = 0.00635 \text{ in. ft}^{1/3} \text{ hr/day-mb-mile.} \qquad \text{(III-11)}$$

The factor of 8.5 in equation III-10 accounts for the fact that when the snow pack is ripe, the latent heat of condensation will supply the latent heat of fusion to melt the snow. Because of the ratio of these latent heats, 600/80 = 7.5, each inch of condensate will cause 7.5 + 1 = 8.5 inches of "melt".

HEAT ADVECTION BY RAIN, H_p

Heat is advected by rain in proportion to the rainfall depth and temperature of the rain (assumed to be equal to the air temperature). Then

$$H_p = 1.41 \text{ d } (T_a - T_s) \qquad \text{(III-12)}$$

where H_p = heat advected in ly/day, and

d = daily rainfall depth, in./day, and

the temperatures are in °F.

COMBINED EQUATIONS

When equations for each component are substituted into equation III-1, and using equation III-2 to generate inches of melt, all equations may be combined into

$$\begin{aligned}
\text{SMELT} = \frac{\Delta H}{203.2} &= \frac{0.97\ \varepsilon_a\ \sigma\ 4\ T_o^3}{203.2}\ (265.2 + 5/9\ T_a) \quad (1) \\
&+ (z_a \cdot z_b)^{-1/6}\ \bar{u}_b \cdot k_c \cdot p_s/p_o \cdot T_a \quad (2) \\
&+ \frac{H_{rs} + H_g}{203.2} \ (3) - \frac{0.97\ \sigma\ T_s^4}{203.2} \ (4) \Bigg|_{°K} \qquad \text{(III-13)} \\
&+ (z_a \cdot z_b)^{-1/6}\ \bar{u}_b [8.5 \cdot k_e\ (e_a - e_s) - k_c\ p_s/p_o\ T_s] \quad (5) \\
&- \frac{0.97\ \varepsilon_a\ \sigma\ 3\ T_o^4}{203.2} \ (6) + \frac{1.41 \cdot d \cdot (T_a - T_s)}{203.2} \ (7)
\end{aligned}$$

where terms have been defined previously, and temperature units are:

T_o = reference temperature, °K,

T_s = snow surface temperature, °F, (except °K in term 4), and

T_a = air temperature, °F.

The units of SMELT are inches/day. The equation is linear in the air temperature, T_a, which will be the only variable when the others are assigned numerical values. Note also the conversion from °K to °F in term 1. A further refinement would make saturation atmospheric vapor pressure a linear function of air temperature, which is valid over say, 10°F ranges. Then,

$$e_a = r \cdot e_{a_s} = r \cdot f(T_a) \qquad \text{(III-14)}$$

where r = relative humidity, fraction, and
e_{a_s} = saturation vapor pressure at air temperature, T_a.

This modification would then add another term in T_a to equation III-13; it is pursued no further here. Note that equation II-8 in Appendix II is only a simplification of equation III-13 under suitable assumptions for rainfall conditions and with units conversions.

NUMERICAL EXAMPLE

The following meteorological parameters are assumed,

H_{rs} = 288 ly/day,

T_o = 35°F = 274.7°K

T_s = 32°F = 273°K

z_a = 6 ft

z_b = 20 ft

$\bar{u}_b$ = 9 mph

$e_s = e_s(32°F) = 6.11$ mb

$r = 0.6$

$e_a = 0.6 \cdot e_s(35°F) = 0.6 \cdot 6.87 = 4.12$ mb

$\varepsilon_a = 0.90$

p_o = 1013.2 mb

p_s = 950 mb (about 2000 ft elevation),

rainfall = zero

H_g = zero

Each of the terms in equation III-13 is now evaluated, with units of inches/day.

Term	Constant	Temperature Term
1	+11.24	+ 0.0235 T_a
2	+ 1.24	+ 0.0239 T_a
3	+ 1.417	
4	- 3.154	
5	- 1.200	
6	- 8.729	
	- 0.426	+ 0.0474 T_a

Then the degree-day or temperature-index equation becomes, with T_a in °F,

$$\begin{aligned} SMELT &= DHM \cdot (T_a - T_b) && \text{(III-15)} \\ &= 0.0474\ T_a - 0.426 && \text{in./day} \\ &= 0.0474\ (T_a - 8.99) && \text{in./day} \\ &= 0.00198\ (T_a - 8.99) && \text{in./hr} \end{aligned}$$

The low value of T_b of about 9°F implies sufficient energy input (via solar radiation and condensation) to cause melt even at low temperatures. This is not really true, however, since the melt equation was linearized about a temperature of 35°F and should only be used in that range. The exercise serves to indicate the range of values that may be found when substituting actual meteorological data into the equations. Although seemingly wrong values may result, e.g., base melt temperatures less than zero, the equation with such values is still valid for the input parameters used and over the range of the linearization.

APPENDIX IV

STORAGE/TREATMENT SIMULATION

OBJECTIVES

The primary objectives of the Storage/Treatment Block are to:

1. provide the capability of modeling a larger number of processes in both the single event and continuous modes;
2. simulate the quality improvement provided by each process;
3. simulate the handling of sludges; and
4. provide estimates of capital, operation and maintenance costs.

Although the objectives of the Storage/Treatment Block have not changed appreciably from earlier versions (Metcalf and Eddy et al., 1971a), the model has been virtually rewritten. The earlier versions were more limited in use and scope. This version is much more flexible in terms of the control units available, pollutant routing and cost estimating. However, the user is advised that increased flexibility implies increased user input and knowledge of the processes to be modeled. In other words, the model does not provide several dozen specialized designs, but provides the tools necessary to simulate the desired processes. Naturally, flexibility precludes ultrasophistication.

Several precautions should be noted before setting up the S/T Block.

1. Local waste characterization data are essential to appraise realistically the performance of treatment units.
2. Lab or pilot plant performance data should be used whenever possible to derive performance functions.
3. Dry-weather treatment performance functions should be applied cautiously to wet-weather units.

PROGRAM DEVELOPMENT AND OVERVIEW

Development

Past versions of the Storage/Treatment Block simulated various processes on the basis of limited empirical data and operating experience. Often the data were localized and/or specialized. Thus, they were of questionable applicability to a wide variety of situations. Additionally, the model did not account for the physical characteristics of the incoming waste stream or the handling of residuals (sludges).

To improve the storage/treatment modeling capabilities of SWMM the following considerations were instrumental in creating a new model.

1. There should be a high degree of flexibility in the simulation of individual units and the interaction among units.
2. In addition to simulating the mass of pollutants, it is important to account for the physical characteristics (i.e., particle size and specific gravity distribution) of each pollutant.
3. Residual (sludge) handling is an important part of any wastewater treatment scheme and should be simulated.
4. All costing routines should be as flexible as the performance algorithms.
5. The model should be capable of modeling wet- and dry-weather facilities.

Overview

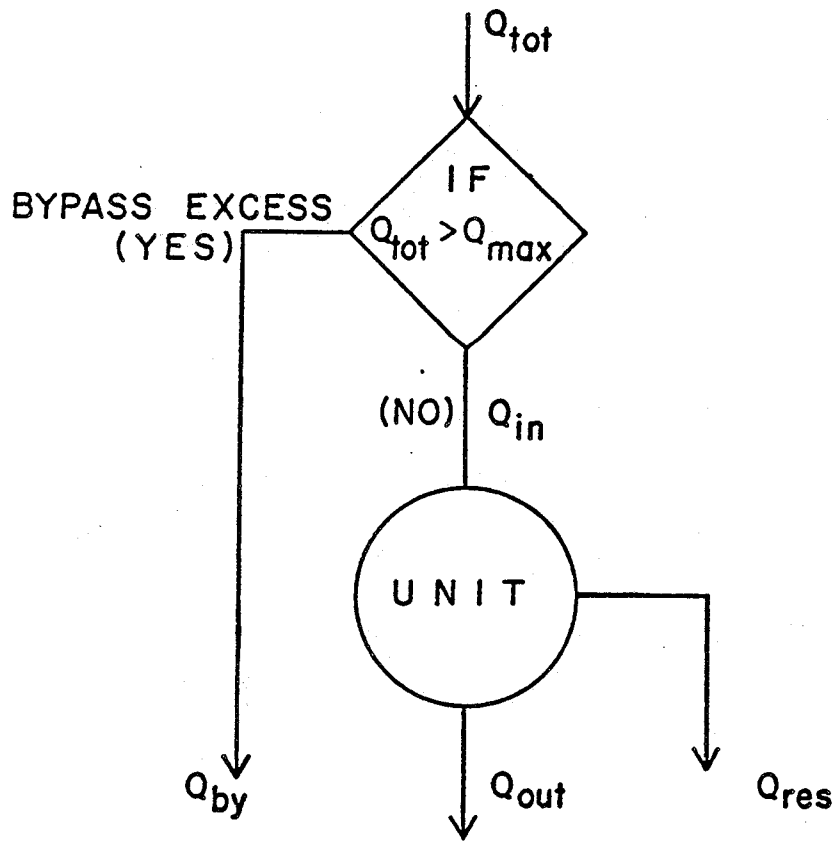
The present Storage/Treatment Block is approximately 2000 Fortran statements in length and consists of eight subroutines. The routing of flow and pollutants through the entire block is controlled by subroutine STRT which is called from the Executive Block. STRT also provides the main driving loop for the model and generally acts as the central coordinating subroutine. Subroutine STRDAT is called in STRT and is responsible for reading the input data provided by the user. Subroutine CONTRL is called each time-step from the main driving loop in STRT. CONTRL directs flow and pollutants from one unit to another as prescribed by the desired scheme and coordinates the majority of the printed output. Subroutine UNIT is called from CONTRL for each unit modeled and is the heart of the Storage/Treatment Block. It contains the necessary flexibility and capability to model most storage/treatment processes (units). Subroutine EQUATE is used by UNIT to provide several forms of pollutant removal equations. Subroutine INTERP is employed by UNIT for linear interpolation. Subroutine PLUGS is used by UNIT to model perfect plug flow through a detention unit. Subroutine STCOST is called from STRT to determine capital and operation and maintenance costs.

The model has become user-intensive rather than program-intensive. The user is responsible for providing the program with the desired storage/treatment scheme and operating characteristics of each unit (along with other information). However, input guidelines are provided in the User's Manual for several types of units. Again, the strength of this approach is to maximize flexibility and applicability to local conditions and design criteria.

SIMULATION TECHNIQUES

Introduction

Flow and pollutants are routed through one or more storage/treatment units by several techniques. The flows into, through and out of a unit are shown in Figure IV-1. The units may be arranged in any fashion, restricted only by the requirements that inflow to the plant enters at only one unit



LEGEND

Q_{tot} = TOTAL INFLOW, ft^3/sec

Q_{max} = MAXIMUM ALLOWABLE INFLOW, ft^3/sec

Q_{by} = BYPASSED FLOW, ft^3/sec

Q_{in} = DIRECT INFLOW TO UNIT, ft^3/sec

Q_{out} = TREATED OUTFLOW, ft^3/sec

Q_{res} = RESIDUAL STREAM, ft^3/sec

Figure IV-1. Flows Into, Through, and Out of a Storage/Treatment Unit.

and that the products (treated outflow, residuals, and bypass flow) from each unit not be directed to more than three units. Treatment and sludge handling units are modeled by the same subroutine (UNIT). Additionally, both wet- and dry-weather facilities may be simulated by the proper selection of unit arrangement and characteristics. Units may be modeled as having a detention capability or instantaneous throughflow. Pollutants or sludges may be represented as mass only or further characterized by a particle size or settling velocity distribution. A unit may remove pollutants (or concentrate sludges) as a function of particle size and specific gravity, detention time, incoming concentration, the removal rate of another pollutant, or a constant percentage. The S/T Block can receive the flow and any three pollutants from any one outlet in any other block of SWMM. Also, flows and pollutants may be provided by the user and fed directly to the S/T Block. If both sources are present they are combined and treated as one input. For example, the user may enter directly dry-weather flows and enter wet-weather flows from the Runoff Block. All flows and pollutant concentrations reported by the S/T Block are average values over each time step. This is necessary for some of the algorithms in the S/T Block (in particular, the plug flow routines); it does not significantly affect the results.

The following sections describe the techniques available for flow and pollutant routing which allow the user to model several types of storage/ treatment units.

Flow Routing

Detention vs. Instantaneous Throughflow --

A unit may be modeled to handle flow in one of two ways; as a detention unit (reservoir) or a unit instantaneously passing all flow. The idea of a detention unit is not limited to storage basins and sedimentation tanks but also includes such processes as dissolved air flotation, activated sludge, and chlorination. Processes that may be modeled as having instantaneous throughflow include microscreens, fine screens and other forms of screening.

Detention Units --

The rate of change of storage in a detention unit or reservoir is found by writing a mass balance equation for the system shown in Figure IV-2.

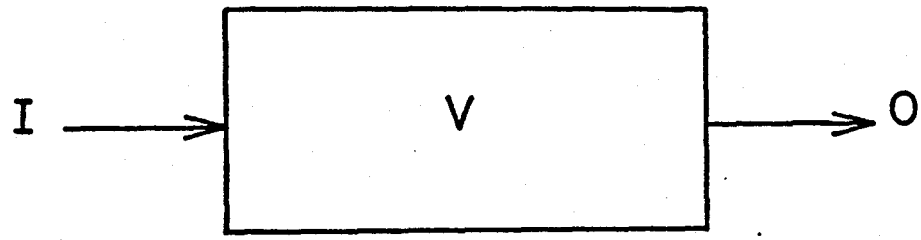


Figure IV-2. Time Varying Inflow and Outflow Rates for a Reservoir.

The rate of change of storage equals inflow minus outflow, or

$$\Delta V/\Delta t = \bar{I} - \bar{O} \qquad \text{(IV-1)}$$

where $\bar{I}$ = average inflow rate during Δt, ft^3/sec,

$\bar{O}$ = average outflow rate during Δt, ft^3/sec,

V = reservoir volume, ft^3, and

Δt = time step, sec.

Let subscripts 1 and 2 denote the beginning and end of the time step, respectively. Then, the average inflow rate $\bar{I}$, is

$$\bar{I} = (I_1 + I_2)/2 \qquad \text{(IV-2)}$$

The average outflow rate, $\bar{O}$, is

$$\bar{O} = (O_1 + O_2)/2 \qquad \text{(IV-3)}$$

Also, the change in reservoir volume is

$$\Delta V = V_2 - V_1 \qquad \text{(IV-4)}$$

Substituting equations IV-2, IV-3, and IV-4 into equation IV-1 and multiplying through by Δt yields the desired expression for the change in volume, i.e.,

$$V_2 - V_1 = \frac{I_1 + I_2}{2} \Delta t - \frac{O_1 + O_2}{2} \Delta t \qquad \text{(IV-5)}$$

For a given time step, I_1, I_2, O_1, and V_1 are known and O_2 and V_2 need to be determined. Grouping the unknowns on the left hand side of the equation and rearranging yields one of two required equations:

$$0.5O_2\Delta t + V_2 = 0.5(I_1 + I_2)\Delta t + (V_1 - 0.5O_1\Delta t) \qquad \text{(IV-6)}$$

The second required equation is found by relating O_2 and V_2, each of which is a function of reservoir depth. The procedure is illustrated in the following example.

Table IV-1 presents geometric and routing data for a hypothetical reservoir with a base elevation of 343.0 ft and a maximum pool elevation of 353.0 ft. The corresponding depths are shown in column 3. Surface area, as a function of depth, is presented in column 4. If the reservoir has an irregular geometry, the surface area is measured from a topographic map. The deptharea data pairs shown in columns 3 and 4 of Table IV-1 are required input data. If the user desires, the depth-discharge relationship may be input directly by assigning values of O_2 to each depth or generated by a user-supplied depth-discharge equation (e.g., weir equation). Similarly, the user may specify the volume, V_2, associated with each depth or allow

Table IV-1. Geometric and Hydraulic Data for Hypothetical Reservoir

n	Elevation h	Depth y	Surface Area A	Discharge O_2	Volume V_2	O2DT2 $0.5O_2\Delta t$	SATERM $0.5O_2\Delta t+V_2$	Remarks
	ft	ft	1000 ft^2	ft^3/sec	1000 ft^3	1000 ft^3	1000 ft^3	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	343.0	0.0	0.	0.	0.	0.	0.	Base of reservoir
2	344.0	1.0	3.	0.	2.	0.	2.	
3	345.0	2.0	15.	0.	10.	0.	10.	
4	346.0	3.0	45.	0.	40.	0.	40.	
5	347.0	4.0	121.	0.	120.	0.	120.	
6	348.0	5.0	225.	0.	300.	0.	300.	
7	349.0	6.0	365.	0.	590.	0.	590.	
8	350.0	7.0	550.	0.	1050.	0.	1050.	
9	351.0	8.0	790.	0.	1720.	0.	1720.	Weir elevation
10	351.5	8.5	910.	30.	2140.	324.	2464.	
11	352.0	9.0	1080.	65.	2650.	702.	3352.	
12	352.2	9.2	1130.	80.	2900.	864.	3764.	
13	352.4	9.4	1190.	105.	3100.	1134.	4234.	
14	352.6	9.6	1270.	130.	3400.	1404.	4804.	
15	352.8	9.8	1350.	165.	3700.	1782.	5482.	
16	353.0	10.0	1440.	200.	3900.	2160.	6060.	Maximum pool

Column
(1) Counter
(2) Elevation from topographic map
(3) Depth = h - 343.0
(4) Measured from topographic map or may be calculated (by user) if geometry is regular
(5) Measured data or calculated from discharge formulas
(6) Measured data or calculated
(7) Calculated from column 5, Δt = 21,600 sec.
(8) Calculated from columns 6 and 7

the model to calculate the depth-volume relationship. This is accomplished by averaging the surface area between adjacent values of depth, multiplying by the difference in depth, and adding the incremental volume to the accumulated total. The depth-area data pairs are also used to estimate the volume lost from the reservoir due to evaporation.

Recalling equation IV-6, the objective is to find

$$0.5O_2\Delta t = f(0.5O_2\Delta t + V_2). \qquad \text{(IV-7)}$$

The data in Table IV-1 give O_2 and V_2 as functions of depth. In this case, discharge or outflow occurs only if the reservoir depth exceeds 8.0 ft. The model uses these data to calculate the values of $0.5O_2\Delta t$ (column 7) and $0.5O_2\Delta t + V_2$ (column 8) for each depth (defined in the model as O2DT2 and SATERM, respectively). Thus, the relationship required by equation IV-7 is indirectly generated. During the simulation, the value of $0.5O_2\Delta t + V_2$ is calculated by equation IV-6 and the corresponding value of $0.5O_2\Delta t$ found by linear interpolation through the previously generated set of O2DT2 - SATERM values. The values of O_2 and V_2 are subsequently calculated. This procedure is repeated each time step with the value of O_2 and V_2 becoming the values of O_1 and V_1 for use in equation IV-6 during the next time step. In a normal simulation the outflow, O_2, represents treated outflow, residual flow, and evaporation.

The computational procedure is summarized as follows:

1. Known values of I_1, I_2, O_1, Δt, and V_1 are substituted into the right hand side of equation IV-6. The result is the first value of $0.5O_2\Delta t + V_2$.
2. Knowing $(0.5O_2\Delta t + V_2)$ the value of $0.5O_2\Delta t$ is obtained by interpolating between adjacent values of O2DT2 and SATERM.
3. The values of V_2 and O_2 are determined and become the values of V_1 and O_1, respectively, in the next time step.
4. Add $0.5(I_1 + I_2)\ \Delta t$ to the new value of $V_1 - 0.5O_1\Delta t$ to get the new value of $0.5O_2\Delta t + V_2$.
5. Continue this process until all inflows have been routed.

To summarize the input alternatives, the earlier version of the storage model permitted the user to read in depth-area data and an outflow condition of a weir, orifice, or pumping. It could not handle the case of a natural reservoir with an irregular stage-discharge relationship. The updated model allows the user to input the required relationship between depth-surface area, treated outflow, residual flow, and storage volume through as many as

sixteen data sets. This approach permits the user to select the data points which best approximate the desired functional relationships. This approach is felt to be preferable to adding more complexity to the model to analyze automatically the wide variety of reservoir geometries and operating policies encountered in practice.

An excellent description of this level-surface routing procedure (the Puls Method) is presented in Viessman et al. (1977). Sound engineering judgement is essential in setting up this routing procedure. The input data and associated assumptions should be checked carefully.

Residual Flow --

Residual flows occur only during dry periods (i.e. no inflow or treated outflow), and thus, serve to drain the detention unit between storms. The user can direct the unit to be drained after a specified number of dry time steps or on a scheduled basis (every i^{th} time, depending on the inflow/outflow status). Residual flows are handled in the same manner as the outflow in the routing procedure outlined previously. These flows contain a mixture of the stored wastewater and removed pollutant quantities (see later discussion). The manner in which pollutants are removed and accumulated is discussed later. In detention units, the residual flow is suspended when wet weather occurs.

Evaporation --

Evaporation losses are also accounted for in detention units. The loss rate is computed by

$$e_v = A \cdot e_d / k \qquad \text{(IV-8)}$$

where e_v = evaporation loss rate, ft^3/sec,

A = surface area at the water level in the unit, ft^2,

e_d = evaporation rate, in./day, and

k = 1036800.0, conversion factor, in./day per ft/sec.

The user must supply the values of e_d for each month of the simulation period.

Instantaneous Throughflow --

If the unit is specified to have no detention capability, then the model assumes that what arrives during a time step leaves as treated outflow that same time step less the residual flow. The residual flow is calculated as a constant fraction of the inflow.

Pollutant Routing

Complete Mixing --

Pollutants are routed through a detention unit by one of two modes: Complete mixing or plug flow. For complete mixing, the concentration of the pollutant in the unit is assumed to be equal to the effluent concentration. The mass balance equation for the assumed well-mixed, variable-volume reservoir shown in Figure IV-3 is (Medina, 1976):

$$\frac{d(VC)}{dt} = I(t)\ C^I(t) - O(t)\ C(t) - K\ C(t)\ V(t) \qquad \text{(IV-9)}$$

where V = reservoir volume, ft^3

C^I = influent pollutant concentration, mg/l,

C = effluent and reservoir pollutant concentration, mg/l,

I = inflow rate, ft^3/sec,

O = outflow rate, ft^3/sec,

t = time, sec, and

K = decay coefficient, sec^{-1}.

Equation IV-9 is very difficult to work with directly. It may be approximated by writing the mass balance equation for the pollutant over the interval, Δt:

Change in mass in basin during Δt = Mass entering during Δt - Mass leaving during Δt - Decay during Δt

$$C_2V_2 - C_1V_1 = \frac{C_1^I\ I_1 + C_2^I\ I_2}{2}\ \Delta t - \frac{C_1O_1 + C_2O_2}{2}\ \Delta t - K\ \frac{C_1V_1 + C_2V_2}{2}\ \Delta t \qquad \text{(IV-10)}$$

where subscripts 1 and 2 refer to the beginning and end of the time step, respectively.

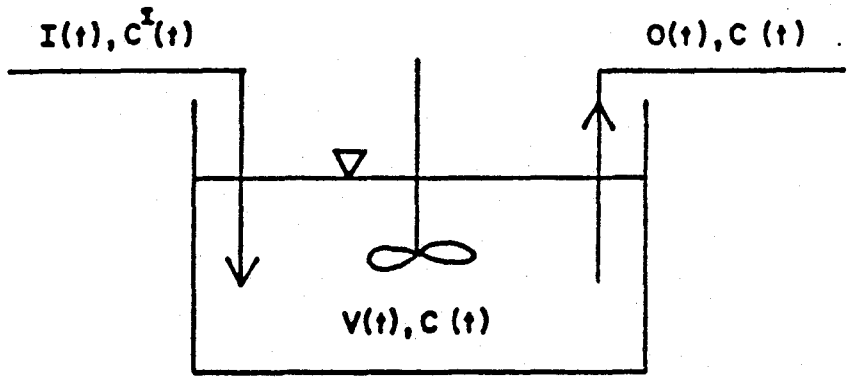


Figure IV-3. Well-Mixed, Variable-Volume Reservoir (Rich, 1973).

From the flow routing procedure discussed earlier, I_1, I_2, O_1, O_2, V_1, and V_2 are known. The concentration in the reservoir at the beginning of the time step, C_1, and the influent concentrations, C_1^I and C_2^I are also known as are the decay rate, K, and the time step, Δt. Thus, the only unknown, the end of time step concentration, C_2, can be found directly by rearranging equation IV-10 to yield

$$C_2 = \frac{C_1V_1 + \frac{(C_1^I\, I_1 + C_2^I\, I_2)}{2}\,\Delta t - \frac{C_1O_1}{2}\,\Delta t - \frac{K\, C_1V_1}{2}\,\Delta t}{V_2(1 + \frac{K\,\Delta t}{2}) + \frac{O_2}{2}\,\Delta t} \qquad \text{(IV-11)}$$

Equation IV-11 is the basis for the complete mixing model of pollutant routing through a detention unit.

Equations IV-9, IV-10, and IV-11 assume that pollutants are removed at a rate proportional to the concentration present in the unit. In other words, a first-order reaction is assumed. The coefficient K is the rate constant. The product of K and Δt is represented by the value of R in a user-supplied removal equation (See Equation IV-14 and accompanying discussion).

Removed pollutant quantities are not allowed to accumulate in a completely-mixed detention unit. Strictly, pollutants cannot settle under such conditions. Therefore, the residual stream is effectively another route for treated outflow. All pollutant removal is assumed to occur by non-physical means (e.g., biological decomposition). Several processes such as flocculation and rapid-mix chlorination are essentially completely-mixed detention units.

Plug Flow --

If the user selects the plug flow option, the inflow during each time step, herein called a plug, is labeled and queued through the detention unit. Transfer of pollutants between plugs is not permitted. The outflow for any time step is comprised of the oldest plugs, and/or fractions thereof, present in the unit. This is accomplished by satisfying continuity for the present outflow volume (which was calculated earlier):

$$\sum_{j=JP}^{LP} V_j \cdot f_j = V_o \qquad \text{(IV-12)}$$

where V_o = volume leaving unit during the present time step, ft^3,

V_j = volume entering unit during j^{th} time step (plug j), ft^3,

f_j = fraction of plug j that must be removed to satisfy continuity with V_o, $0 \leqq f_j \leqq 1$,

JP = time step number of the oldest plug in the unit, and

LP = time step number of the youngest plug required to satisfy continuity with V_o.

As in a completely-mixed detention unit, detention time is the most important indicator of pollutant removal ability. Removal equations are specified by the user (see later discussion) and, in this case, should be written as a function of detention time (along with other possible parameters). The detention time for each plug j is calculated as

$$(t_d)_j = (KKDT - j)\Delta t \qquad \text{(IV-13)}$$

where KKDT = present time step number. The detention time is calculated in the same manner during dry- and wet-weather periods because the plugs always maintain their identity.

Removed pollutant quantities accumulate in a plug-flow unit until they are drawn off by residual flow. The accumulated pollutants do not affect the amount of available storage and are assumed to be conservative (i.e., no decay). When residual flow occurs the entire unit contents (including the removed pollutant quantities) are mixed and drawn off until the unit is empty or wet weather continues. If wet weather (i.e., inflow) occurs before the unit is empty, the contents are placed into one plug for further routing.

Instantaneous Throughflow --

Pollutants are routed instantaneously through units modeled as having no detention capability. In other words, the pollutants arriving during a time step leave the same time step less the removed portion. The amount of removed pollutants is determined by user-supplied removal equations (see later discussion). The removed pollutants are routed with the residuals stream.

Pollutant Characterization

Pollutants are characterized by their magnitude (i.e., mass flow and concentration) and, if the user desires, by particle size/specific gravity or settling velocity distributions. Describing pollutants by their particle size distribution is especially appropriate where small or large particles dominate or where several storage/treatment units are operated in series. For example, if the influent is primarily sand and grit, then a sedimentation unit would be very effective; if clay and silt predominate, sedimentation may be of little use. Also, if several units are operated in series, the first units will remove a certain range of particle sizes thus affecting the performance of downstream units. Therefore, the need for describing pollutants in more detail is obvious for modeling purposes. The pollutant removal mechanism peculiar to each characterization is discussed below.

Pollutant Removal

Characterized by Magnitude --

If pollutants are characterized only by their magnitude then the model improves the quality of the waste stream by removal equations. Removal of a pollutant may be simulated as a function of (1) detention time (detention units only), (2) time step size, (3) its influent concentration, (4) inflow rate, (5) the removal fractions of pollutants, and/or (6) the influent concentrations of other pollutants. This selection is left to the user but there are some restrictions (depending on the unit type). A single flexible equation is provided by the program to construct the desired removal equation:

$$R = \left(a_{12} e^{a_1 x_1} x_2^{a_2} + a_{13} e^{a_3 x_3} x_4^{a_4} + a_{14} e^{a_5 x_5} x_6^{a_6} + a_{15} e^{(a_7 x_7 + a_8 x_8)} x_9^{a_9} x_{10}^{a_{10}} x_{11}^{a_{11}} \right)^{a_{16}} \qquad \text{(IV-14)}$$

where x_i = removal equation variables,

a_j = coefficients, and

R = removal fraction, $0 \leq R \leq 1.0$

The user assigns the removal equation variables, x_i to specific program variables (detention time, flow rate, etc.). If an equation variable is not assigned it is set equal to 1.0 for the duration of the simulation. The values of the coefficients, a_j, are directly specified by the users. There is considerable flexibility contained in equation IV-14 and, with a judicious selection of coefficients and assignment of variables, the user probably can create the desired equation. Three examples are given below.

An earlier version of the Storage/Treatment Block employed the following removal equation for suspended solids in a sedimentation tank (Huber et al., 1975):

$$R_{SS} = R_{max}(1 - e^{-Kt_d}) \qquad \text{(IV-15)}$$

where R_{SS} = suspended solids removal fraction, $0 \leqq R_{SS} \leqq R_{max}$,

R_{max} = maximum removal fraction,

t_d = detention time, sec, and

K = first order decay coefficient, sec^{-1}.

This same equation could be built from equation IV-14 by setting $a_{12} = R_{max}$, $a_{13} = -R_{max}$, $a_3 = -K$, $a_{16} = 1.0$, and letting x_3 = detention time, t_d. All other coefficients, a_j, would equal zero.

Another example is taken from a study by Lager et al. (1977a). Several curves for suspended solids removal from microstrainers with a variety of aperture sizes were derived. Fitting a power function to the curve representing a 35-micron microstrainer yields

$$R_{SS} = 0.0963\ SS^{0.286} \qquad \text{(IV-16)}$$

where R_{SS} = suspended solids removal fraction, and $0 \leqq R_{SS} \leqq 1.0$, and,

SS = influent suspended solids concentration, mg/l.

Equation IV-14 can be used to duplicate this removal equation by setting $a_{12} = 0.0963$, $a_2 = 0.286$, $a_{16} = 1.0$, and x_2 = influent suspended solids concentration, SS. All other a_j are zero.

Sludge handling may also be modeled with equation IV-14. Figure IV-4 shows the reduction in volatile solids in raw sludge (suspended solids --see earlier discussion) by a digester as a function of percent volatile solids and detention time (Rich, 1973). These curves can be approximated by

$$R_{VS} = 1.31 \times 10^{-4} \left(\frac{t_d}{86400}\right)^{0.33} P_{VS}^{1.67} \qquad \text{(IV-17)}$$

where R_{VS} = volatile solids reduction, $0 \leqq R_{VS} \leqq 1.0$

t_d = detention time, sec,

P_{VS} = percent volatile solids in raw sludge,

$$P_{VS} = 100\ \frac{VS}{SS} \qquad \text{(IV-18)}$$

where VS = influent volatile solids concentration, mg/l, and

SS = influent suspended solids (raw sludge) concentration, mg/l.

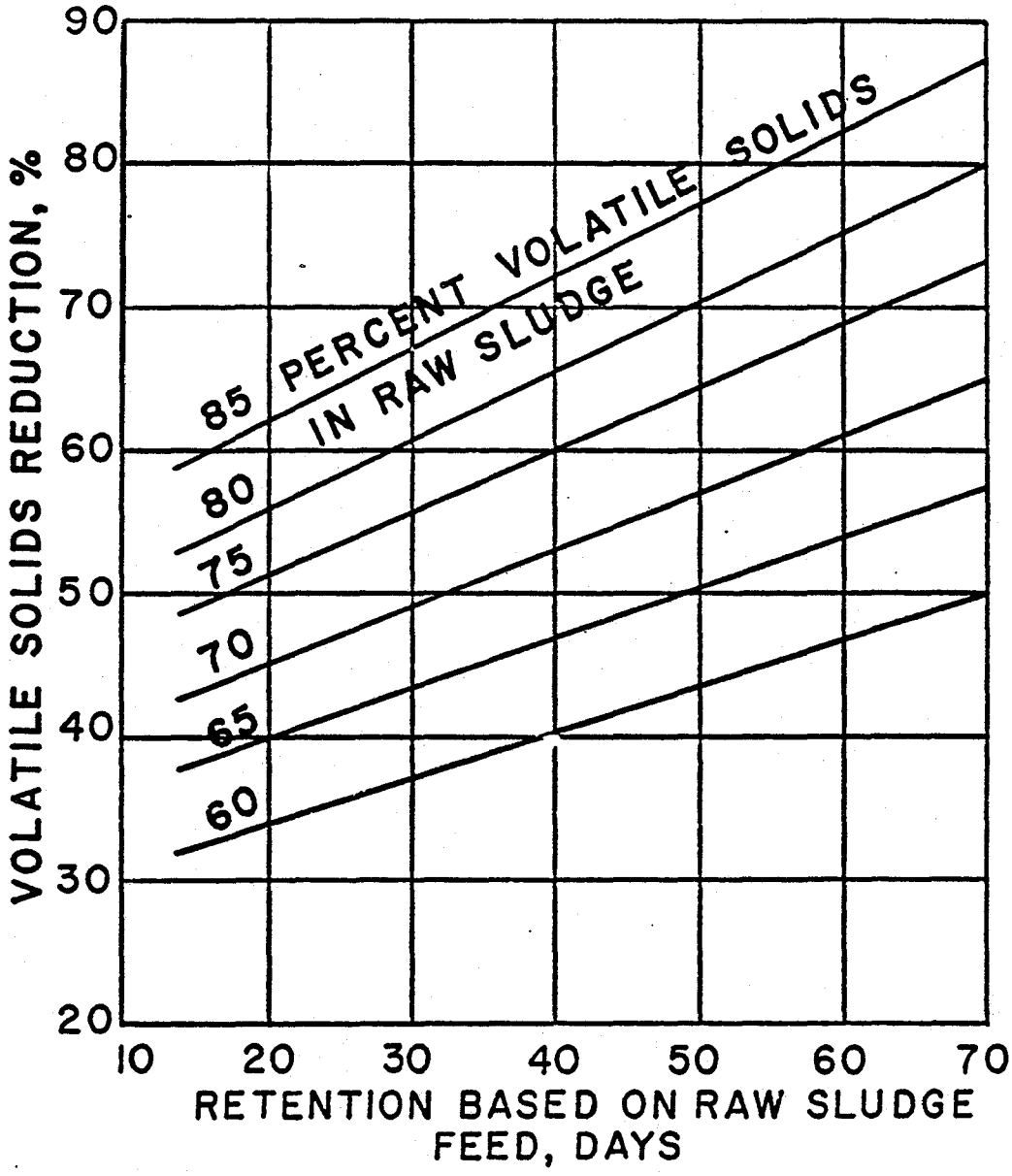


Figure IV-4. Reduction in Volatile Solids in Raw Sludge (Rich, 1973).

Equation IV-14 can be used to construct equation IV-17 by setting $a_{15} = (1.31 \times 10^{-4})(1440)^{-0.33}(100)^{1.67}$, $a_9 = 0.33$, $a_{10} = 1.67$, $a_{11} = -1.67$, $a_{16} = 1.0$, x_9 = detention time, t_d, x_{10} = influent volatile solids concentration, VS, and x_{11} = influent suspended solids (raw sludge) concentration, SS. A current description of sludge handling can be found in several references (Gupta et al., 1977, Huibregtse, 1977, Osantowski et al., 1977).

Characterized by Particle Size Specific Gravity or Settling Velocity Distribution --

Particle Sizes and Specific Gravities -- If a pollutant is characterized by its particle size/specific gravity or settling velocity distribution, then it is removed from the waste stream by particle settling or obstruction. Many storage/treatment processes use these physical methods to treat wastewater; sedimentation and screening are among the most obvious examples.

In this mode, the pollutant is apportioned over several (up to 10) particle size/specific gravity ranges (e.g., ten percent of the BOD is found in the range from 10 to 50 microns) or settling velocities. Each of the ranges is preset by the user and assigned an upper and lower bound on the particle diameter and a value for specific gravity. If a size/specific gravity distribution is specified the model estimates the average settling velocity for each range. Alternatively, the user may specify a set of settling velocity ranges. The user also specifies the apportionment of the pollutant over the various ranges as it enters the first unit. This distribution is modified as it passes through the storage/treatment plant. Unfortunately, the distribution entered at the first unit must remain constant over time since the other blocks of SWMM do not provide a time-varying particle size or settling velocity distribution.

Each unit removes all or some portion of the particles in each range or velocity; the associated removal of the pollutant is easily determined. For example, if a sedimentation unit removes 50 percent of the particles in the 50 to 100 micron range and ten percent of the pollutant in question is found in this range, then five percent of the total pollutant load is removed. The total removal is determined by summing the effects of the several ranges or settling velocities passing through this unit. Once certain particles are removed, the distribution of particle sizes or settling velocities for the outflow can be determined and passed on to the next unit or receiving water. The removed particles constitute the size or settling velocity distribution for the sludge volume. The next several paragraphs describe the two mechanisms available to the user for pollutant removal when a pollutant is characterized by particle size or settling velocity.

Particle Settling -- There are several forms of settling: unhindered settling by discrete particles, settling by flocculating particles, and hindered settling by closely spaced particles (Fair et al., 1968). For simplicity, the unhindered settling of discrete particles will be the removal mechanism simulated in this model. This procedure is only applicable to detention basins modeled as plug-flow reactors.

Discrete particles settling in a quiescent fluid accelerate to the point where the drag force exerted by the suspending fluid reaches equilibrium with the gravitational force exerted on the particle (Fair et al., 1968). At this point, the particle settles at a constant velocity known as the terminal velocity. By equating the forces acting on such a particle, the equation for the terminal or settling velocity of the particle is derived and approximated by

$$v_s = \sqrt{\frac{4}{3}\frac{gd}{C_D}(S_p - 1)} \qquad \text{(IV-19)}$$

where v_s = terminal velocity of particle, ft/sec,

g = gravitational constant, 32 ft/sec^2,

C_D = drag coefficient,

S_p = specific gravity of particle, and

d = diameter of particle, ft.

Additionally,

$$C_D = \frac{24}{N_R}, \text{ if } N_R < 0.5, \text{ or} \qquad \text{(IV-20)}$$

$$C_D = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34, \text{ if } 0.5 \leq N_R < 10^4, \text{ or} \qquad \text{(IV-21)}$$

$$C_D \cong 0.4, \text{ if } N_R \geq 10^4. \qquad \text{(IV-22)}$$

where N_R = Reynolds number, dimensionless,

$$N_R = v_s\, d/\nu \qquad \text{(IV-23)}$$

and ν = kinematic viscosity, ft^2/sec. Kinematic viscosity is a function of temperature and is approximated by (Fair et al., 1969)

$$\nu \cong 8.46 \times 10^{-4}/(T + 10) \qquad \text{(IV-24)}$$

where T = water temperature, °F.

The procedure for finding v_s under any of the above conditions is demonstrated by Sonnen (1977). The average of the high and low ends of each particle size range is used as the representative particle size for use in the above calculations. If a settling velocity distribution is provided by the user these calculations are omitted.

A range of conditions may exist in an actual detention unit, from very quiescent, to highly turbulent and nonquiescent. Camp's (1946) ideal removal efficiency, E_Q, will be used for quiescent conditions, and an adaptation of

his sedimentation trap efficiency curves (Camp, 1946, Dobbins, 1944, Brown, 1950) as described by Chen (1975) will be used to make the extension to nonquiescent conditions, as described below.

For quiescent conditions,

$$E_Q = \min \begin{cases} 1 \\ v_s/v_u \end{cases} \qquad \text{(IV-25)}$$

where E_Q = particle removal efficiency as a fraction, $0 \leq E_Q \leq 1$,

v_s = terminal velocity of particle, ft/sec, and

v_u = overflow velocity, ft/sec.

Additionally,

$$v_u = Q/A = \frac{Ay/t_d}{A} = y/t_d \qquad \text{(IV-26)}$$

where Q = flow rate, ft^3/sec,

A = surface area of detention unit, ft^2,

y = depth of water in unit, ft, and

t_d = detention time, sec.

Equation IV-26 assumes a rectangular detention unit with vertical sides. However, a circular unit (with vertical sides) may also be modeled when characterizing pollutants by particle size. In other words, equation IV-26 is restricted to units that allow the surface area to remain constant at any depth. Applying this equation (and, thus, the entire methodology) to other unit types should only be done when the surface area is independent of depth.

Equation IV-25 represents an ideal quiescent basin in which all particles with settling velocities greater than v_u will be removed. Deviations from quiescent conditions can be handled explicitly based on Camp's (1946) sedimentation trap efficiency curves, which were developed as a complex function of particle settling velocity and several basin parameters, i.e.,

$$E = f\left(\frac{v_s y}{2\varepsilon}, \frac{v_s A}{Q} = \frac{v_s \ell}{v_t y} = \frac{v_s}{v_u} \right) \qquad \text{(IV-27)}$$

where E = particle removal efficiency, $0 \leqq E \leqq 1$,
ε = vertical turbulent diffusivity or mixing coefficient, ft^2/sec,
v_t = flow through velocity of detention unit, ft/sec,
ℓ = travel length of detention unit, ft, and
other terms are defined previously.

Camp (1946) solves for the functional form of equation IV-27 assuming a uniform horizontal velocity distribution and constant diffusivity, ε. A form of the advective-diffusion equation then results in which local changes in concentration at any vertical elevation are equal to the net effect of settling from above and diffusion from below. The diffusivity will be constant if the horizontal velocity is assumed to have a parabolic distribution, (although this assumption is clearly at variance with the uniform velocity distribution assumption above). For the parabolic distribution, ε is then found from

$$\varepsilon = 0.075\ y\sqrt{\tau_o/\rho} \qquad \text{(IV-28)}$$

where τ_o = boundary shear stress, lb/ft^2 and

ρ = density of water $\cong$ 1.94 slug/ft^3 (1.00 g/cm^3).

The term $\sqrt{\tau_o/\rho}$ is known as the shear velocity, u_*, and can be evaluated using Manning's equation for open channel flow (Brown, 1950),

$$u_* = \sqrt{\tau_o/\rho} = \frac{v_t n\sqrt{g}}{1.49\ y^{1/6}} \qquad \text{(IV-29)}$$

where n = Manning's roughness coefficient.

The flow through ("horizontal") velocity, v_t, is also given by

$$v_t = \ell/t_d \qquad \text{(IV-30)}$$

where ℓ = travel length of detention unit, ft, and

t_d = detention time, sec.

Equations IV-27 and IV-28 are then used to convert $v_s y/2\varepsilon$ to a more usable form,

$$\alpha = 0.1\frac{v_s y}{2\varepsilon} = \frac{v_s}{1.5u_*} = \frac{v_s y^{1/6}}{v_t\ n\sqrt{g}} \qquad \text{(IV-31)}$$

where α = turbulence factor, dimensionless when all parameters are in units of feet and seconds.

Camp's sedimentation trap efficiency curves (Camp, 1946; Dobbins, 1944, Brown, 1950, Chen, 1975) are the solution to the advective-diffusion equation mentioned previously and are shown in Figure IV-5 as a function of α. Ideally, these curves could be included in the model in some manner, but their representation is not straight forward from a programming standpoint. Instead, a simplification is used, based on early work of Hazen (1904) and the Bureau of Reclamation as described by Chen (1975).

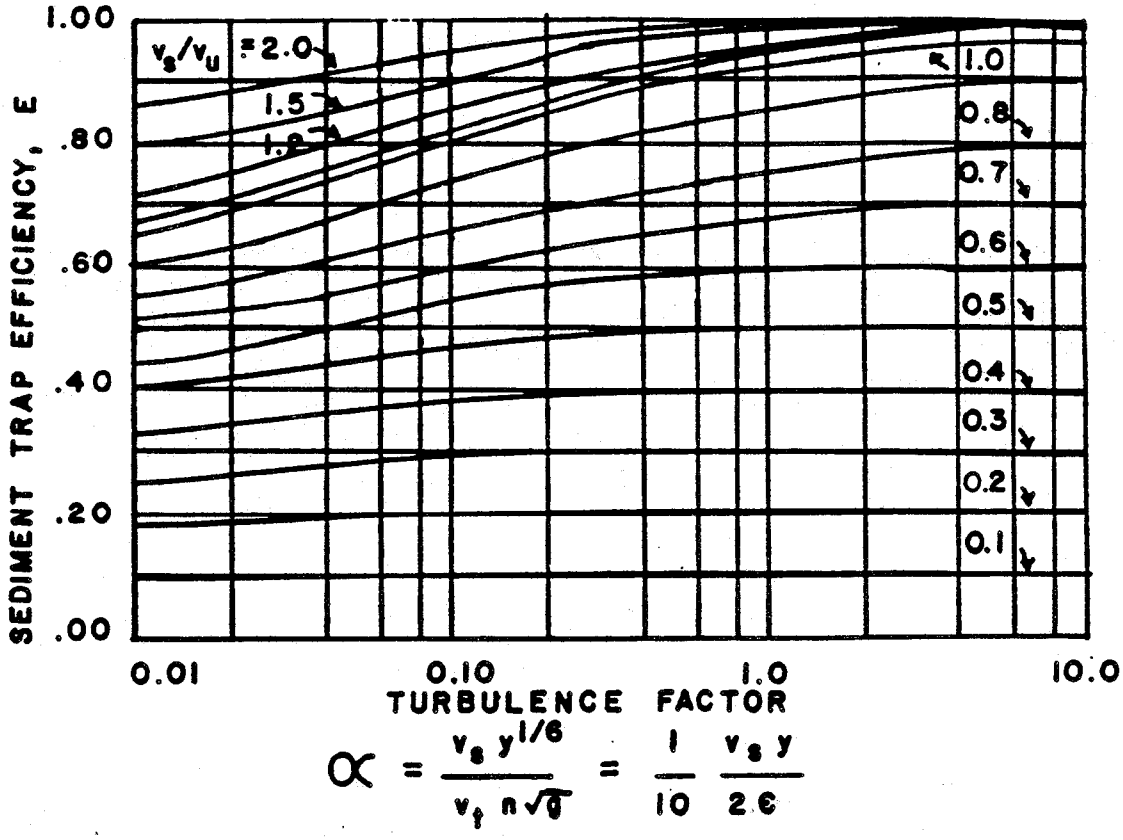


Figure IV-5. Camp's Sediment Trap Efficiency Curves (Camp, 1946, Dobbins, 1944, Brown, 1950, Chen, 1975).

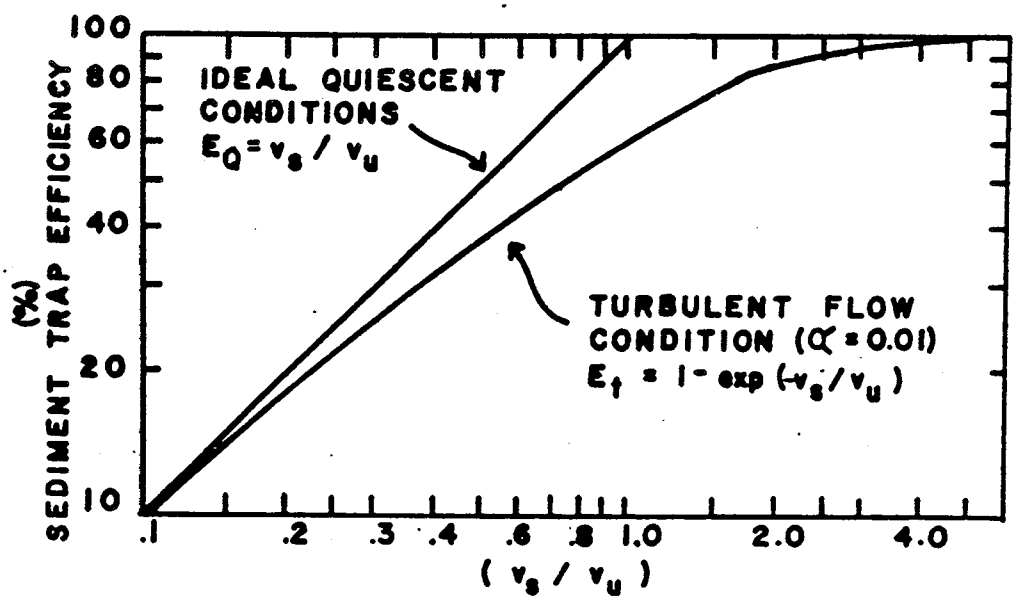


Figure IV-6. Limiting Cases in Sediment Trap Efficiency (Chen, 1975).

It is assumed that an upper limit on turbulent conditions is given by $\alpha = 0.01$. Removal efficiency under these conditions is accurately represented by the function (fitted to the ordinate of Figure IV-5),

$$E_T = (1 - e^{-v_s/v_u}) \qquad \text{(IV-32)}$$

or

$$E_T = (1 - e^{-v_s\, t_d/y}) \qquad \text{(IV-33)}$$

where E_T = particle removal efficiency under turbulent conditions, $0 \leq E_T \leq 1$.

Quiescent conditions are assumed to exist for $\alpha = 1.0$ for which removal is given by equation IV-25. Equations IV-25 and IV-32 are shown in Figure IV-6. The parameter α may now be used as a weighting factor to obtain the overall removal efficiency, E,

$$E = E_T + \frac{\ln \alpha - \ln 0.01}{\ln 1 - \ln 0.01} (E_Q - E_T) = E_Q + \frac{\ln \alpha}{4.605} (E_Q - E_T) \qquad \text{(IV-34)}$$

Thus, a linear approximation (with respect to $\ln \alpha$) is made of the curves shown in Figure IV-5. Within the program, values of the turbulence factor are limited to $0.01 \leq \alpha \leq 1.0$. If a value computed from equation IV-31 is less than 0.01 it is set equal to 0.01 and similarly for the quiescent boundary.

To summarize, the particle settling computations proceed as follows.

1. For each size and specific gravity range a settling velocity is computed using equations IV-19 to IV-24 or a distribution of settling velocities is provided by the user. If a settling velocity distribution is used the end points of each range are averaged to estimate the representative velocity. Then for each velocity (in each plug leaving the unit) all steps below are performed.

2. The turbulence factor, α, is computed from equation IV-31.

3. E_Q is computed using equation IV-25.

4. E_T is computed using equation IV-32 or IV-33.

5. Finally, the removal efficiency for the particular particle settling velocity is computed from equation IV-34.

In a normal simulation, several plugs leave the detention unit in any given time step. The effluent is all or part of a number of plugs depending on the required outflow as determined by the storage routing techniques discussed earlier. Thus, the effluent particle size or settling velocity distribution is a composite of several plugs. This composite distribution is

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determined by taking a weighted average (by pollutant weight in each plug) over the effluent plugs. This distribution is then routed downstream for release or further treatment. The particles that were removed from each plug are also composited and are used to characterize the sludge volume.

Particle Obstruction -- The second removal mechanism used when a pollutant is characterized by a particle size or settling velocity distribution is obstruction. The most obvious example of a storage/treatment process using this mechanism is screening. This mechanism is assumed by the model whenever a non-detention unit is encountered (and a pollutant is characterized by a size or settling velocity distribution). The user simply specifies a "critical" size or settling velocity and any particles with a greater size or settling velocity are removed (and, in turn, so are the associated pollutants). The program operation is simple but the interpretation of the "critical" size or settling velocity is more complex.

The primary intent of including this mechanism in the model is to simulate screens. Pollutant removal by screens is a result of two actions: the straining of the screens, and the additional filtration provided by the mat produced by the initial screening (Maher, 1974). Screens vary widely in the size of the aperture and the manner in which the waste water flows through them. To simplify the analysis, the removal of particles may be assumed to be a function of screen size only; i.e., the filtration by the mat is ignored. In other words, a particular screen size will remove only those particles larger than that size. If a settling velocity distribution is employed, the user must specify a settling velocity. This is not entirely accurate, of course, but the result is a conservative removal estimate that may be accurate in cases where backwashing is at a relatively high rate. In fact, a study by Maher indicates that this simplifying assumption is reasonable (Maher, 1974). In this case, a microstrainer with a Mark "O" screen (aperture of 23 microns) was installed in a residential area of Philadelphia, Pennsylvania. The analysis of the backwash material for two storms (one in which a coagulant was used) revealed that, by particle count, 88 to 96 percent of the particles were indeed smaller than 23 microns. However, by weight, over 99 percent of the material was found in particles greater than 23 microns. Although Maher did not report the distribution in terms of weight, it was a simple matter to convert by assuming a specific gravity.

During the simulation, a screen alters a particle size distribution for a particular time step without detention time. Again, only the particles larger than a specified or "critical" size are removed. The specified size may or may not correspond to the screen aperture, but such an assumption is probably valid given the preceeding discussion. If the specified size falls between the high and low ends of any range, the pollutants are removed by simple linear interpolation. For example, if 20 percent of the suspended solids are found in the range from 10 to 50 microns and the "critical" size is 20 microns, then 75 percent of the suspended solids in that range will be removed or 15 percent of the total suspended solids load. Of course, if the entire range is larger than the specified size, then all pollutants in that range are removed. If a pollutant is characterized by a settling velocity distribution (in lieu of a size distribution) the user specifies a "critical" settling velocity. The portion associated with velocities greater than or equal to the "critical" value is removed.

ie on Characterization by Particle Size Distribution -- Pollutants
:a rized by a particle size or settling velocity distribution are
:ricted by the model to the two removal mechanisms discussed above. This
.t the user somewhat if this characterization is chosen. The types of
:s that could be considered in this case would include sedimentation
:s and storage basins (operating as plug-flow reactors), bar racks, fine
:e s and microscreens. However, these units probably represent a large
:i n of the processes applied to the problem of combined sewer overflow
stormwater runoff. Thus, the limits of the applicability of the model
ıg this mode are probably not too severe.

: alculations

nitial capital and operation and maintenance costs are calculated at
d of a simulation. These costs are computed using only the informa-
ı processed for the simulation period. In other words, no attempt is
p derive costs for particular time intervals (e.g., annual). It is
r the user to interpret the results produced by the subroutine STCOST.

The capital cost for each unit is computed as a function of a design
r volume specified by the user or is calculated by the model as a
on of the maximum value recorded during the simulation.

$$C_{cap} = a\, Q_{max}^{b} \qquad \text{(IV-35)}$$

or

$$C_{cap} = a(Q_{in})_{max}^{b} \qquad \text{(IV-36)}$$

or

$$C_{cap} = a\, V_{max}^{b} \qquad \text{(IV-37)}$$

or

$$C_{cap} = a(V_{obs})_{max}^{b} \qquad \text{(IV-38)}$$

re C_{cap} = initial capital cost, dollars,

Q_{max} = maximum allowable inflow, ft^3/sec,

$(Q_{in})_{max}$ = maximum inflow encountered during the simulation, ft^3/sec,

V_{max} = maximum allowable storage (detention units only), ft^3,

$(V_{obs})_{max}$ = maximum storage encountered during the simulation (detention units only), ft^3, and

a, b = coefficients (specified by the user).

ver functions are frequently used in wastewater treatment cost estimations.
erefore, the above equations should be widely applicable.

peration and maintenance costs are calculated as functions of the
riables listed above and the total operating time (calculated as the
nb of time steps with inflow to the unit).

$$C_{om} = d\ Q_{max}^{f} + hD_{op} \quad \text{(IV-39)}$$

or

$$C_{om} = d(Q_{in})_{max}^{f} + hD_{op} \quad \text{(IV-40)}$$

or

$$C_{om} = d\ V_{max}^{f} + hD_{op} \quad \text{(IV-41)}$$

or

$$C_{om} = d(V_{obs})_{max}^{f} + hD_{op} \quad \text{(IV-42)}$$

where C_{om} = operation and maintenance costs, dollars,

D_{op} = total operating time during the simulation period, hours, and

d,f,h = coefficients (supplied by the user).

The user is cautioned not to misinterpret the cost calculated by the model. For example, in a single event simulation the calculated capital cost could only be considered an estimator of the true capital cost when the event simulated is a design event. Likewise, when operating time is a factor in computing operation and maintenance costs, the calculated costs can be a valid estimator of the true costs only when a long term simulation is performed. Recent EPA publications provide useful information for the proper selection of the coefficients required in equations IV-35 through IV-42 (EPA, 1976, Benjes, 1976).

SUMMARY

A new Storage/Treatment Block has been developed that is somewhat different from its predecessor. The model requires greater user input and knowledge of the processes being modeled. Storage/Treatment units may be modeled as detention or non-detention units. Pollutants may be characterized by their magnitude alone or by magnitude and their particle size/specific gravity distribution. Any three of the pollutants available from other blocks may be routed through the S/T Block. A simple cost routine is also included.

In summary, the Storage/Treatment Block offers the user a flexible tool for modeling wet- and dry-weather facilities and evaluating their performance and costs.

APPENDIX V

RUNOFF BLOCK EVAPORATION, INFILTRATION AND ROUTING

EVAPORATION

Evaporation is input for each month as parameter VAP (in subroutine RHYDRO) or as a time series in the Temp Block and used in equations in subroutine WSHED as parameter EVAP It is considered as a loss "off the top." That is, evaporation is subtracted from rainfall depths and/or ponded water prior to calculating infiltration. Thus, subsequent use of the symbol i for "rainfall intensity" is really rainfall intensity less evaporation rate. Although evaporation and infiltration are summed to form one total loss (RLOSS in subroutine WSHED) for the subcatchment runoff calculations, separate totals are maintained for the overall continuity check.

INFILTRATION

Introduction

For pervious areas SWMM users have the option of specifying one of two alternative infiltration models: the Horton model or the modified Green-Ampt model (Horton, 1940; Green and Ampt, 1911). Horton's model is empirical and is perhaps the best known of the infiltration equations. Many hydrologists have a "feel" for the best values of its three parameters despite the fact that little published information is available. In its usual form it is applicable only to events for which the rainfall intensity always exceeds the infiltration capacity, although the modified form used in SWMM is intended to overcome this deficiency.

On the other hand the Green-Ampt equation is a physically based model which can give a good description of the infiltration process. The Mein-Larson (1973) formulation of it is applicable also for the case of rainfall intensity being less than the infiltration capacity at the beginning of the storm. New data have been published to help users evaluate the parameter values (e.g., Carlisle et al., 1981). With results from these studies now being published, use of the Green-Ampt model for estimating infiltration should increase.

Integrated Horton's Equation

Cumulative Infiltration --

SWMM and many other hydrologic analysis techniques have used Horton's equation (Horton, 1940) for prediction of infiltration capacity into the

soil as a function of time,

$$f_p = f_\infty + (f_o - f_\infty)\, e^{-\alpha t} \qquad \text{(V-1)}$$

where f_p = infiltration capacity into soil, ft/sec,

f_∞ = minimum or ultimate value of f_p (at $t = \infty$), ft/sec,

f_o = maximum or initial value of f_p (at $t = 0$), ft/sec,

t = time from beginning of storm, sec, and

α = decay coefficient, sec^{-1}.

See Figure V-1 for a sketch of equation V-1. Actual infiltration is

$$f(t) = \min\,[f_p(t),\ i(t)] \qquad \text{(V-2)}$$

where f = actual infiltration into the soil, ft/sec, and

i = rainfall intensity, ft/sec.

Equation V-2 simply states that actual infiltration will be the lesser of actual rainfall and infiltration capacity.

Typical values for parameters f_o and f_∞ are often greater than typical rainfall intensities. Thus, when equation V-1 is used such that f_p is a function of time only, f_p will decrease even if rainfall intensities are very light, as sketched in Figure V-1. This results in a reduction in infiltration capacity regardless of the actual amount of entry of water into the soil.

To correct this problem, the integrated form of Horton's equation V-1 may be used,

$$F(t_p) = \int_0^{t_p} f_p\, dt = f_\infty\, t_p + \frac{(f_o - f_\infty)}{\alpha}\,(1 - e^{-\alpha t_p}) \qquad \text{(V-3)}$$

where F = cumulative infiltration at time t_p, ft.

This is shown schematically in Figure V-2 and assumes that actual infiltration has been equal to f_p. In fact, this is seldom the case, as sketched in Figure V-1. Thus, the true cumulative infiltration will be

$$F(t) = \int_0^t f(\tau)\, d\tau \qquad \text{(V-4)}$$

where f is given by equation V-2.

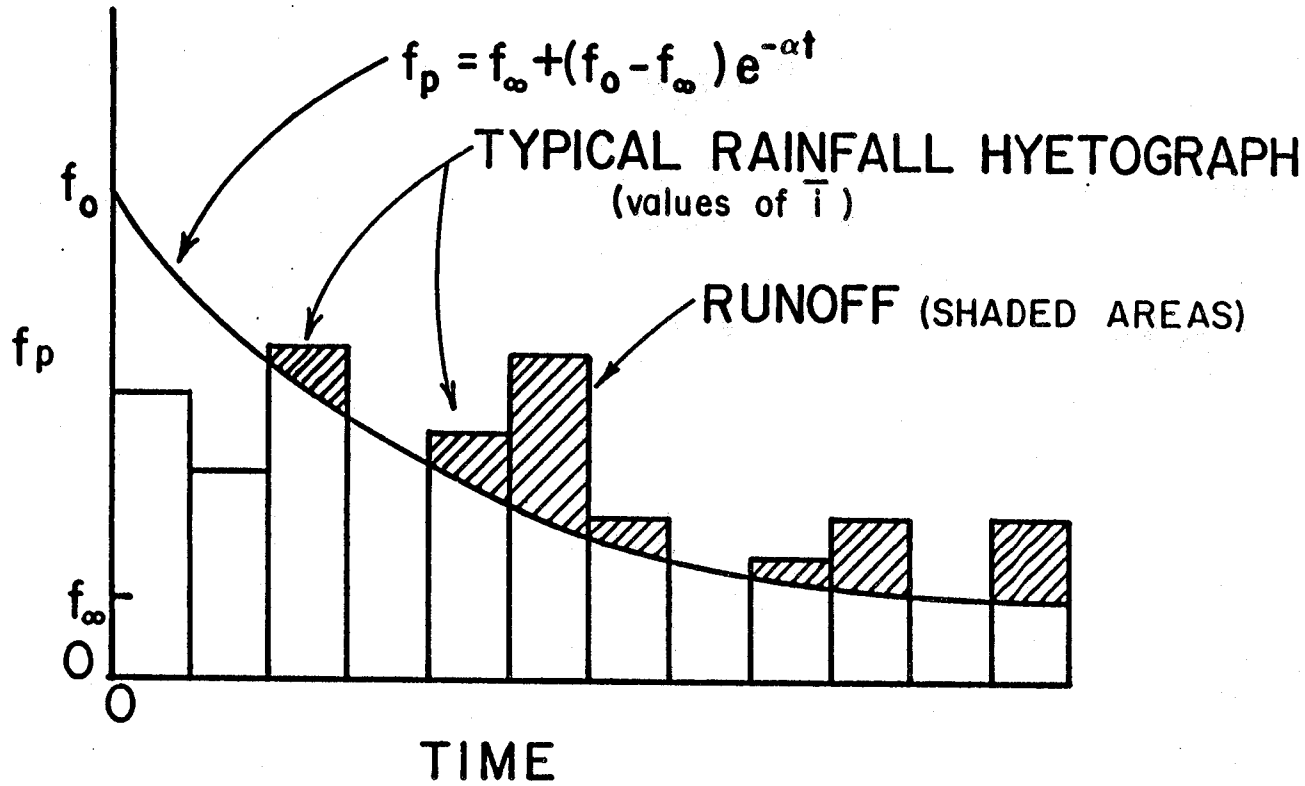


Figure V-1. Horton Infiltration Curve and Typical Hyetograph. For the case illustrated, runoff would be intermittent.

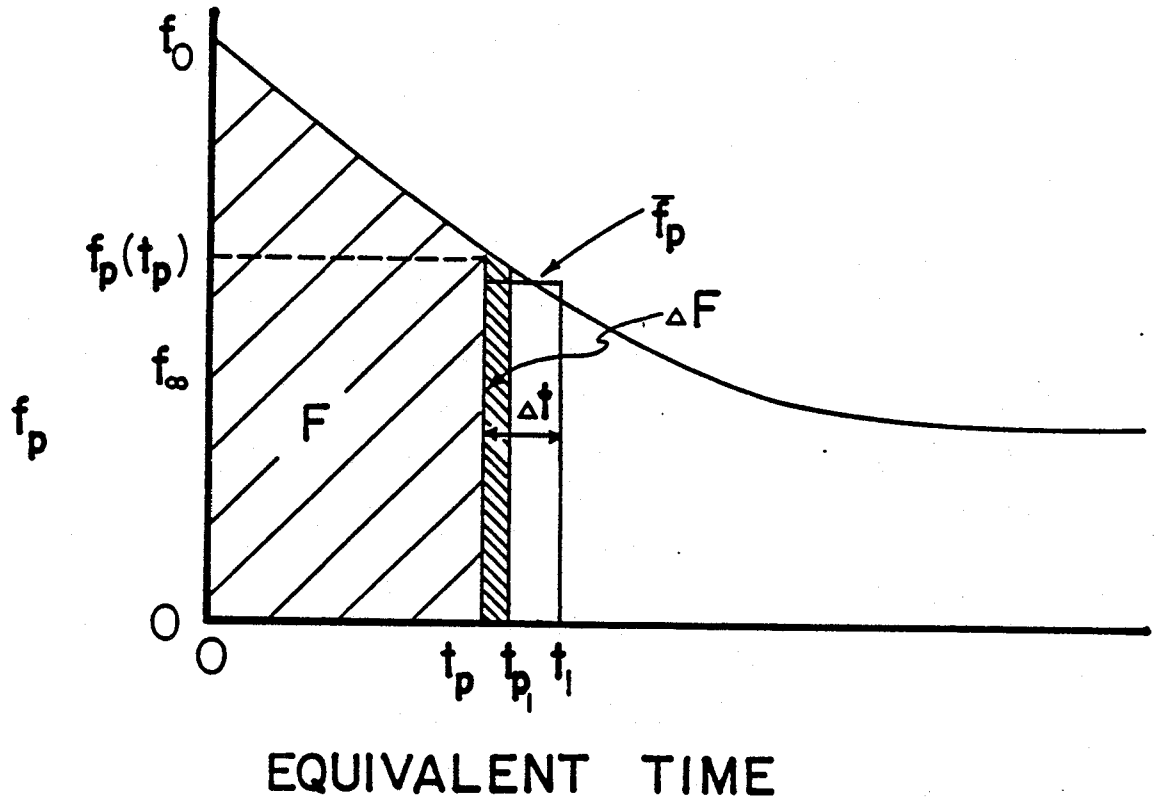


Figure V-2. Cumulative Infiltration, F, is the Integral of f, i.e., the Area Under the Curve.

Equations V-3 and V-4 may be used to define the time t_p. That is, actual cumulative infiltration given by equation V-4 is equated to the area under the Horton curve, given by equation V-3, and the resulting equation is solved for t_p and serves as its definition. Unfortunately, the equation

$$F = f_\infty t_p + \frac{(f_o - f_\infty)}{\alpha} (1 - e^{-\alpha t_p}) \qquad \text{(V-5)}$$

cannot be solved explicity for t_p, and it must be done iteratively. Note that

$$t_p \leq t \qquad \text{(V-6)}$$

which states that the time t_p on the cumulative Horton curve will be less than or equal to actual elapsed time. This also implies that available infiltration capacity, $f_p(t_p)$ in Figure V-2, will be greater than or equal to that given by equation V-1. Thus, f_p will be a function of actual water infiltrated and not just a function of time that ignores other effects.

Summary of Procedure --

Use of the cumulative Horton function in SWMM may be summarized as follows. Note that average values over time intervals are used.

1. At each time step, the value of f_p depends upon F, the actual infiltration up to that time. This is known by maintaining the value of t_p. Then the average infiltration capacity, $\bar{f}_p$, available over the next time step is

$$\bar{f}_p = \frac{1}{\Delta t} \int_{t_p}^{t_1 = t_p + \Delta t} f_p \, dt = \frac{F(t_1) - F(t_p)}{\Delta t} \qquad \text{(V-7)}$$

2. Equation V-2 is then used.

$$\bar{f} = \begin{cases} \bar{f}_p & \text{if } \bar{i} \geq \bar{f}_p \\ \bar{i} & \text{if } \bar{i} < \bar{f}_p \end{cases} \qquad \text{(V-8)}$$

where $\bar{f}$ = average actual infiltration over the time step, ft/sec, and

$\bar{i}$ = average rainfall intensity over the time step, ft/sec.

3. Cumulative infiltration is then incremented.

$$F(t + \Delta t) = F(t) + \Delta F = F(t) + \bar{f}\,\Delta t \qquad \text{(V-9)}$$

where $\Delta F = \bar{f}\,\Delta t$ = additional cumulative infiltration, ft, (see Figure V-2).

4. A new value of t_p is then found, t_{p_1}, from equation V-5. If $\Delta F = \bar{f}_p \Delta t$, t_{p_1} is found simply by $t_{p_1} = t_p + \Delta t$. However, it is necessary to solve equation V-5 iteratively when the new t_{p_1} will be less than $t_p + \Delta t$, as sketched in Figure V-2. This is done using the Newton-Raphson procedure:

$$FF = 0 = f_\infty t_p + \frac{(f_o - f_\infty)}{\alpha} (1 - e^{-\alpha t_p}) - F \qquad \text{(V-10)}$$

$$FF' = f_p(t_p) = f_\infty + (f_o - f_\infty)\, e^{-\alpha t_p} \qquad \text{(V-11)}$$

An initial guess is made for t_{p_1}, say $t_{p_1}(n) = t_p + \Delta t/2$ (V-12)

where n refers to the number of the iteration. Then a correction is made to $t_{p_1}(n)$ using FF and FF',

$$t_{p_1}(n+1) = t_{p_1}(n) - FF/FF' \qquad \text{(V-13)}$$

The convergence criterion is

$$FF/FF' < 0.001\ \Delta t \qquad \text{(V-14)}$$

and is achieved quite rapidly.

5. If $t_p \geq 16/\alpha$, the Horton curve is essentially flat and $f_p = f_\infty$. Beyond this point there is no need to iterate since f_p will be constant at f_∞ and independent of F.

Regeneration of Infiltration Capacity --

For continuous simulation, infiltration capacity will be regenerated (recovered) during dry weather. SWMM performs this function whenever there are dry time steps - no precipitation or surface water - according to the hypothetical drying curve sketched in Figure V-3.

$$f_p = f_o - (f_o - f_\infty)\, e^{-\alpha_d (t - t_w)} \qquad \text{(V-15)}$$

where α_d = decay coefficient for the recovery curve, sec^{-1}, and

t_w = hypothetical projected time at which $f_p = f_\infty$ on the recovery curve, sec.

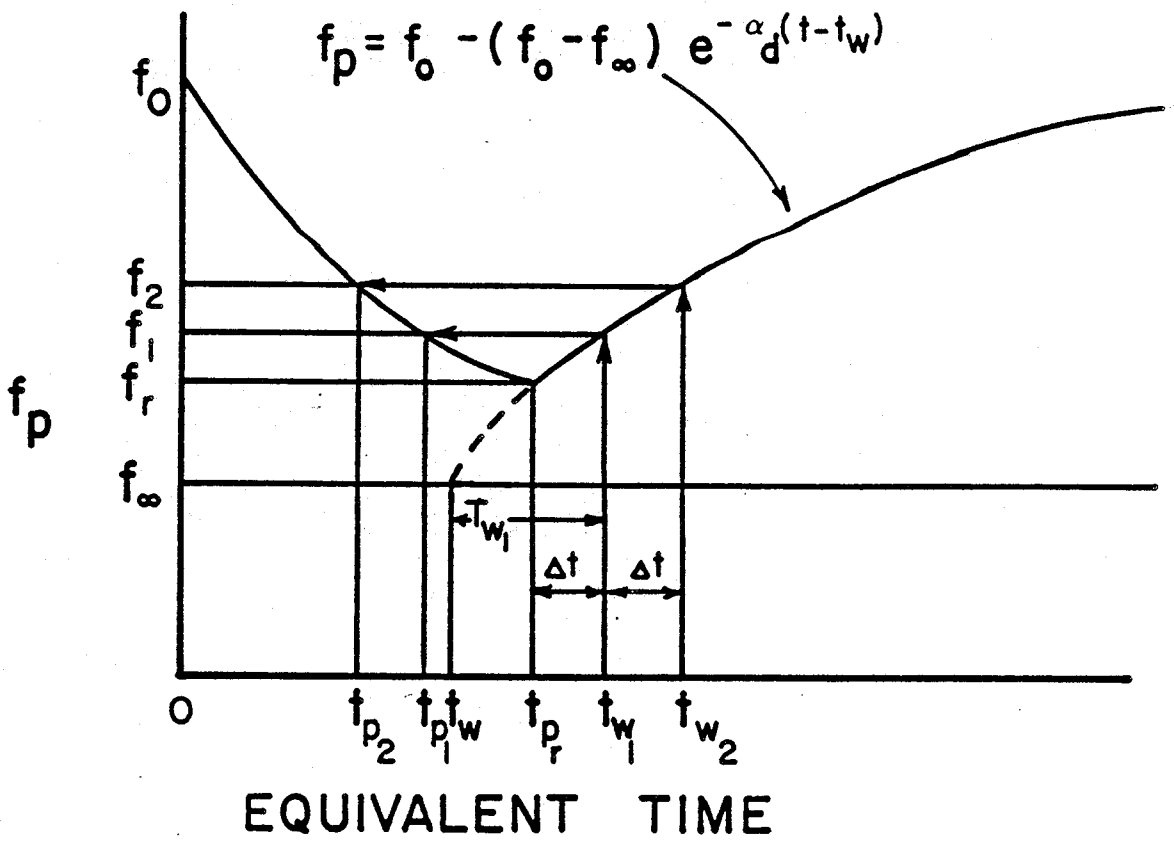


Figure V-3. Regeneration (Recovery) of Infiltration Capacity During Dry Time Steps.

In the absence of better knowledge of α_d, it is taken to be a constant fraction or multiple of α,

$$\alpha_d = R\,\alpha \tag{V-16}$$

where R = constant ratio, probably << 1.0, (implying a "longer" drying curve than wetting curve).

New values of t_p are then generated as indicated in Figure V-3. Let

t_{p_r} = value of t_p at beginning of recovery, sec,

f_r = corresponding value of f_p, ft/sec, and

$T_{w_1} = t_{w_1} - t_w$, $T_{w_2} = t_{w_2} - t_w$, etc.

Thus, along the recovery curve, for example,

$$f_1 = f_p(t_{w_1}) = f_o - (f_o - f_\infty)\, e^{-\alpha_d T_{w_1}} \tag{V-17}$$

Solving equation V-17 for the initial time difference, T_{w_r},

$$T_{w_r} = t_{p_r} - t_w = \frac{1}{\alpha_d} \ln \frac{f_o - f_\infty}{f_o - f_r} \tag{V-18}$$

Then

$$T_{w_1} = T_{w_r} + \Delta t \tag{V-19}$$

and f_1 in Figure V-3 is found from equation V-17. Finally t_{p_1} is found from equation V-1,

$$t_{p_1} = \frac{1}{\alpha} \ln \frac{f_o - f_\infty}{f_1 - f_\infty} \tag{V-20}$$

The procedure may be summarized as follows:

1. Knowing t_{p_r}, find f_r from equation V-1.
2. Solve for T_{w_r} from equation V-18.
3. Increment T_{w_r} according to equation V-19.
4. Solve for f_1 from equation V-17.
5. Solve for t_{p_1} from equation V-20.

All steps are combined in

$$t_{p_1} = -\frac{1}{\alpha} \ln \left[1 - e^{-\alpha_d \Delta t} (1 - e^{-\alpha t_{p_r}}) \right] \qquad \text{(V-21)}$$

On succeeding time steps, t_{p_1} may be substituted for t_{p_r} and t_{p_2} may be substituted for t_{p_1}, etc. Note that f_p has reached it maximum value of f_o when $t_p = 0$.

Program Variables --

The infiltration computations are performed in subroutine WSHED in the Runoff Block of SWMM. Correspondence of program variables to those of this subsection is as follows:

Δt = DELT	t_{p_1} = TP1
f_o = WLMAX	FF = FF
f_∞ = WLMIN	FF' = DFF
α = DECAY	$\bar{f}$ = RLOSS (RLOSS is also the sum of infiltration plus evaporation)
R = REGEN	$\bar{i}$ = RI
t_p = TP	$\bar{f}_p$ = RLOSS1
F = CUMINF = CUMI	

Green-Ampt Equation

Infiltration During Rainfall Events --

The Green-Ampt equation (Green and Ampt, 1911) has received considerable attention in recent years. The original equation, was for infiltration with excess water at the surface at all times. Mein and Larson (1973) showed how it could be adapted to a steady rainfall input and proposed a way in which the capillary suction parameter could be determined. More recently Chu (1978) has shown the applicability of the equation to the unsteady rainfall situation, using data for a field catchment.

The Mein-Larson formulation is a two-stage model. The first step predicts the volume of water which will infiltrate before the surface becomes saturated. From this point onward, infiltration capacity is predicted by the Green-Ampt equation. Thus,

For $F < F_s$:

$$F_s = \frac{S \cdot IMD}{i/K_s - 1} \quad \text{for } i > K_s$$

$$f = i \qquad \text{and} \qquad \text{No calculation of } F_s \quad \text{for } i \leq K_s \tag{V-22}$$

For $F \geq F_s$:

$$f = f_p \qquad \text{and} \qquad f_p = K_s\left(1 + \frac{S \cdot IMD}{F}\right) \tag{V-23}$$

where f = infiltration rate, ft/sec,

f_p = infiltration capacity, ft/sec,

i = rainfall intensity, ft/sec,

F = cumulative infiltration volume, this event, ft,

F_s = cumulative infiltration volume required to cause surface saturation, ft,

S = average capillary suction at the wetting front, ft. water,

IMD = initial moisture deficit for this event, ft/ft, and

K_s = saturated hydraulic conductivity of soil, ft/sec.

Equation V-22 shows that the volume of rainfall required to saturate the surface depends on the current value of the rainfall intensity. Hence, at each time step for which $i > K_s$, the value of F_s is calculated and compared with the volume of rainfall already infiltrated for this event. Only if $F \geq F_s$ does the surface saturate, and further calculations for this condition use equation V-23.

When rainfall occurs at an intensity less than or equal to K_s, all rainfall infiltrates and is used only to update the initial moisture deficit, IMD. (The mechanism for this is discussed in the next subsection with reference to equation V-31.) The cumulative infiltration is not altered for this case of low rainfall intensity (relative to the saturated hydraulic conductivity, K_s).

Equation V-23 shows that the infiltration capacity after surface saturation depends on the infiltrated volume, which in turn depends on the infiltration rates in previous time steps. To avoid numerical errors over long time steps, the integrated form of the Green-Ampt equation is more suitable. That is, f_p is replaced by dF/dt and integrated to obtain

$$K_s(t_2 - t_1) = F_2 - C \cdot \ln(F_2 + C) - F_1 + C \cdot \ln(F_1 + C) \tag{V-24}$$

where $C = IMD \cdot S$, ft of water,

t = time, sec, and

1,2 = subscripts for start and end of time interval respectively.

Equation V-24 must be solved iteratively for F_2, the cumulative infiltration at the end of the time step. A Newton-Raphson routine is used.

The infiltration volume during time step $(t_2 - t_1)$ is thus $(t_2 - t_1) \cdot i$ if the surface does not saturate, and $(F_2 - F_1)$ if saturation has previously occurred and a sufficient water supply is at the surface. If saturation occurs during the time interval, the infiltration volumes over each stage of the process within the time steps are calculated and summed. When rainfall ends (or falls below infiltration capacity) any water ponded on the surface is allowed to infiltrate and added to the cumulative infiltration volume.

Recovery of Infiltration Capacity (Redistribution) --

Evaporation, subsurface drainage, and moisture redistribution between rainfall events decrease the soil moisture content in the upper soil zone and increase the infiltration capacity of the soil. The processes involved are complex and depend on many factors. In SWMM a simple empirical routine is used as outline below; commonly used units are given in the equations to make the description easier to understand.

Infiltration is usually dominated by conditions in the uppermost layer of the soil. The thickness of this layer depends on the soil type; for a sandy soil it could be several inches, for a heavy clay it would be less. The equation used to determine the thickness of the layer is

$$L = 4 \cdot \sqrt{K_s} \qquad \text{(V-25)}$$

where L = thickness of layer, in, and

K_s = saturated hydraulic conductivity, in/hr.

Thus for a high K_s of 0.5 in/hr (12.7 mm/hr) the thickness computed by equation V-25 is 2.83 inches (71.8 mm). For a soil with a low hydraulic conductivity, say K_s = 0.1 in/hr (2.5 mm), the computed thickness is 1.26 inches (32.1 mm).

A depletion factor is applied to the soil moisture during all time steps for which there is no infiltration from rainfall or depression storage. This factor is indirectly related again to the saturated hydraulic conductivity of the soil and is calculated by

$$DF = L/300 \qquad \text{(V-26)}$$

where DF = depletion factor, hr^{-1}, and

L = depth of upper zone, in.

Hence, for K_s = 0.5 in/hr (12.7 mm/hr), DF = 0.9 percent per hour; for K_s = 0.1 in/hr (2.5 mm/hr), DF = 0.4 percent per hour. The depletion volume (DV) per time step is then

$$DV = DF \cdot FU_{max} \cdot \Delta t \qquad \text{(V-27)}$$

where $FU_{max} = L \cdot IMD_{max}$ = saturated moisture content of the upper zone, in,

IMD_{max} = maximum initial moisture deficit, in/in, and

Δt = time step, hr.

The computations used are

$$FU = FU - DV \quad \text{for} \quad FU \geq 0 \qquad \text{(V-28)}$$

$$F = F - DV \quad \text{for} \quad F \geq 0 \qquad \text{(V-29)}$$

where FU = current moisture content of upper zone, in, and

F = cumulative infiltration volume for this event, in.

To use the Green-Ampt infiltration model in continuous SWMM, it is necessary to choose a time interval after which further rainfall will be considered as an independent event. This time is computed as

$$T = 6/(100 \cdot DF) \qquad \text{(V-30)}$$

where T = time interval for independent event, hr.

For example, when K_s = 0.5 in/hr (12.7 mm/hr) the time between independent events as given by equation V-30 is 6.4 hr; when K_s = 0.1 in/hr (2.5 mm/hr) the time is 14.3 hr. After time T has elapsed the variable F is set to zero, ready for the next event. The moisture remaining in the upper zone of the soil is then redistributed (diminished) at each time step by equation V-28 in order to update the current moisture deficit (IMD). The deficit is allowed to increase up to its maximum value (IMD_{max}, an input parameter) over prolonged dry periods. The equation used is

$$IMD = \frac{FU_{max} - FU}{L} \quad \text{for } IMD \leq IMD_{max} \qquad \text{(V-31)}$$

When light rainfall ($i \leq K_s$) occurs during the redistribution period, the upper zone moisture storage, FU, is increased by the infiltrated rainfall volume and IMD is again updated using equation V-31.

Guidelines for estimating parameter values for the Green-Ampt model are given in Section 4. As is also the case for the Horton equation, different soil types can be modeled for different subcatchments.

Program Variables --

The infiltration computations are performed in subroutines WSHED and GAMP in the Runoff Block. Correspondence of program variables to those of this subsection is as follows:

S = SUCT(J)	L = UL(J)
IMD_{max} = SMDMAX (J)	DF = DF(J)
K_s = HYDCON(J)	i = RI
FU_{max} = FUMAX(J)	t = TIME
FU = FU(J)	Δt = DELT
IMD = SMD(J)	DV = DEP
F = F(J)	F_s = FS

SUBCATCHMENT RUNOFF CALCULATIONS

Overland Flow

The Runoff Block forms the origin of flow generation within SWMM, and much of the emphasis in data preparation and user effort is aimed at successful execution of this block. In order to understand better the conversion of rainfall excess (rainfall and/or snowmelt less infiltration and/or evaporation) into runoff (overland flow), this subsection briefly describes the equations used for this purpose. It is intended to supplement the material presented in the original SWMM documentation (Metcalf and Eddy et al., 1971a).

As discussed in Section 4, subcatchments are subdivided into three subareas that simulate impervious area, with and without depression (detention) storage, and pervious area (with depression storage). These are areas A1, A3 and A2 respectively on Figure V-4 and are denoted in subroutine WSHED by the subscript J, (J = 1, 2, 3, 4). When snowmelt is included, a fourth subarea is added to account for the presence or absence of snow cover, (see Figure II-5 in Appendix II) but that case will not be considered further here. The depth of depression storage is an input parameter (WSTORE) for the impervious and pervious areas of each catchment. The impervious area without depression storage is specified for all subcatchments by parameter PCTZER (as a percent),

$$A3 = \frac{PCTZER}{100} \cdot (A1 + A3) \qquad \text{(V-32)}$$

Of course, any subcatchment may be assigned zero depression storage over its entirety through the use of parameter WSTORE.

Overland flow is generated from each of the three subareas by approximating them as non-linear reservoirs, as sketched in Figure V-5. This is a

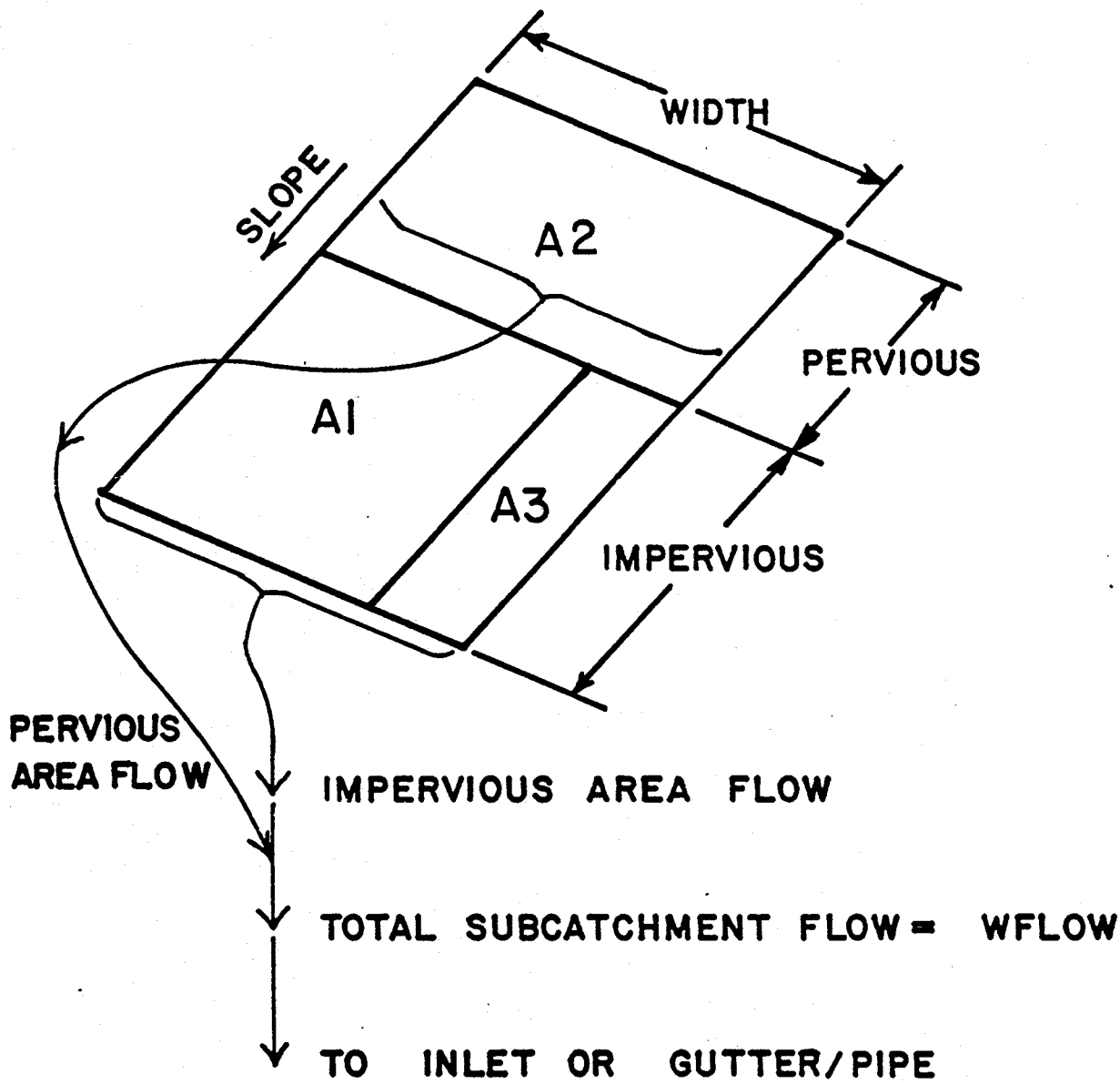


Figure V-4. Subcatchment Schematization for Overland Flow Calculations. Flow from each subarea is directly to an inlet or gutter/pipe. Flow from one subarea is not routed over another subarea.

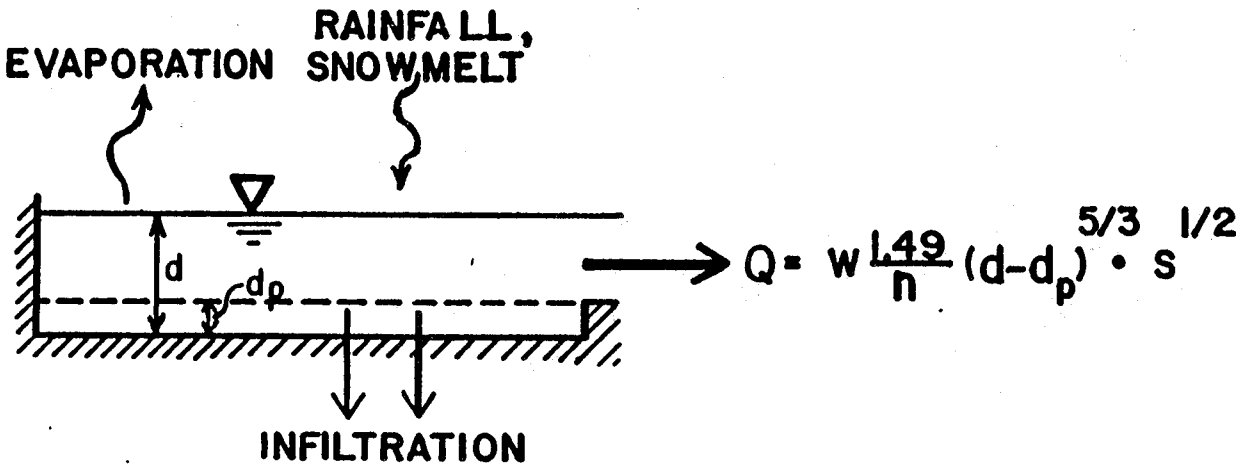


Figure V-5. Non-linear Reservoir Model of Subcatchment.

spatially "lumped" configuration and really assumes no special shape. However, if the subcatchment width, W, is assumed to represent a true prototype width of overland flow, then the reservoir will behave as a rectangular catchment, as sketched in Figure V-4. Otherwise, the width (and the slope and roughness) may be considered calibration parameters and used to adjust predicted to measured hydrographs.

The non-linear reservoir is established by coupling the continuity equation with Manning's equation. Continuity may be written for a subarea as

$$\frac{dV}{dt} = A \frac{dd}{dt} = A \cdot i^* - Q \qquad \text{(V-33)}$$

where $V = A \cdot d$ = volume of water on the subarea, ft^3,

d = water depth, ft,

t = time, sec,

A = surface area of subarea, ft^2,

i^* = rainfall excess = rainfall/snowmelt intensity minus evaporation/infiltration rate, ft/sec, and

Q = outflow rate, cfs.

The outflow is generated using Manning's equation

$$Q = W \cdot \frac{1.49}{n} (d - d_p)^{5/3} \; S^{1/2} \qquad \text{(V-34)}$$

where W = subcatchment width, ft.

n = Manning's roughness coefficient,

d_p = depth of depression storage, ft, and

S = subcatchment slope, ft/ft.

Equations V-33 and V-34 may be combined into one non-linear differential equation that may be solved for one unknown, the depth, d. This produces the non-linear reservoir equation,

$$\frac{dd}{dt} = i^* - \frac{1.49 \cdot W}{A \cdot n} (d - d_p)^{5/3} \; S^{1/2} \qquad \text{(V-35)}$$

$$= i^* + WCON \cdot (d - d_p)^{5/3}$$

where $$WCON = - \frac{1.49 \cdot W \cdot S^{1/2}}{A \cdot n} \qquad \text{(V-36)}$$

Note the grouping of width, slope and roughness into only one parameter.

Equation V-35 is solved at each time step by means of a simple finite difference scheme. For this purpose, the net inflow and outflow on the right hand side (RHS) of the equation must be averages over the time step. The rainfall excess, i*, is given in the program as a time step average. The average outflow is approximated by computing it using the average between the old and new depths. That is, letting subscripts 1 and 2 denote the beginning and the end of a time step, respectively, equation V-35 is approximated by

$$\frac{d_2 - d_1}{\Delta t} = i^* + WCON \cdot [d_1 + \frac{1}{2}(d_2 - d_1) - d_p]^{5/3} \qquad \text{(V-37)}$$

where Δt = time step, sec.

Equation V-37 is then solved for d_2 using a Newton-Raphson iteration; the Fortran coding is located near the end of subroutine WSHED.

Given d_2, the instantaneous outflow at the end of a time step, WFLOW, is computed using equation V-34. Parameter WFLOW is used in runoff quality calculations and is the flow value that is input to inlets and gutter/pipes. The instantaneous outflow at a given time is also the flow value transfered to subsequent SWMM blocks.

Although the solution of equation V-37 is straightforward and simple (and in fact may be performed on programmable hand calculators), some peculiarities exist in the way the parameters for individual subareas (A1, A2, A3 in Figure V-4) are specified. In particular, only two values of WCON are computed (equation V-36), one for the pervious and one for the total impervious subareas. Thus, WCON is the same for calculating depths on subareas A1 and A3 and is computed from equation V-36 using the total impervious area, A1 plus A3, in the denominator. However, the instantaneous flow is computed using the individual area of each subarea (e.g., A1 or A3). The net effect for subareas A1 and A3 is approximately to reduce the subcatchment width by the ratio A1/(A1 + A3) or A3/(A1 + A3) as implied in Figure V-4. Numerical tests of this scheme versus one that uses the individual areas (and proportional widths) in parameter WCON indicate only about a half percent difference between the two methods. Hence, it should be satisfactory.

Prior to performing these calculations, a check is made to see if losses are greater than the rainfall depth plus ponded water. If so, the losses (evaporation plus infiltration) absorb all water and outflow is zero. Similarly, if losses alone would be sufficient to lower the depth below the depression storage, the new depth is computed on this basis only and the outflow is zero.

The computational scheme (equations V-37 and V-38) has proven quite stable. The only instance for which non-convergence problems arise (or an attempt to compute a negative depth) is when the subarea values are very small (e.g., a few square feet) coupled with a large time step (e.g., ten minutes). Should a non-convergence message be printed, the problem may usually be cured by increasing the appropriate area or decreasing the time step.

Channels and Pipes

Flow routing in channel/pipes is also performed by coupling the continuity equation with Manning's equation to produce a non-linear reservoir. The solution technique is performed in subroutine GUTNR and is entirely analogous to that just described for overland flow; no details will be given here. However, a few comments are in order. Three cross sectional shapes are available for channel/pipes: circular, trapezoidal, and parabolic. Trapezoidal channels and circular pipes are shown in Figure V-6 (parabolic channels are shown in Figure 4-9). Parameters representing depth (e.g., GDEPTH, D1, DO) are actual depths, in feet, for trapezoidal channels but not for circular pipes. Rather, for pipes the "depth" parameters are half of the angle subtended by the wetted perimeter, in radians, as shown in Figure V-6. Knowledge of this fact aids in understanding the Fortran coding in subroutine GUTTER.

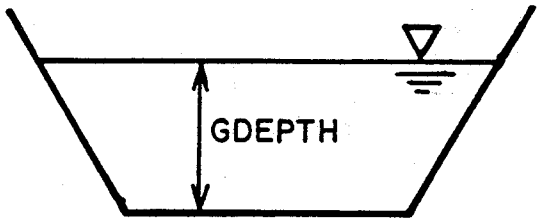
Since a channel/pipe acts as a reservoir with a water surface parallel to the invert, inflows are automatically "distributed" along its length. Hence, concentration of subcatchment inflows only at the upstream end of a channel/pipe may be reasonable. On the other hand, this leads to considerable dispersion or flattening of a hydrograph peak when it is routed through a cascade of channel/pipes. Of course, for this flow routing scheme, downstream changes are not "felt" upstream, and no backwater effects can be simulated.

Non-convergence messages may be encountered during channel/pipe routing if short channel/pipes of small dimensions are included in the simulation. Again, this can usually be cured by increasing the dimensions (e.g., length and width/diameter) or decreasing the time step. The iterative equation for the Newton-Raphson technique used to solve for the new depth in the channel/pipe has been adjusted to eliminate most convergence problems. This new iterative equation plus the method used for variable time steps in Runoff will let the user have reasonably sized pipes in his/her simulation even for long time steps.

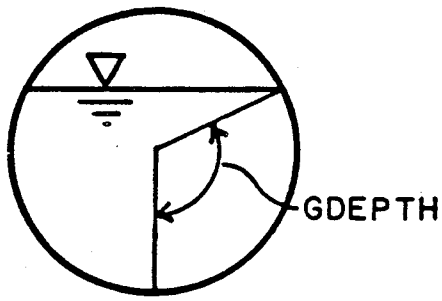
Variable Time Step

Runoff has three time steps: (1) a wet time step (WET), (2) the transitional time step(s) between wet and dry (WETDRY), and (3) the dry (DRY) time step. WET will normally be less than or equal to the rainfall interval entered on data group D1. It can be longer, but information is lost by averaging the rainfall over a longer time period. A wet time step is a time step with precipitation occurring on <u>any</u> subcatchment. A transitional time step has no precipitation input on any subcatchment, but the subcatchment(s) still have water remaining in surface storage. A dry time step has no precipitation input or surface storage. However, it can have groundwater flow. The model is considered either globally wet, globally transitional, or globally dry.

The time step should be smaller for periods of rapid change, i.e., during rainfall, and longer during periods of slower change, i.e., during transitional and dry time steps. Runoff by using the concept of extrapolation to the limit can use any time step from 1 second to 1 year. The solution technique is stable and convergent for any length time step.



TRAPEZOIDAL
GUTTER



CIRCULAR
PIPE

Figure V-6. Depth Parameters for Trapezoidal Channel and Circular Pipe

Typically the WET time step should be a fraction of the rainfall interval. Five minute rainfall should have wet time steps of 1, 2.5 or 5.0 minutes for example. The rainfall intensity is constant over the wet time step when WET is a fraction of the rainfall interval. A smaller wet time step would be desirable when the subcatchment is small and the time of concentration is a fraction of the rainfall interval. When using one-hour rainfall from the NWS, wet time steps of 10 minutes, 15 minutes etc. can be used by the model.

The Runoff overland flow routing technique loses water through infiltration, evaporation, and surface water outflow during the transition periods. A subcatchment's surface storage and surface flow always decrease during the transition from a wet condition to a dry condition. A smooth curve or straight line is a good model for the shape of the hydrograph. Transport and Extran usually have small time steps and use linear or parabolic interpolation for input hydrographs with longer time steps. The transition time step, WETDRY, can be substantially longer than WET and generate a good overland flow hydrograph. For example, a WET of 5 minutes can be coupled with a WETDRY of 15 minutes or 30 minutes. When using hourly rainfall input, a WET of 15 minutes can be coupled to a WETDRY of 2 hours or 3 hours.

The dry time step should be one day to a week. The dry time step is used to update the infiltration parameters, generate groundwater flow, and produce a time step value for the interface file. The dry time step should be day(s) in wet climates and days or week(s) in very dry climates. The synoptic analysis performed by the Rain Block will be of use in selecting the appropriate dry time step. Examine the average storm interevent duration in the storm summary table. The average storm interevent duration ranges from half a week to months depending on station location.

The model can achieve substantial time savings with judicious usage of WET, DRY, and WETDRY for both short and long simulations. As an example consider the time step saving using a WET of 15 minutes, a WETDRY of 2 hours, and a DRY of 1 day versus using a single time step of 1 hour for a year. Using Florida rainfall as input (average annual rainfall between 50 and 60 inches) gives 300 wet hours per year, flow for approximately 60 days per year, and 205 dry days per year. This translates to 1975 time steps. A constant hourly time step for one year requires 8760 time steps. This is greater than a 400 percent savings in time with a better representation of the flow hydrograph due to the 15 minute wet time step.

Extrapolation Technique

The accuracy of the solution technique using variable time steps is enhanced (aided) by a numerical technique called Richardson extrapolation (Press et al., 1986). Richardson extrapolation is also called Richardson's deferred approach to the limit. The extrapolated value is the solution that would be obtained if an infinitely small time step was used in watershed, channel/pipe or infiltration routing.

The concept of extrapolation to the limit may be more familiar to the reader in connection with Romberg integration. Romberg integration repeatedly calls a trapezoidal rule integration subroutine in the sequence 1, 2, 4, 8, 16

panels etc. to extrapolate a more accurate solution than that obtained by the trapezoidal rule alone.

The Runoff Block uses the same concept to extrapolate the watershed depth at the end of a time step. The subroutine WSHED uses the iterative techniques described earlier in this appendix to solve for the infiltration volume and watershed depth at the end of a time step. The WET, DRY, and WETDRY time steps are broken up into smaller and smaller steps using the relationships: WET/n, DRY/n, and WETDRY/n where n is the number of subintervals used by WSHED. The sequence of subintervals n used by WSHED is

n = 1,2,4,6,8,12,24,32,48,64

Experience has shown that time steps smaller than 5 minutes do not have to be broken into subintervals. The integrated depth or infiltration volume for one subinterval is almost equal to the extrapolated depth or infiltration volume obtained from using more subintervals. For time steps longer than 5 minutes the extrapolated answer obtained from using one and two subintervals usually has a small estimated error. The exceptions are due to large rainfall intensities over long time periods (i.e., 15 minute to 1 hour rainfall). It may be necessary for the time step to be broken up into more than 32 subintervals during these conditions.

The extrapolation to an infinitely small time step is illustrated in Figure V-7. A rational function, which is a analytical function dependent on the step size h, is fit to the various estimates of the integrated watershed depth or infiltration volume. The rational function (a function with polynomial numerator and denominator) is then evaluated at h = Ø. The evaluated depth or volume is the extrapolated value.

The Runoff Block treats overland flow, infiltration, and groundwater flow as coupled processes. The extrapolated value is actually a vector of estimates. This is in contrast to SWMM 3 where the infiltration and overland flow were not coupled.

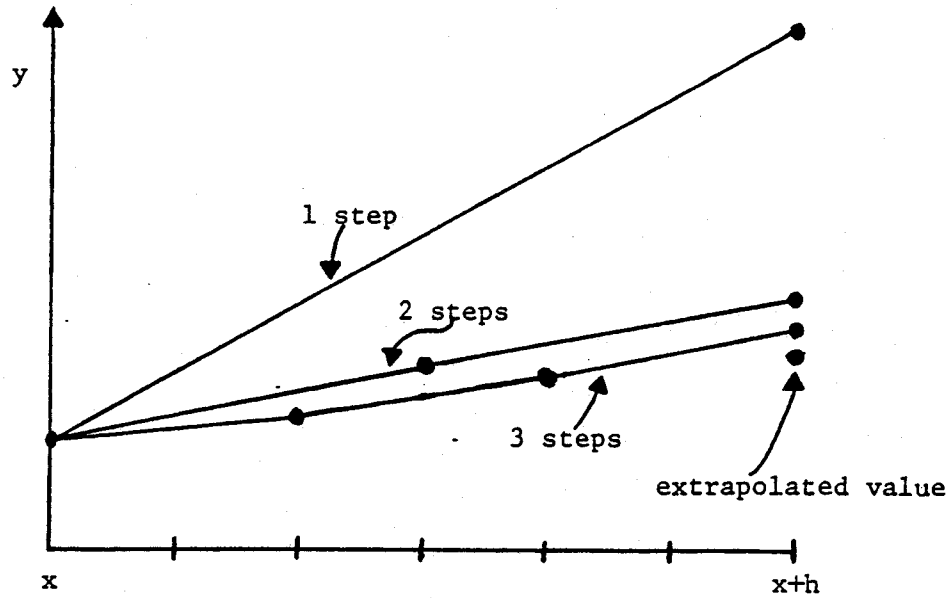


Figure V-7. Richardson Extrapolation as used in the Runoff Block. A large interval is spanned by different sequences of finer and finer substeps. Their results are extrapolated to an answer that corresponds to an infinitely small time step. Runoff uses a Newton-Raphson iteration solution for the y values at each time step, and a rational function extrapolation to calculate the extrapolated y value. (This graph is adapted from Press et al., 1986).

APPENDIX VI

TRANSPORT BLOCK SCOUR AND DEPOSITION

INTRODUCTION

Deposition of solid material during dry-weather flow (DWF) in combined sewers and subsequent scour during wet-weather flow has long been assumed to form a significant contribution of solids to combined sewer overflows. The deposition-scour phenomenon is also evident in the "first flush" — high solids concentrations at the beginning of a storm event -- found in many sewer systems. Even storm sewer systems may show a first flush if there is a base flow due to infiltration or illegal connections.

Deposition and scour processes were included in the original SWMM Transport Block as described in the documentation (Metcalf and Eddy et al., 1971a). It simulated solids buildup during DWDAYS dry days prior to the storm and scour during the storm, as velocities increased. A constant horizontal approximation to the dimensionless shear stress on Shields' curve (described subsequently) was used to determine incipient motion, and one fixed particle size distribution (for suspended solids only) and specific gravity of 2.7 were used to characterize the solids.

Several problems existed in the routine, perhaps unknown to most SWMM users. The deposition-scour was dependent on the time step. Buildup of solids would occur using a 1-hr time step for the dry days prior to simulation, but scour would occur using, say, a 10-min simulation time step with the same flow conditions. The particle size distribution was unaffected by the amount scoured from the bottom or deposited from the flow. Thus, there was no simulation of large particles being deposited in upstream conduits (and thereby unavailable for deposition further downstream). It was not possible to calibrate the routine or even "turn it off" since all constants were incorporated into the program and were not input parameters. Finally, there were situations in which conservation of solids mass was violated. Although the revised routine still represents a gross approximation to the real sediment transport processes at work in sewer systems, it is at least consistent within itself, it conserves mass, and is both calibratable and avoidable.

There have been other recent investigations of solids deposition in sewers, most notably the work of Sonnen (1977) and Pisano et al. (1979). Sonnen's work is highly relevant to the modeling aspect since he developed

a deposition-scour routine to accompany the Extran Block of SWMM. This model simulated both bed load and suspended load sediment transport and characterized the sediment by up to ten particle size-specific gravity ranges. Although his routines worked satisfactorily, they are not compatible with the "old" Transport Block, and the "new" Extran Block no longer routes quality parameters. In addition, they are perhaps overly sophisticated for the present needs. Thus, the current programming utilizes an approximate method that is not as sound as Sonnen's but does have the attributes described earlier.

The best characterization of solids in real sewer systems is given by Pisano et al. (1979) in their description of extensive field and analytical work done in the Boston area. The many problems inherent in dealing with real systems are amply demonstrated.

METHODOLOGY AND ASSUMPTIONS

Overview

Since the criterion for deposition and scour depends upon the sediment characteristics (notably size and specific gravity), one option for simulation of the range of characteristics found in real sewer sediment is to carry along a group of different sizes and specific gravities and route each range individually. This is done in the Storage/Treatment Block of SWMM and was done by Sonnen (1977). This has the disadvantage of requiring large array sizes since each range must be simulated for each conduit and preferably for each pollutant.

As an alternative, the present methodology utilizes a fixed particle size distribution and specific gravity (input by the user) for each desired pollutant and maintains a time history for each conduit of the maximum particle diameter (DS) in suspension (really, in motion — via bed or suspended load) and the minimum particle diameter (DB) in the bed. Thus, the particle size distribution of particles in motion is the input distribution truncated on the right at DS, and the particle size distribution of deposited solids is the input distribution truncated on the left at DB. Mass-weighted values of DS are routed downstream for entry to subsequent conduits.

Assumptions

Several assumptions are inherent in the following development, including the following:

1. Solids in sewer systems are assumed to behave like ideal non-cohesive sediment described in various texts (e.g., Graf, 1971, Vanoni, 1975). Unfortunately, the work of Pisano et al. (1979) shows little evidence of this, and in fact, it may be an impossible task to provide an accurate theoretical description of transport of the highly heterogeneous material constituting "solids" in real sewer systems. The only hope is that the theory will appear to behave in a "reasonable" manner.

2. No distinction is made between particle size distributions resulting from different pollutant sources, e.g., dry-weather flow and storms water. Only one distribution (and one average specific gravity) is used for each pollutant.

3. Shields' criterion is used to determine the dividing particle size between motion and no motion.

4. Once in motion, no distinction is made between bed and suspended load. Particles in motion ("suspension") are routed downstream in each conduit by complete mixing, the same as other quality parameters.

5. When a critical diameter (CRITD) is determined for scour, all particles with diameter less than or equal to CRITD are eroded. There is no effect simulated of armoring or of erosion of layers of the bed.

6. Scour-deposition is considered only in conduits. It is not simulated in non-conduits, including storage elements.

7. The effect of deposited sediment on the bed geometry is not considered. When the hydraulic radius (an important parameter) is calculated to determine the critical diameter for motion, the bed is assumed to have the geometry of the conduit. This leads to some underestimation of deposited material, mainly at low flows.

SHIELDS' CRITERION

Shields' diagram for the definition of incipient motion is shown in Figure VI-1. It is widely accepted as a good definition of the beginning of particle motion and describes the balance between the hydrodynamic forces of drag and lift on a particle (tending to induce motion) and the submerged weight of a particle (tending to resist motion). When hydrodynamic forces acting on a sediment particle reach a value such that if increased even slightly will put the particle into motion, critical or threshold conditions are said to have been reached. Dimensional analysis of this condition leads to

$$\frac{\tau_c}{(\gamma_s-\gamma)d} = f\left(\frac{u_* d}{\nu}\right) \qquad \text{(VI-1)}$$

where τ_c = critical shear stress required to induce particle motion, lb/ft^2,

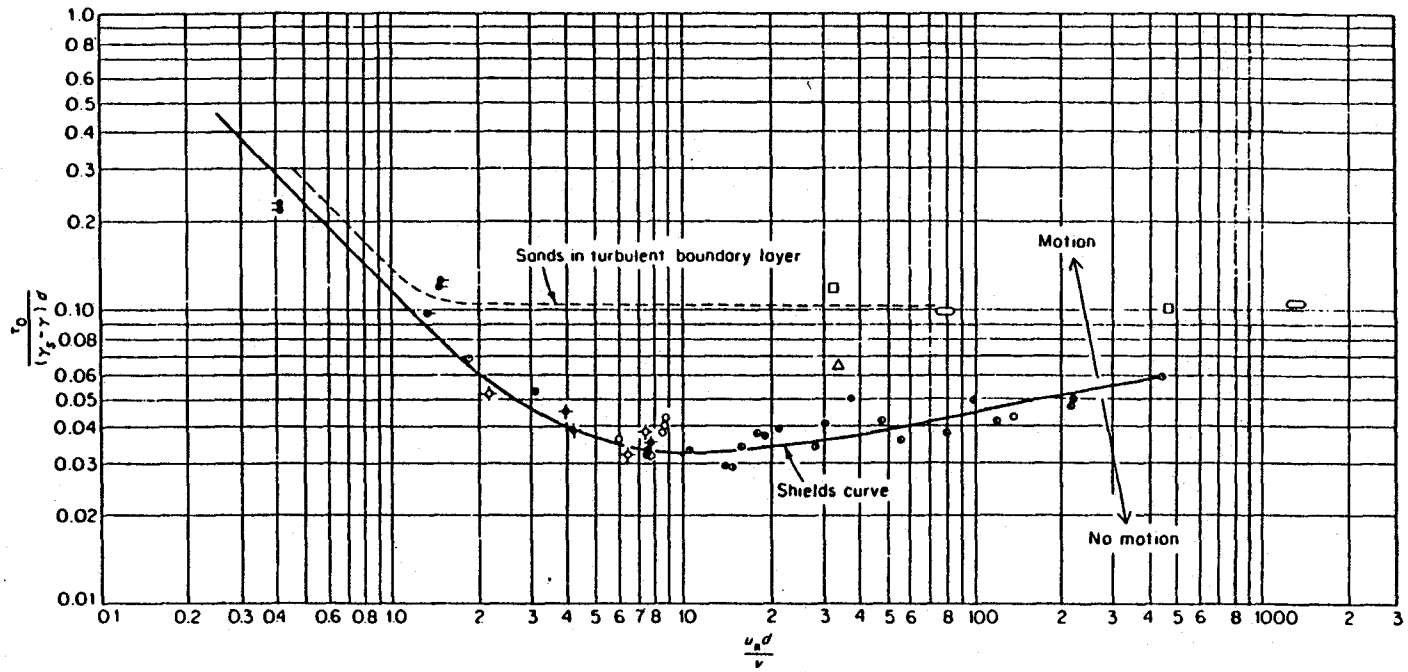
γ_s = specific weight of the sediment, lb/ft^3,

γ = specific weight of water = 62.4 lb/ft^3,

d = sediment diameter, ft (a conversion is made from mm),

u_* = shear or friction velocity, ft/sec, and

ν = kinematic viscosity of water, ft^2/sec.



Fully developed turbulent velocity profile	Sym	Description	γ_s, g/cm³
	○	Amber (Shields)	1.06
	●	Lignite (Shields)	1.27
	●	Granite (Shields)	2.7
	●	Barite (Shields)	4.25
	●	Sand (Casey)	2.65
	◇	Sand (Kramer)	2.65
	✦	Sand (U.S.W.E.S)	2.65
	●	Sand (Gilbert)	2.65

Turbulent boundary layer			
	●←	Sand (Vanoni)	2.65
	●→	Glass beads (Vanoni)	2.49
	□	Sand (White)	2.61
	⬭	Sand in air (White)	2.10
	△	Steel shot (White)	7.9

Figure VI-1. Shields' Diagram for Definition of Incipient Motion. (After Graf, 1971, p. 96)

The equation may be stated in words that the dimensionless critical shear stress is a function of the shear Reynolds number. The critical shear stress and shear velocity are related to each other and to flow properties by

$$u_* = \sqrt{\tau_c/\rho} = \sqrt{g\ R\ S} \qquad \text{(VI-2)}$$

where ρ = water density = 1.98 slug/ft^3,

g = gravity = 32.2 ft/sec^2,

R = hydraulic radius, ft, and

S = slope of energy grade line (assumed equal to invert slope).

In addition, the specific weight difference may be related to the specific gravity difference between sediment and water,

$$\gamma_s - \gamma = \gamma(SPG - 1) \qquad \text{(VI-3)}$$

where SPG = specific gravity of the sediment,

and the specific gravity of water is taken as 1.0.

Experiments on critical shear stress (e.g., see Graf, 1971 and Vanoni, 1975) reveal the motion of sediment grains to be highly unsteady and non-uniformly distributed. Near critical conditions, observations of a large area of the sediment bed will show that the incidence of sediment motion occurs as gusts and is random in both time and space. Shields and others observed the process of initiation of motion to be stochastic in nature, so that there is no true "critical condition" at which motion suddenly begins. In fact, data on critical shear stress are based upon arbitrary definitions of critical conditions by several investigators. Shields himself determined τ_c as the value for zero sediment discharge obtained by extrapolation on a graph of observed sediment discharge versus shear stress.

Although experiments have been performed incorporating various materials, (e.g., sand, glass beads, steel shot, minerals), size ranges and specific gravities, the Shields criterion is generally not used for cohesive sediment that may be more characteristic of sewer systems. Nonetheless, it appears to be the only well documented criterion for initiation of motion and is utilized in spite of its limitations.

In SWMM, the Shields diagram is used to determine the dividing sediment diameter between motion and no motion. Thus, it is necessary to solve the functional relationship for the critical diameter, d = CRITD. For programming purposes, the diagram is approximated as shown in Figure VI-2, where two straight line segments bound a central polynomial approximation, all on a log-log plot. Letting the dimensionless shear stress $\equiv$ Y, and the shear Reynolds number $\equiv R_*$, then the functional forms and their best-fit parameters are as follows:

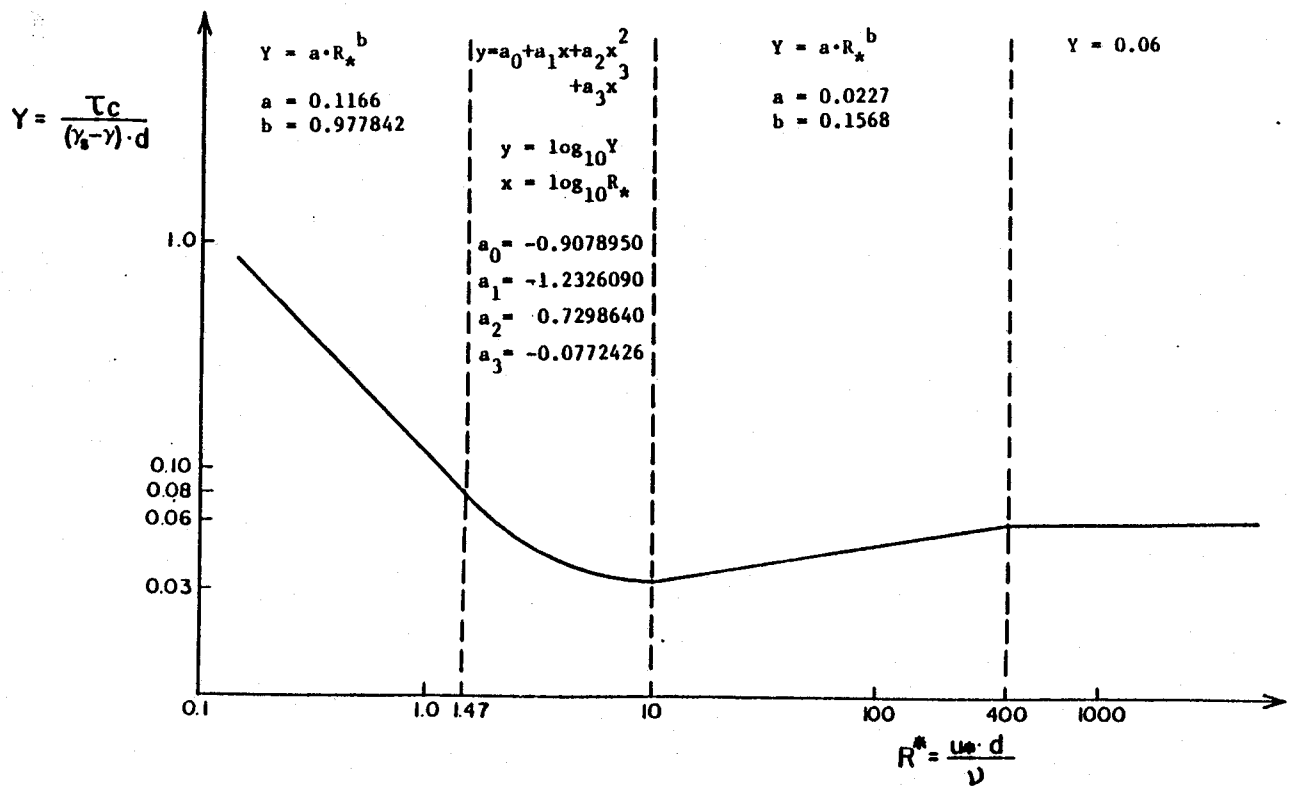


Figure VI-2. Linear and Parabolic Approximation of Shields' Diagram

$\underline{R_* \leq 1.47}$

$$Y = a \cdot R_*^{\,b} \qquad \text{(VI-4)}$$

with $a = 0.1166$, and

$b = -0.977842 \simeq -1$

$\underline{1.47 \leq R_* \leq 10}$

$$y = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 \qquad \text{(VI-5)}$$

where $y = \log_{10} \dfrac{\tau_c}{(\gamma_s - \gamma)d}$

$x = \log_{10} R_*$

and with $a_0 = -0.9078950$

$a_1 = -1.2326090$

$a_2 = 0.7298640$

$a_3 = -0.0772426$

$\underline{10 \leq R_* \leq 400}$

$$Y = a \cdot R_*^{\,b} \qquad \text{(VI-6)}$$

with $a = 0.0227$, and

$b = 0.1568$

$\underline{R_* \geq 400}$

$Y = 0.06$ or

$$d = \frac{R \cdot S}{(SPG-1) \cdot 0.06} \qquad \text{(VI-7)}$$

The straight line segments may be solved directly for the critical diameter from

$$\frac{\tau_c}{(\gamma_s - \gamma)d} = a\left(\frac{u_* d}{\nu}\right)^b \qquad \text{(VI-8)}$$

and using the relationships of equations VI-2 and VI-3, resulting in

$$CRITD = \left[\frac{(R \cdot S)^{1-b/2}\ \nu^b}{(SPG-1) \cdot a \cdot g^{b/2}}\right]^{\frac{1}{1+b}} \qquad \text{(VI-9)}$$

Equation VI-9 works well for the coefficients a and b of equation VI-6. But for equation VI-4, b ≈ -1 and the exponent approaches infinity. For the region $R_* \leq 1.47$, all sediment particles are within the laminar sublayer of the flow, and motion is independent of the diameter (Graf, 1971). For practical purposes, there is no apparent motion, and the critical diameter is assumed to be the value at $R_* = 1.47$ in the model,

that is $d = \frac{1.47 \cdot \nu}{\sqrt{RSg}}$.

The polynomial for the transition region, $1.47 \leq R_* \leq 10$, is rapidly solved using a Newton-Raphson iteration. In the program, equation VI-9 is first solved using the a and b values for equation VI-6 ($10 \leq R_* \leq 400$). If the resulting value of R_* is greater than 400, the critical diameter is evaluated from equation VI-7. If R_* is less 10, the polynomial approximation is then solved. If the resulting value of R_* from polynomial is greater than 10, the critical diameter is assumed to be the value at $R_* = 10$, and if R_* is less than 1.47, the value at $R_* = 1.47$ is used as a default.

Regarding the parameters of equation VI-9, the slope, S is taken as the invert slope (SLOPE) for each conduit, used by the Transport Block. The hydraulic radius is calculated at each time step, and the kinematic viscosity, ν, (GNU) is input for each run. (It incorporates any temperature effects.) The specific gravity (SPG) of sewer particles ranges from 1.1 for organic material to 2.7 for sand and grit. An average value, based upon the rough composition of the sediment, must be used. When quality parameters are input in card group F1 of the Transport Block, if SPG $\leq$ 1.0, the deposition-scour routine will not be used. It may be seen that if SPG is greater than 1.0 but very close to it, the value of CRITD in equation VI-9 becomes highly sensitive to it.

PARTICLE SIZE DISTRIBUTION

The particle size distribution for each pollutant for which it is desired to simulate deposition and scour is input by up to four straight line segments, as shown in Figure VI-3 (see also Figure 6-6). The distribution may be based upon characteristics of surface sediment for simulation of storm sewers, but should utilize sewer conduit samples for combined sewers.

An example will best illustrate the use of the particle size distribution. Consider first an example of scour. The distribution of Figure VI-3 is sketched again in Figure VI-4a. At the beginning of the time step, all particles in the bed are assumed to have diameters $\geq$ DB = 0.6 mm in the example. If a new critical diameter, CRITD, is calculated that is greater than DB, (CRITD = 1.5 mm in the example), the new bed distribution will become as shown in Figure VI-4b. The percent of the bed mass that is scoured is

$$\frac{72-35}{72} \times 100 = 51\%$$

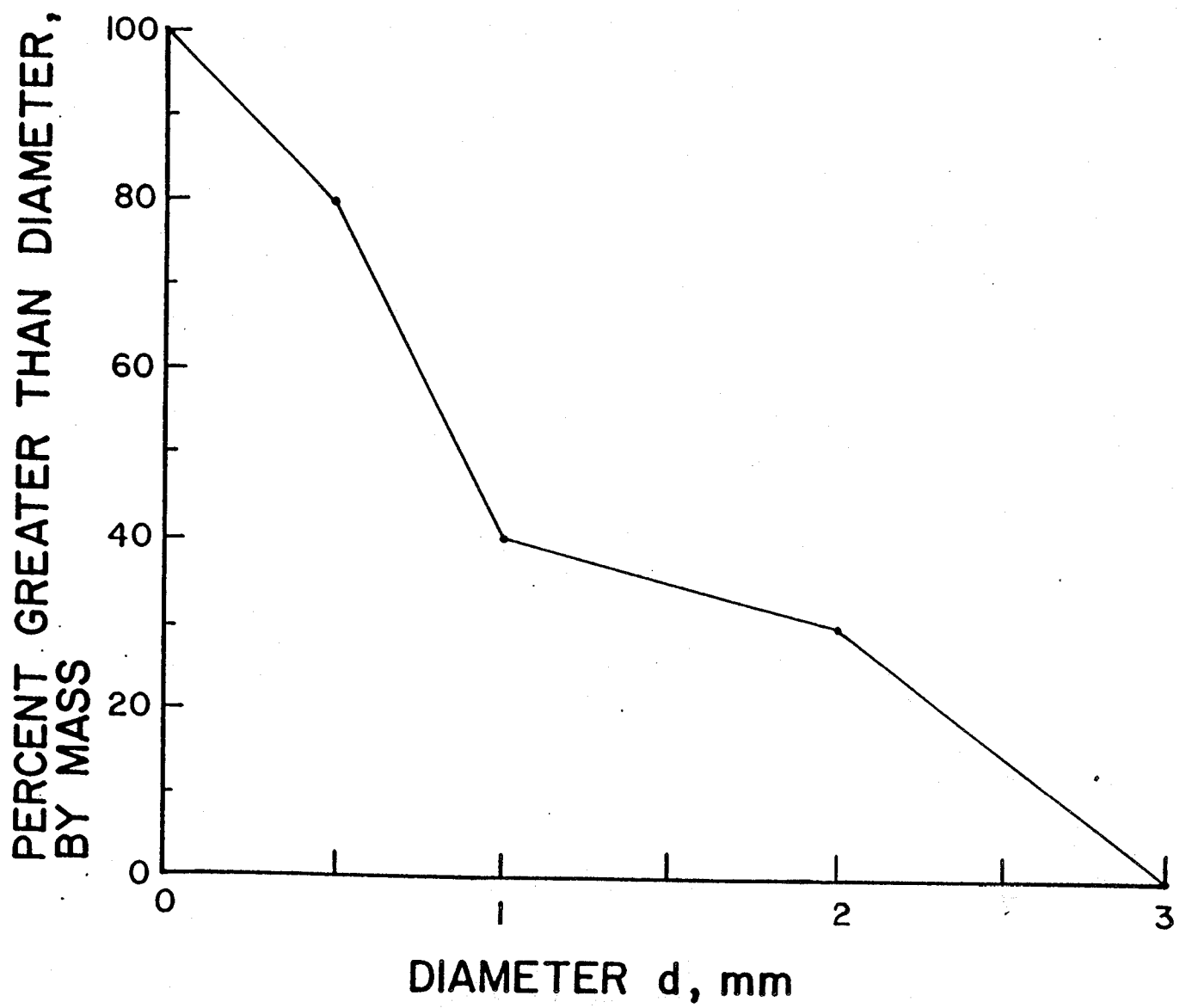


Figure VI-3. Particle Size Distribution for a Pollutant.

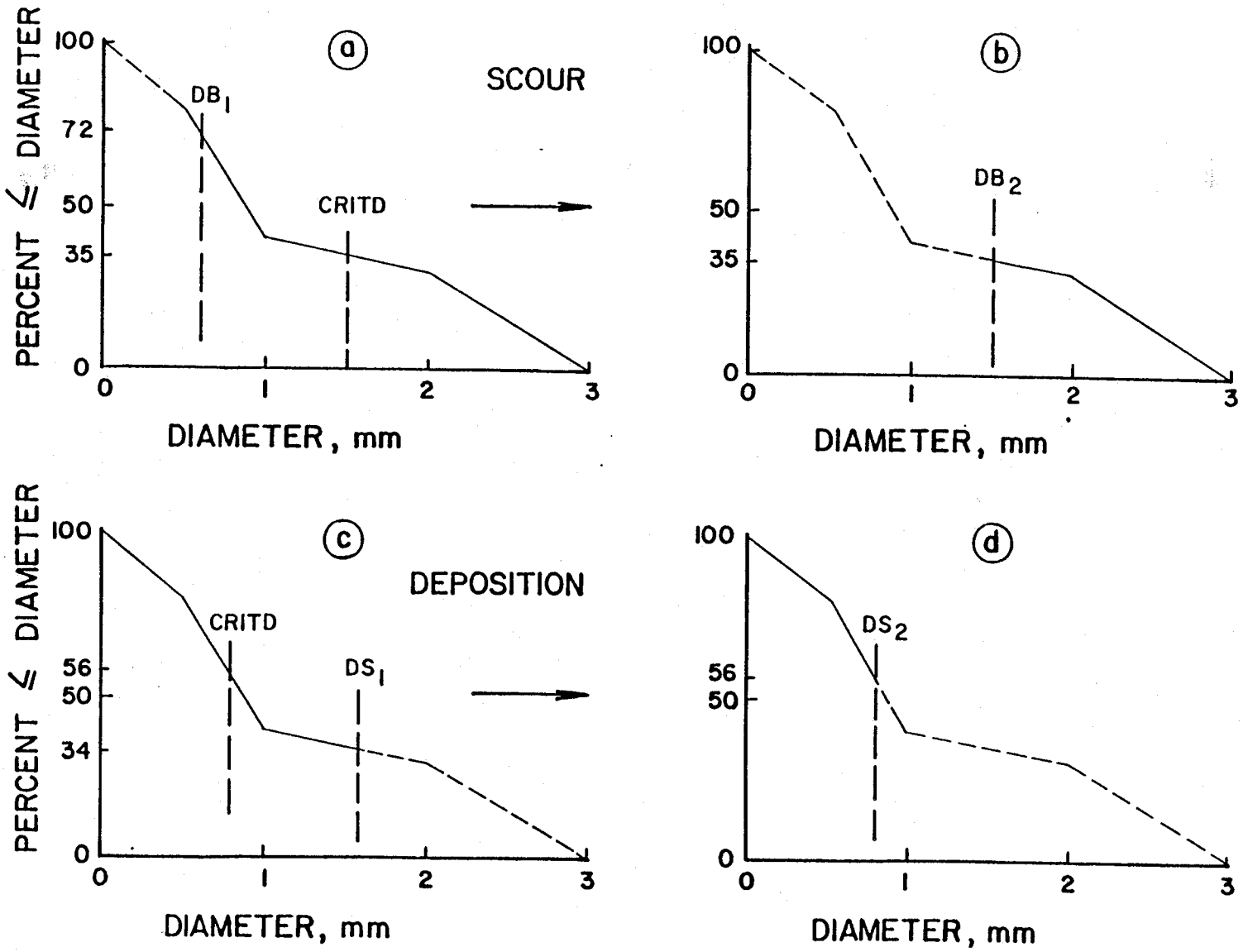


Figure VI-4. Truncation of Particle Size Distribution During Scour and Deposition.

(Under the original methodology in the Transport Block, it would have been assumed that 100-35 or 65 percent of the mass of the bed would be scoured.)

A similar calculation applies to deposition. If the suspended material (particles in motion) have the distribution shown in Figure VI-4c, it becomes that of Figure VI-4d. The percent of the suspended load that is deposited is

$$\frac{56-34}{100-34} \times 100 = 33\%$$

(Under the original methodology in the Transport Block, it would have been assumed that 56 percent of the suspended load would be deposited.) When scoured material is added to suspended material, a new value of DS is computed by mass-weighting:

$$DS_2 = \frac{DS_1 \cdot M_s + CRITD \cdot M_e}{M_s + M_e} \qquad \text{(VI-10)}$$

where DS_2 = new value of DS, mm,

DS_1 = old value of DS, mm,

M_s = original mass in suspension, mg, and

M_e = mass eroded from bed, mg.

Similarly, if suspended material is deposited,

$$DB_2 = \frac{DB_1 \cdot M_b + CRITD \cdot M_d}{M_b + M_d} \qquad \text{(VI-11)}$$

where DB_2 = new value of DB, mm,

DB_1 = old value of DB, mm,

M_b = original mass of bed material, mg, and

M_d = mass deposited from flow, mg.

Due to this weighting, ordinarily it will not be true that DB=DS even though the same critical diameter, CRITD, applies to both.

Another reason why DB will not necessarily equal DS results from the condition in which CRITD < DB_1 for scour (or CRITD > DS_1 for deposition). In these cases, $DB_2 = DB_1$ (or $DS_2 = DS_1$), prior to addition of mass from the flow (or bed), since no mass would be lost from the bed (or from the suspended material).

INFLOWS AND JUNCTIONS

To allow some difference between surface inflows to the sewer system and dry-weather flow inflows (e.g., domestic sewage) a maximum particle size, PSDWF, may be specified (in card group F1) for the pollutant found in DWF. This also applies to pollutants entering as a base flow in manholes. Pollutants entering via infiltration are assumed to be completely dissolved and have "zero particle sizes."

At junctions (manholes or other non-conduits), a new value of DS is computed by mass weighting the merging values. For instance,

$$DS_m = \frac{\sum_{i=1}^{3} DS_{u_i} \cdot Q_{u_i} \cdot C_{u_i} + PSDWF \cdot Q_{DWF} \cdot C_{DWF}}{\sum_{i=1}^{3} Q_{u_i} \cdot C_{u_i} + Q_{DWF} \cdot C_{DWF} + Q_{inf}} \qquad \text{(VI-12)}$$

where DS_m = value of DS of mixture, mm,

DS_{u_i} = DS value in upstream conduit i, mm,

Q_{u_i} = outflow from upstream conduit i, cfs,

C_{u_i} = concentration in upstream conduit i, mg/l, and

subscripts DWF and inf refer to dry-weather flow and infiltration respectively.

APPENDIX VII

EXAMPLE ANALYSIS OF URBAN RUNOFF QUALITY DATA FOR MODELING APPLICATIONS

Options for simulation of surface runoff quality in SWMM have been described in Section 4 of this report. They are basically two: use of a buildup-washoff equation or use of a rating curve. The former (equation 4-35) results in a characteristic loop effect when intra-storm loads are plotted versus runoff rate (Figure 4-36) while the latter must result in a single valued function. In this appendix, data from three separate sewered catchments in Seattle and one combined sewered catchment in Lancaster, PA are examined in order to see if SWMM has the ability to mimic their load and concentration versus flow characteristics. The data were taken from the EPA Urban Rainfall-Runoff-Quality Data Base (Huber et al., 1979) and analyzed using library statistical packages.

Three parameters were chosen for analysis:

1) Five day biochemical oxygen demand, BOD_5,

2) Total suspended solids, TSS, and

3) NO_2+NO_3-N for Seattle and NO_3-N for Lancaster.

The first parameter, BOD, is likely to be associated with solids; the second parameter is a solid, and the nitrogen parameters are likely to be dissolved. Hence, they may exhibit different characteristic relationships.

Results are presented in the following figures. (See also Figure 4-37.) Loops are evident in the Lancaster data (Figures VII-17 to VII-19) although eratic, since the runoff hydrographs are eratic. Loops are also present for the Seattle data although harder to detect since sucessive points are not connected (Figures VII-4 to VII-6). As expected, nitrate concentrations decrease with increasing flow rate (Figures VII-16 and VII-20). Log-log plots tend to reduce the magnitude of the loops and could form the basis of a rating curve approximation. When loads for the three Seattle catchments are normalized by dividing by their respective catchment areas the data are grouped with less scatter (Figure VII-12) than when not normalized (Figure VII-11). The runoff rate in inches/hr is already a normalized flow rate for these catchments.

SEATTLE VIEW RIDGE 1 (MAIL) CATCHMENT AREA = 630 ACRES
EVENT #1 2/14/73

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
1300	0.100	0.159E-03	1.3	6.	2.30	3.68	17.0	6.51
1330	0.100	0.159E-03	1.3	6.	2.30	3.68	17.0	6.51
1345	0.100	0.159E-03	1.0	4.	2.20	2.83	11.3	6.23
1415	0.150	0.238E-03	1.0	4.	2.20	4.25	17.0	9.35
1447	0.481	0.765E-03	8.0	12.	2.40	109.	163.	32.7
1507	0.686	0.109E-02	94.0	216.	1.20	0.183E 04	0.420E 04	23.3
1526	0.620	0.984E-03	32.0	416.	0.90	913.	0.750E 04	13.8
1544	0.522	0.829E-03	20.0	170.	0.90	276.	0.251E 04	11.8
1604	0.344	0.546E-03	35.0	74.	1.30	299.	0.118E 04	20.8
1621	0.600	0.952E-03	17.1	70.	0.80	291.	0.119E 04	12.6
1717	0.461	0.732E-03	17.1	58.	0.80	223.	757.	10.4
1734	0.386	0.613E-03	12.2	54.	1.10	133.	590.	12.0
1833	0.270	0.429E-03	12.2	54.	1.10	93.3	412.	8.41
1853	0.237	0.376E-03	13.0	40.	0.90	87.3	268.	6.04
2000	0.120	0.190E-03	13.0	40.	0.90	44.2	134.	3.06

SEATTLE VIEW RIDGE 1
EVENT #6 10/20/74

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
320	0.040	0.635E-04	97.0	4380.	2.00	110.	0.496E 04	2.27
335	1.600	0.254E-02	150.0	260.	1.70	0.680E 04	0.118E 05	77.0
350	2.180	0.346E-02	110.0	124.	1.60	0.679E 04	0.766E 04	98.8
405	2.710	0.430E-02	95.0	124.	1.60	0.729E 04	0.952E 04	107.
420	63.690	0.101	34.0	446.	0.74	0.613E 05	0.804E 06	0.133E 04
440	21.910	0.348E-01	23.0	194.	0.80	0.143E 05	0.122E 06	494.
455	19.980	0.317E-01	16.0	66.	0.74	0.903E 04	0.373E 05	419.
510	16.360	0.260E-01	14.0	40.	0.67	0.649E 04	0.185E 05	310.
525	14.680	0.233E-01	12.0	24.	0.63	0.499E 04	0.998E 04	238.
530	6.890	0.109E-01	12.0	18.	0.61	0.234E 04	0.351E 04	119.
545	3.940	0.625E-02	11.0	18.	0.68	0.122E 04	0.201E 04	93.9
600	4.430	0.704E-02	13.0	22.	0.67	0.164E 04	0.277E 04	84.4
615	6.450	0.102E-01	13.0	20.	0.67	0.219E 04	0.345E 04	122.
630	9.650	0.153E-01	9.3	36.	0.56	0.231E 04	0.864E 04	148.
645	4.450	0.706E-02	8.3	48.	0.45	0.109E 04	0.605E 04	54.7
700	2.180	0.346E-02	7.6	52.	0.55	449.	0.321E 04	34.0
715	1.010	0.160E-02	8.3	30.	2.80	237.	858.	80.1
730	0.700	0.111E-02	9.0	68.	2.20	178.	0.135E 04	43.6
745	0.500	0.794E-03	8.0	16.	3.30	113.	227.	46.7
800	0.330	0.524E-03	3.9	24.	4.30	34.4	224.	40.2

SEATTLE VIEW RIDGE 1
EVENT #7 11/17/74

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
730	0.040	0.635E-04	120.0	22.	1.20	136.	29.9	1.36
745	0.700	0.111E-02	72.0	26.	0.79	0.143E 04	513.	15.7
800	0.700	0.111E-02	64.0	24.	0.55	0.127E 04	513.	10.9
815	0.930	0.148E-02	70.0	24.	0.49	0.184E 04	632.	12.9
830	3.290	0.522E-02	140.0	48.	0.43	0.130E 05	0.447E 04	40.1
845	2.850	0.452E-02	57.0	38.	0.59	0.460E 04	0.307E 04	46.8
900	3.410	0.573E-02	49.0	58.	0.28	0.301E 04	0.593E 04	28.6
915	10.440	0.166E-01	85.0	130.	0.26	0.231E 05	0.384E 05	76.9
930	7.120	0.113E-01	64.0	150.	0.22	0.129E 05	0.302E 05	44.4
945	13.090	0.208E-01	54.0	150.	0.23	0.200E 05	0.536E 05	85.3
1000	18.130	0.288E-01	55.0	80.	0.21	0.282E 05	0.411E 05	108.
1015	19.980	0.317E-01	63.0	120.	0.17	0.356E 05	0.679E 05	96.2
1030	14.030	0.223E-01	56.0	108.	0.15	0.223E 05	0.429E 05	59.6
1045	16.340	0.260E-01	85.0	66.	0.15	0.394E 05	0.306E 05	69.5
1100	18.490	0.293E-01	37.0	74.	0.16	0.194E 05	0.387E 05	83.8
1115	11.380	0.184E-01	45.0	56.	0.16	0.148E 05	0.184E 05	32.3
1130	9.350	0.148E-01	40.0	46.	0.17	0.106E 05	0.122E 05	45.0
1145	4.100	0.651E-02	35.0	48.	0.20	0.406E 04	0.557E 04	23.2
1200	2.300	0.365E-02	30.0	20.	0.24	0.193E 04	0.193E 04	13.6
1300	2.850	0.452E-02	28.0	24.	0.38	0.224E 04	0.194E 04	30.7
1400	0.700	0.111E-02	31.0	48.	0.44	613.	932.	8.72
1500	0.240	0.381E-03	31.0	42.	0.42	211.	283.	4.23

Figure VII-1. Flow and Quality Data for Seattle, Washington View Ridge I Catchment (Single Family Residential, Separate Sewers), Event 1, Event 6, Event 7.

SEATTLE SOUTH SEATTLE (WA13) CATCHMENT AREA = 27.5 ACRES
EVENT 03 6/6/73

STORET CODE	41		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
1110	0.010	0.364E-02	22.0	24.	0.10	6.23	6.80	0.283E-01
1215	0.010	0.364E-02	22.0	24.	0.10	6.23	6.80	0.283E-01
1230	0.040	0.218E-02	42.0	170.	1.43	71.4	289.	2.46
1245	0.180	0.435E-02	88.0	300.	1.40	449.	0.153E 04	7.14
1300	0.140	0.509E-02	40.0	200.	1.30	159.	793.	5.15
1315	0.170	0.618E-02	22.0	95.	1.00	154.	497.	4.81
1330	0.220	0.800E-02	22.0	100.	1.00	199.	622.	6.23
1345	0.220	0.800E-02	21.0	95.	0.70	193.	592.	4.36
1400	0.171	0.622E-02	20.0	125.	0.70	96.9	603.	3.39
1415	0.130	0.345E-02	13.0	25.	0.70	33.2	104.	2.97
1430	0.220	0.800E-02	20.0	60.	0.70	123.	374.	4.36
1445	0.220	0.800E-02	20.0	20.	0.70	123.	125.	4.36
1530	0.250	0.909E-02	20.0	20.	0.70	142.	142.	4.96
1545	0.510	0.185E-01	44.0	80.	0.70	644.	0.114E 04	10.1
1630	0.140	0.509E-02	44.0	80.	0.70	182.	317.	2.78
1645	0.220	0.800E-02	42.0	95.	0.90	263.	592.	5.41
1830	0.037	0.135E-02	42.0	95.	0.90	44.0	99.5	0.943

SEATTLE SOUTH SEATTLE
EVENT 04 8/16/73

STORET CODE	41		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
1100	0.003	0.109E-03	9.4	36.	0.10	0.714	4.90	0.850E-02
1230	0.023	0.909E-03	1.0	12.	0.20	0.708	8.50	0.142
1250	0.032	0.114E-02	18.0	88.	1.40	16.3	79.7	1.27
1300	0.025	0.909E-03	25.0	76.	1.80	17.7	53.8	1.27
1320	0.019	0.691E-03	28.0	32.	0.60	15.1	17.3	0.323
1329	0.013	0.473E-03	30.0	88.	1.70	11.0	32.4	0.624
1350	0.014	0.509E-03	81.0	140.	1.60	32.1	55.5	0.634
1400	0.034	0.124E-02	40.0	140.	2.00	38.5	135.	1.93
1420	0.028	0.136E-02	38.0	92.	1.60	64.4	156.	2.25
1300	0.022	0.800E-03	36.0	92.	1.60	34.1	87.3	0.967
1330	0.042	0.153E-02	40.0	170.	1.60	47.6	202.	1.90
1335	0.030	0.182E-02	27.0	270.	1.40	52.4	382.	1.98
1350	0.032	0.116E-02	22.0	44.	1.60	19.4	38.0	1.45
1439	0.011	0.400E-03	22.0	44.	1.60	6.83	13.9	0.498
1630	0.006	0.291E-03	18.0	36.	1.60	4.08	12.7	0.363
1735	0.005	0.182E-03	18.0	36.	1.60	2.35	7.93	0.227

SEATTLE SOUTH SEATTLE
EVENT 05 9/19/73

STORET CODE	41		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
1000	1.490	0.542E-01	26.0	240.	0.73	0.110E 04	0.101E 05	31.6
1015	1.470	0.607E-01	25.0	210.	0.80	993.	0.993E 04	32.8
1030	1.380	0.575E-01	25.0	170.	0.73	0.112E 04	0.761E 04	33.6
1045	1.430	0.442E-01	24.0	80.	0.80	0.124E 04	0.412E 04	41.2
1100	1.490	0.542E-01	20.0	28.	0.73	844.	0.116E 04	31.6
1115	1.580	0.575E-01	13.0	44.	0.85	471.	0.204E 04	38.0
1130	1.380	0.575E-01	13.0	44.	0.85	471.	0.204E 04	38.0
1145	1.860	0.676E-01	18.0	34.	0.85	948.	0.190E 04	44.8
1200	1.440	0.524E-01	13.0	2.	1.20	330.	81.6	48.9
1215	1.190	0.432E-01	13.0	2.	1.20	438.	67.4	40.4
1230	1.030	0.375E-01	8.9	2.	1.40	260.	58.3	40.8
1745	2.230	0.811E-01	14.0	208.	0.90	884.	0.429E 04	36.8
1800	1.840	0.676E-01	14.0	200.	1.00	737.	0.105E 05	32.7
1815	1.380	0.575E-01	7.0	60.	1.40	313.	0.179E 04	62.4
1830	1.480	0.538E-01	0.1	60.	1.40	4.19	0.168E 04	58.7

Figure VII-2. Flow and Quality Data for Seattle, Washington South Seattle Catchment (Industrial, Separate Sewers), Event 3, Event 4, Event 5.

SEATTLE SOUTHCENTER (MA14) CATCHMENT AREA = 24 ACRES
EVENT 42 3/10/73

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
30	1.140	0.475E-01	11.0	36.	0.73	137.	0.116E 04	24.4
45	0.123	0.513E-02	8.0	32.	0.65	27.9	111.	2.24
100	2.449	0.103	13.0	140.	0.30	904.	0.9776 04	21.0
115	3.000	0.125	8.0	344.	0.15	680.	0.2726 04	12.7
130	1.840	0.767E-01	6.8	128.	0.10	354.	0.4476 04	5.21
145	1.380	0.575E-01	1.8	44.	0.46	70.3	0.1726 04	15.6
200	1.559	0.650E-01	2.9	34.	0.35	128.	0.1596 04	13.3
215	1.300	0.542E-01	1.4	34.	0.35	51.3	0.1336 04	12.9
300	1.359	0.650E-01	1.4	34.	0.35	61.8	0.1546 04	15.3
315	1.218	0.508E-01	2.2	8.	0.30	73.9	274.	10.3
400	1.650	0.687E-01	2.2	8.	0.30	103.	374.	14.0
415	1.559	0.650E-01	1.0	4.	0.30	44.2	177.	13.2
500	0.443	0.276E-01	1.0	4.	0.30	18.8	75.1	3.63
515	0.245	0.102E-01	1.0	1.	0.30	6.94	6.94	2.08
600	0.210	0.875E-02	1.0	1.	0.30	5.95	5.95	1.78
615	0.210	0.875E-02	1.0	4.	0.30	5.95	23.8	1.78
630	0.210	0.875E-02	1.0	4.	0.30	5.95	23.8	1.78

SEATTLE SOUTHCENTER
EVENT 43 6/6/73

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
1145	0.012	0.500E-03	1.6	37.	0.23	0.344	12.5	0.9506-01
1200	0.012	0.500E-03	1.6	37.	0.23	0.344	12.5	0.9506-01
1230	0.014	0.583E-03	74.0	84.	0.23	30.1	34.2	0.9726-01
1245	1.790	0.746E-01	20.0	910.	1.60	0.101E 04	0.461E 03	81.1
1300	1.400	0.583E-01	16.0	140.	1.10	434.	0.3556 04	45.4
1315	1.180	0.492E-01	8.0	88.	0.70	234.	0.2606 04	20.5
1330	1.390	0.442E-01	9.0	90.	0.50	409.	0.4056 04	23.2
1345	1.120	0.467E-01	8.2	70.	0.40	260.	0.2226 04	12.7
1400	1.060	0.442E-01	5.7	54.	0.35	171.	0.1436 04	10.5
1415	0.920	0.383E-01	6.3	34.	0.30	169.	0.1446 04	7.82
1430	1.120	0.467E-01	7.1	36.	0.30	222.	0.1786 04	9.35
1445	0.830	0.346E-01	9.3	30.	0.30	219.	709.	7.05
1530	0.780	0.325E-01	9.3	20.	0.30	205.	442.	6.63
1545	1.030	0.429E-01	6.4	34.	0.30	187.	756.	8.73
1630	0.430	0.187E-01	6.4	26.	0.30	81.6	331.	3.82
1645	0.230	0.104E-01	3.4	20.	0.33	34.1	142.	2.48
1730	0.093	0.345E-02	3.4	20.	0.33	9.15	33.8	0.942

SEATTLE SOUTHCENTER
EVENT 67 11/17/74

STORET CODE	61		310	530	630			
HOUR	FLOW (CFS)	RUNOFF (IN/HR)	BOD (MG/L)	TSS (MG/L)	NO2+NO3 (MG/L)	BOD LOAD (MG/SEC)	TSS LOAD (MG/SEC)	NO2+NO3 LOAD (MG/SEC)
715	0.090	0.208E-02	8.4	460.	0.43	17.9	408.	0.942
730	0.310	0.127E-01	13.0	44.	0.34	142.	562.	4.43
745	0.360	0.223E-01	103.0	43.	0.85	0.1478 04	983.	13.3
800	0.590	0.244E-01	70.0	46.	0.79	0.1178 04	769.	13.0
815	0.460	0.575E-01	10.0	30.	0.34	187.	541.	11.0
830	0.750	0.313E-01	8.6	40.	0.32	183.	850.	11.0
845	0.800	0.333E-01	32.0	32.	0.34	729.	729.	8.16
900	0.300	0.208E-01	9.4	30.	0.30	90.6	435.	7.85
915	1.290	0.537E-01	5.3	43.	0.30	287.	0.2446 04	7.87
930	1.190	0.496E-01	5.3	40.	0.17	179.	0.2026 04	5.73
945	1.750	0.729E-01	4.1	38.	0.14	203.	0.1886 04	4.44
1000	1.350	0.562E-01	23.0	76.	0.13	879.	0.2916 04	4.47
1015	1.350	0.562E-01	3.6	63.	0.10	138.	0.2216 04	3.82
1030	1.270	0.529E-01	3.7	73.	0.08	130.	0.2576 04	2.88
1045	1.350	0.562E-01	2.8	44.	0.07	107.	0.1686 04	2.68
1100	1.250	0.520E-01	3.0	36.	0.08	99.7	0.1256 04	2.78
1115	1.190	0.496E-01	3.0	20.	0.08	101.	674.	2.70
1130	0.660	0.275E-01	1.3	30.	0.08	24.3	374.	1.30
1145	0.310	0.129E-01	2.1	10.	0.10	16.4	87.8	0.878
1345	0.370	0.154E-01	2.8	24.	0.16	27.3	291.	1.46
1345	0.100	0.417E-02	4.1	18.	0.20	11.9	51.0	0.451
1715	0.100	0.417E-02	7.7	16.	0.30	21.8	46.3	0.850

Figure VII-3. Flow and Quality Data for Seattle, Washington Southcenter Catchment (Shopping Center, Separate Sewers), Event 2, Event 3, Event 7.

Figure VII-4. BOD Load vs. Flow. Top: View Ridge 1 catchment - (*) Event 1, (0) Event 6, (X) Event 7. Middle: South Seattle catchment - (*) Event 3, (0) Event 4, (X) Event 5. Bottom: Southcenter catchment - (*) Event 2, (0) Event 3, (X) Event 7.

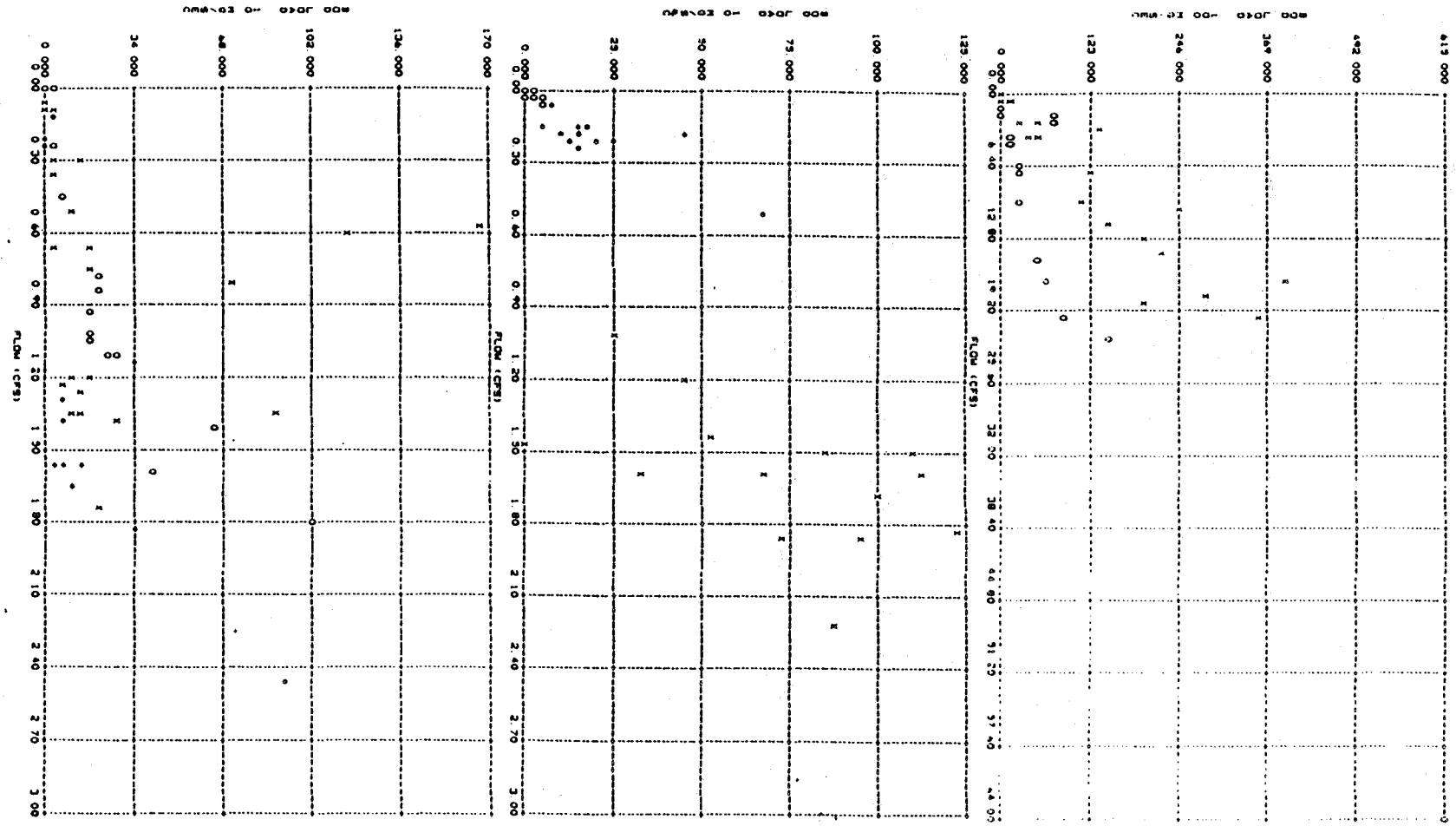


Figure VII-5. TSS Load Vs. Flow. Same symbols as Figure VII-4.

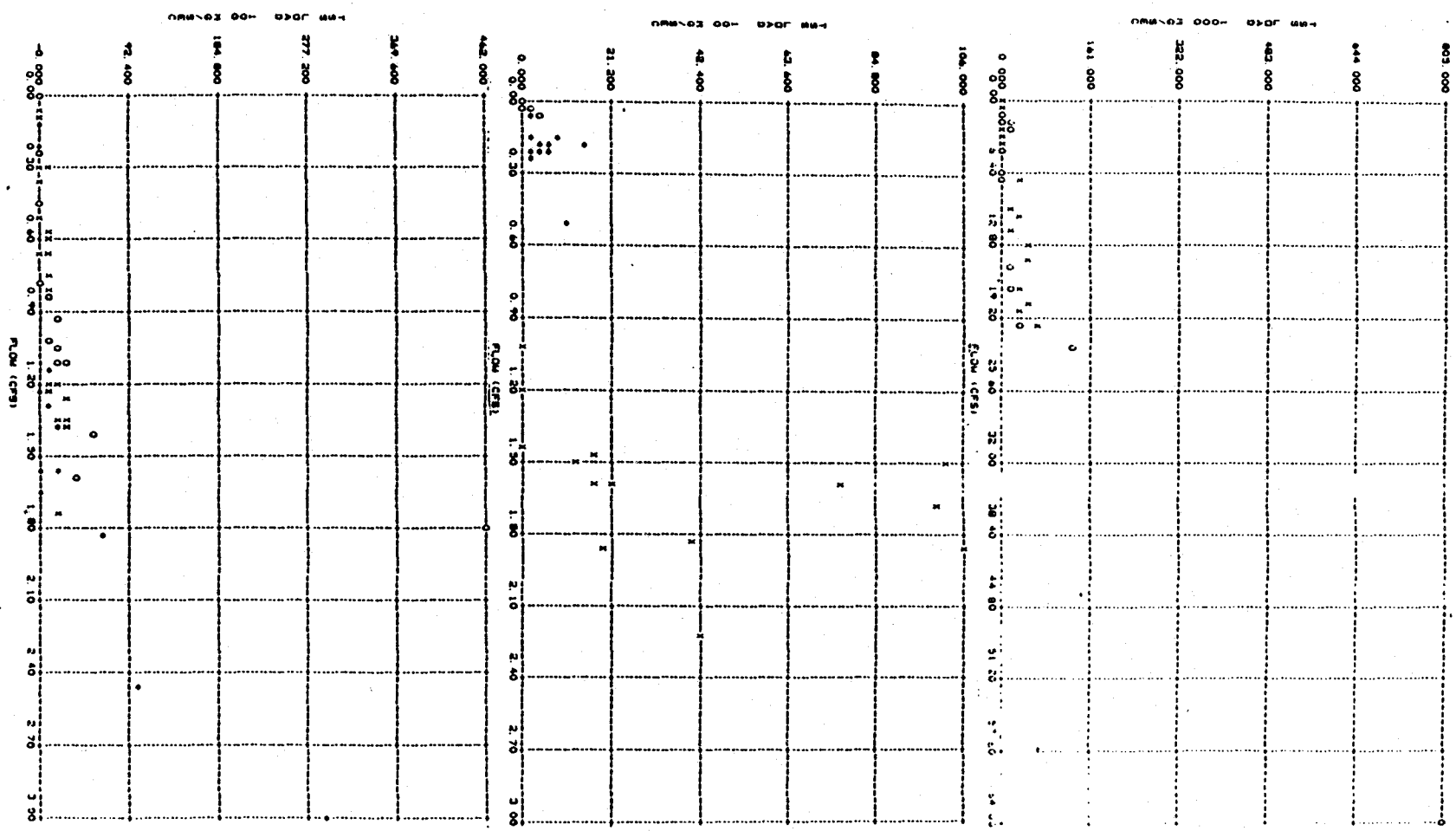


Figure VII-6. NO_2-N + NO_3-N Load Vs. Flow. Same symbols as Figure VII-4.

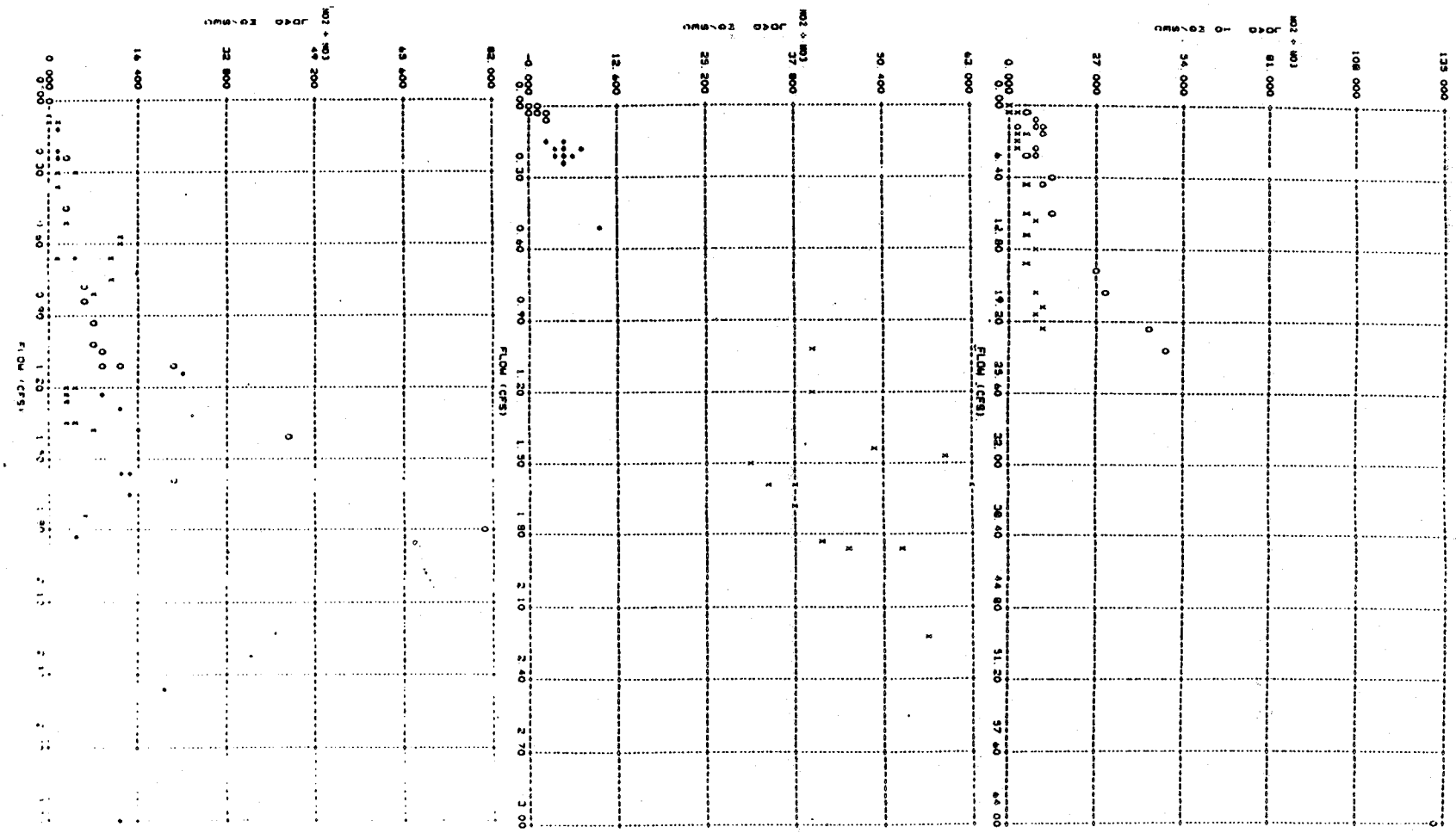


Figure VII-7. Log_{10} BOD Load Vs. Log_{10} Flow. Same symbols as Figure VII-4.

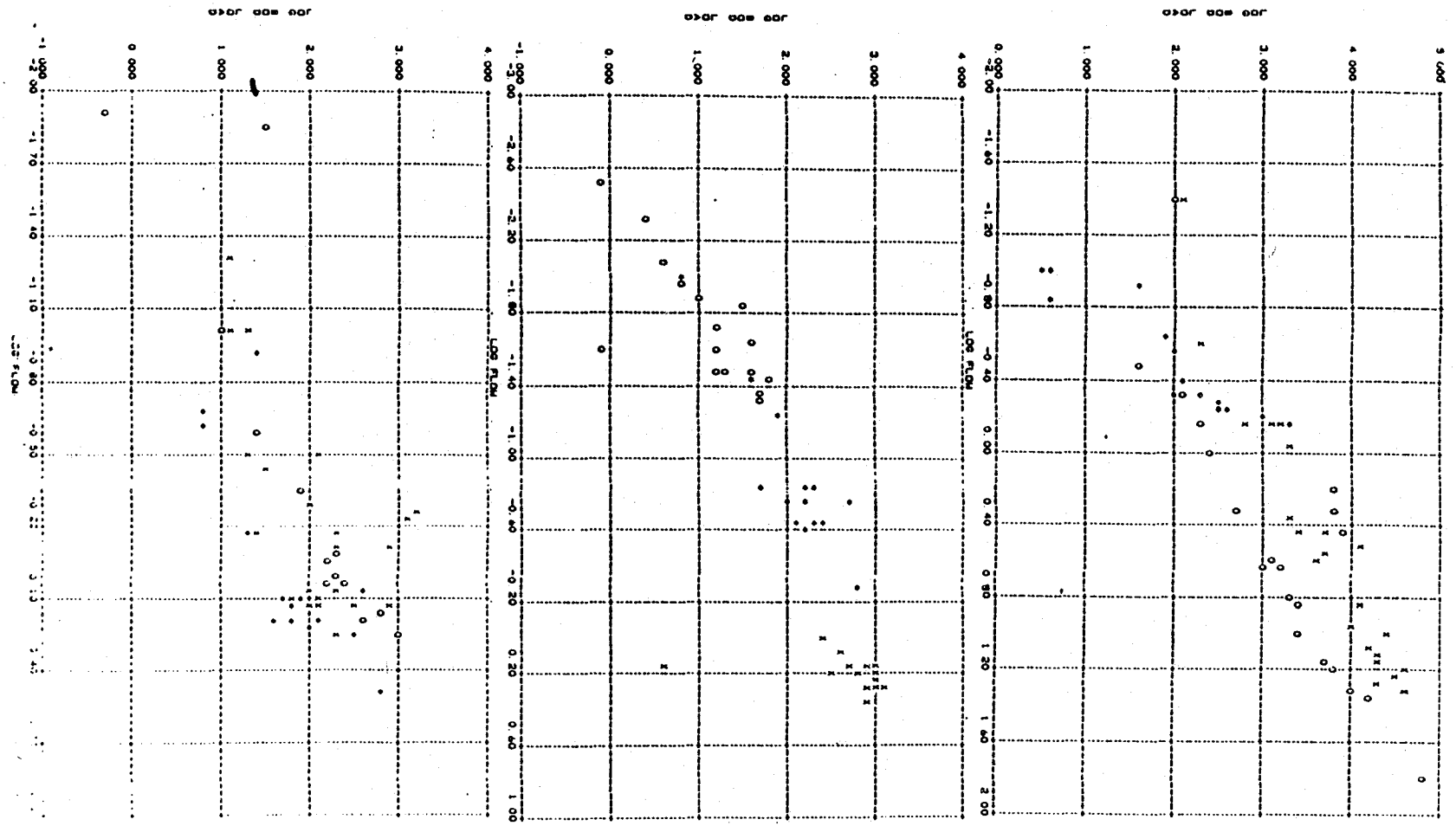


Figure VII-8. Log_{10} TSS Load Vs. Log_{10} Flow. Same symbols as Figure VII-4.

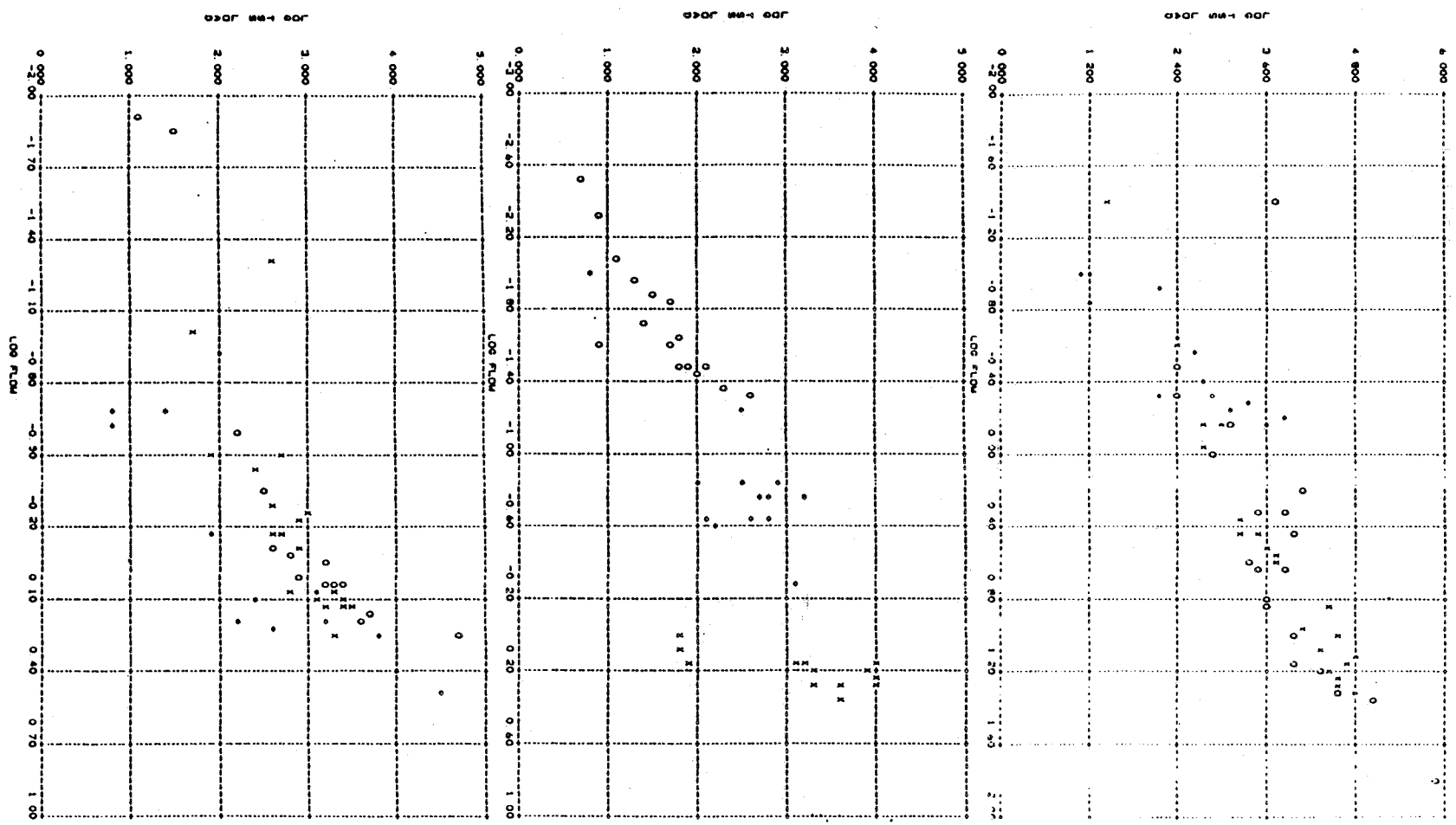


Figure VII-9. Log_{10} NO_2-N + NO_3-N Load Vs. Log_{10} Flow. Same symbols as Figure VII-4.

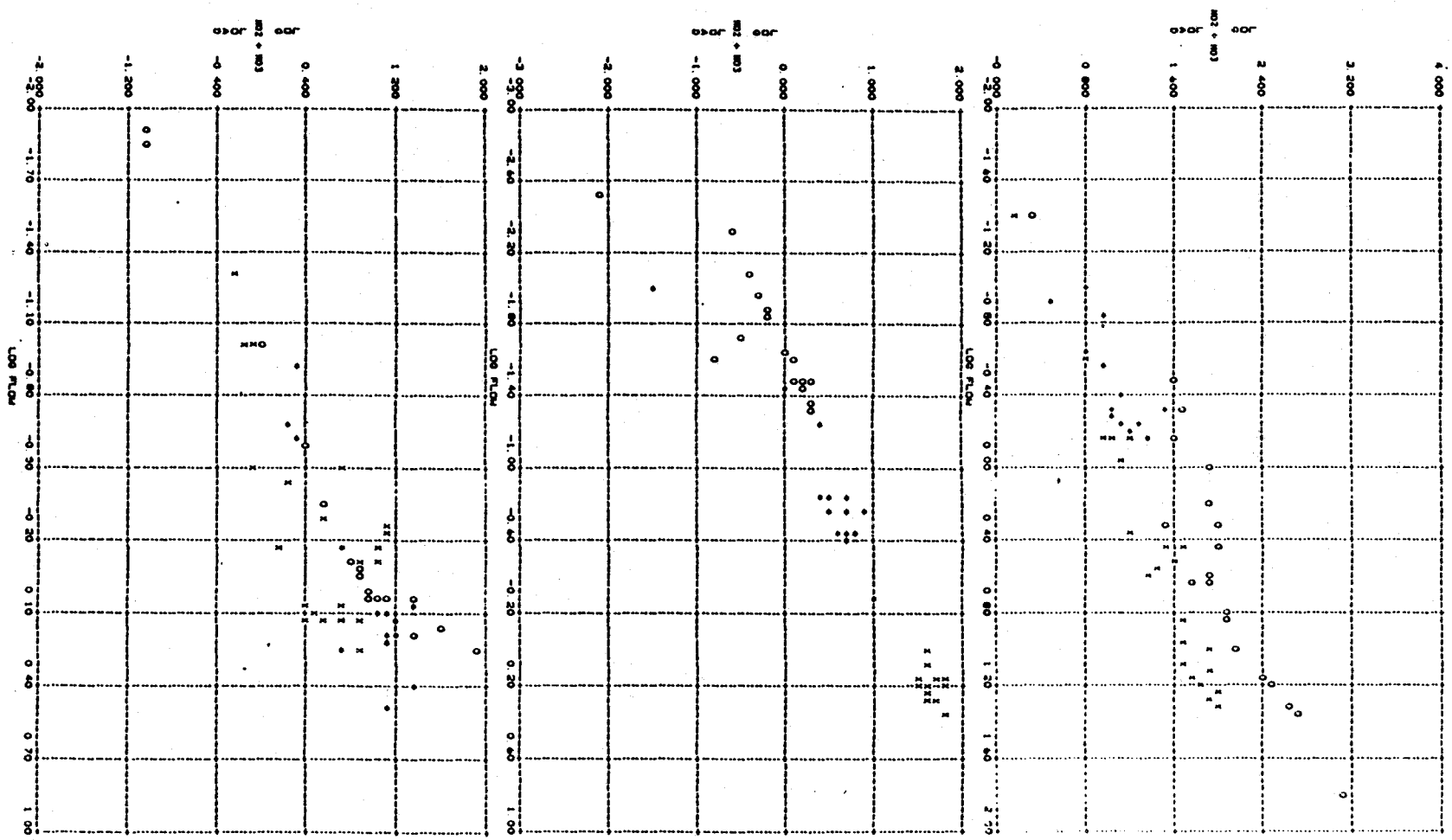


Figure VII-10. Log_{10} Load Vs. Log_{10} Flow for all Events. (1) View Ridge 1 - Event 1, (2) View Ridge 1 - Event 6, (3) View Ridge - Event 7, (4) South Seattle - Event 3, (5) South Seattle - Event 4, (6) South Seattle - Event 5, (7) Southcenter - Event 2, (8) Southcenter - Event 3, (9) Southcenter - Event 7.

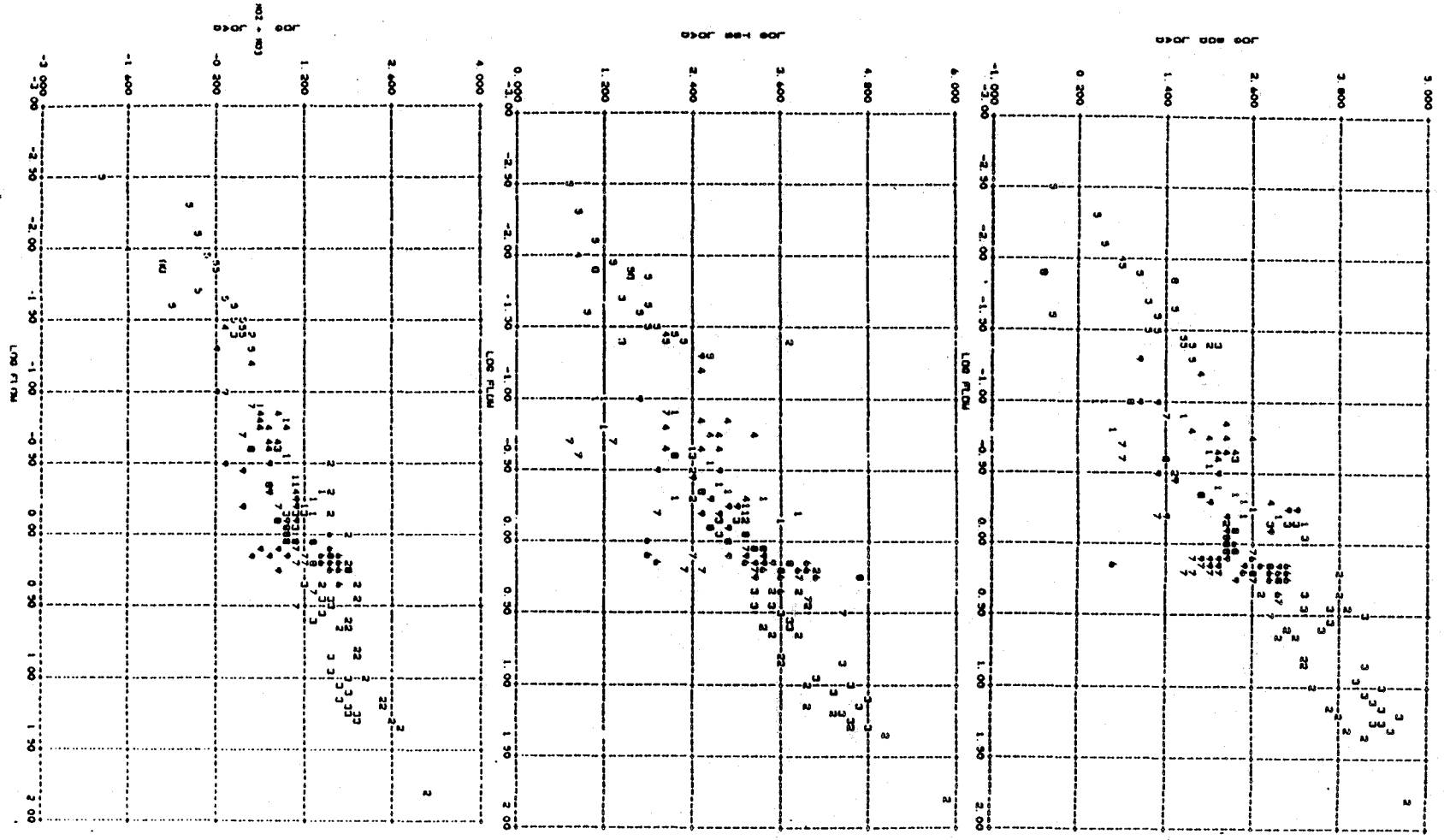


Figure VII-11. Log_{10} Load Vs. Log_{10} Runoff for All Events BOD, TSS and NO_2-N + NO_3-N. Same notation as Figure VII-10.

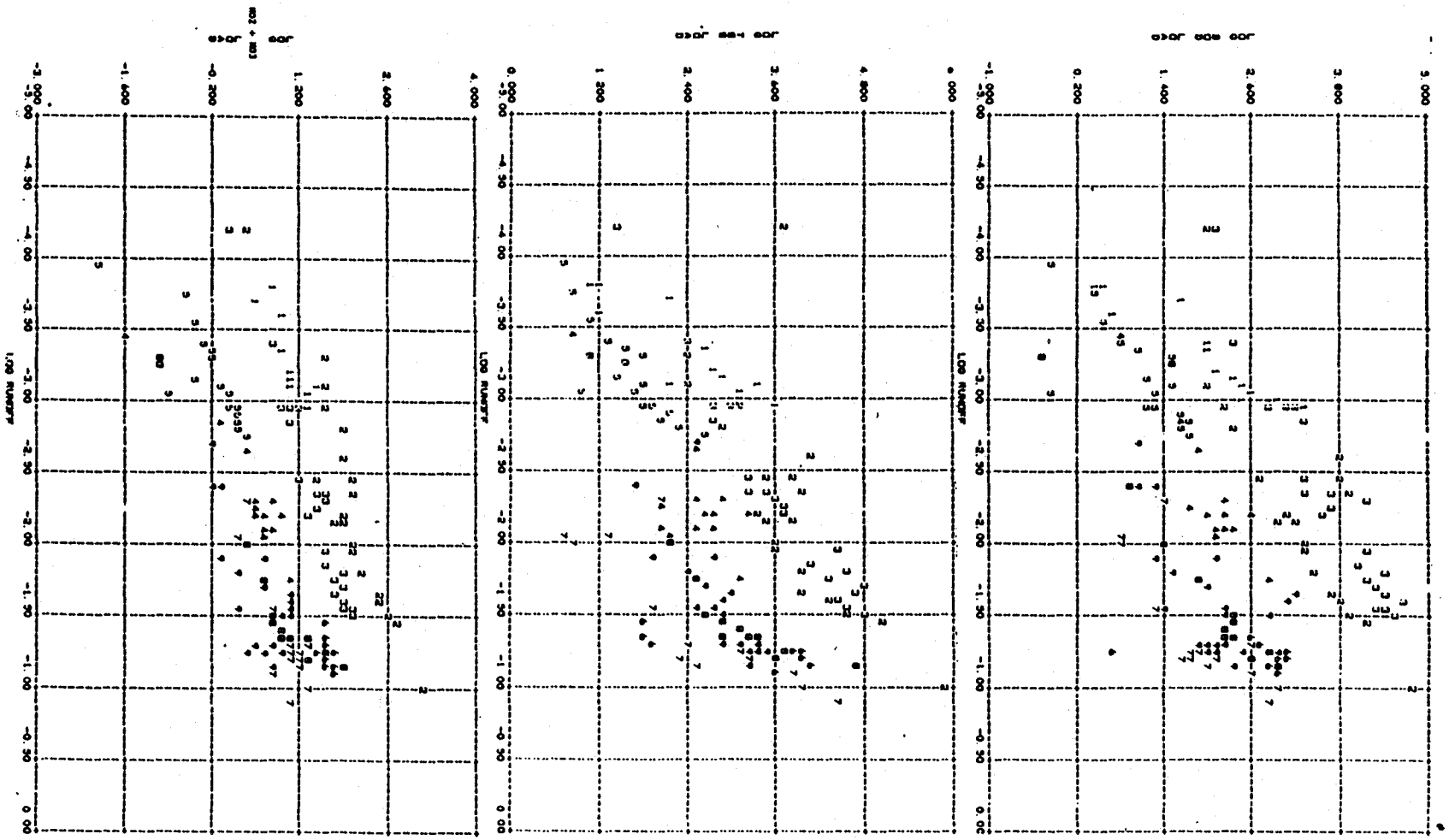
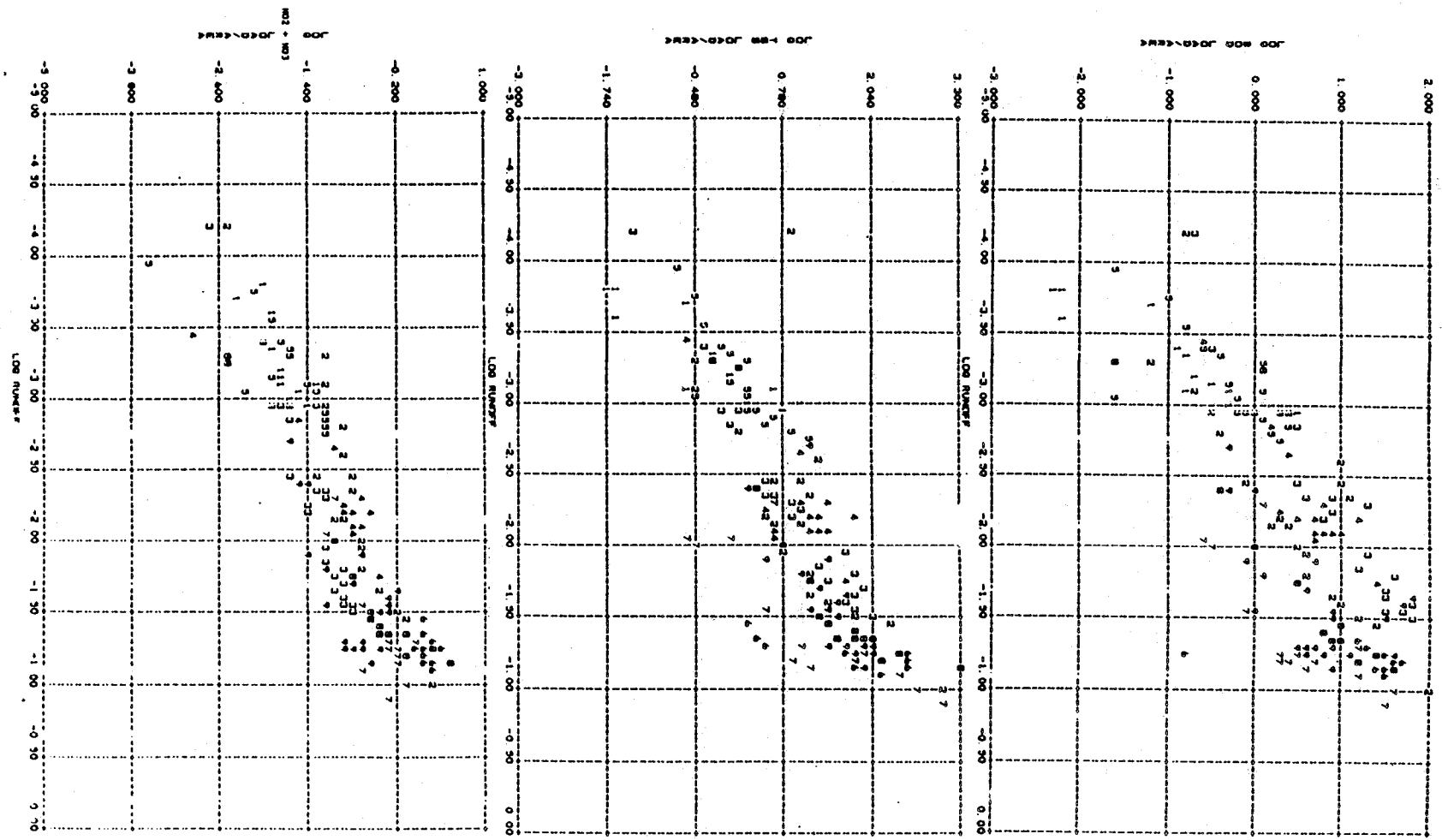


Figure VII-12. Log_{10} Load/Area Vs. Log_{10} Runoff for All Events BOD, TSS, & NO_2-N + NO_3-N. Same notation as Figure VII-10.



LANCARTER, PA. EVENT01 9/14/73

OBS	TIME1	FLOW1	BOD1	TSS1	NO31	LOADBOD1	LOADTSS1	LOADNO31
1	733	2.180	43	31	9.0	2694.7	3149	955.44
2	743	1.893	45	115	13.0	2412.4	6163	996.92
3	753	1.123	50	34	13.0	1593.0	1083	414.18
4	803	0.710	130	38	14.0	2613.9	764	281.30
5	813	1.784	170	52	12.0	10675.3	2922	720.43
6	823	1.134	105	34	14.0	3941.3	1734	449.61
7	833	2.943	74	81	13.0	5554.3	4686	752.13
8	843	2.253	47	126	10.0	3131.9	8396	666.37
9	853	1.706	43	123	9.0	2077.5	3943	434.82
10	903	1.920	41	130	9.0	2229.4	7649	489.37
11	913	2.456	34	47	8.0	1808.4	3269	334.43
12	923	0.920	34	28	9.0	751.2	1004	227.80
13	933	2.273	37	144	6.0	2402.7	9731	387.43
14	943	6.718	45	149	5.0	8180.9	32133	951.37
15	953	7.300	45	244	5.0	9509.9	50444	1033.48
16	1003	23.436	22	153	5.0	15265.3	101547	2318.34
17	1013	9.120	18	93	5.0	4649.0	24020	1291.39
18	1023	3.219	20	46	6.0	1823.2	3470	346.97
19	1033	4.304	17	44	5.0	2148.4	8419	537.77
20	1043	3.760	23	45	5.0	1797.8	4490	470.82
21	1053	3.282	22	66	5.0	1480.9	7443	363.83
22	1113	2.740	21	34	7.0	2405.3	4345	343.18
23	1143	0.869	23	64	0.7	1590.4	1573	17.23
24	1213	4.924	25	73	0.6	4903.2	14707	117.63
25	1243	2.042	44	1	0.3	2344.3	58	28.91
26	1313	2.384	23	1	0.6	1392.8	68	40.51

LANCARTER, PA. EVENT02 10/29/73

OBS	TIME2	FLOW2	BOD2	TSS2	NO32	LOADBOD2	LOADTSS2	LOADNO32
1	811	23.047	74	120	12	49976	81042	8106.2
2	821	11.144	72	141	10	22723	44499	3136.0
3	831	16.503	96	219	9	44601	101749	4181.3
4	841	42.347	38	154	7	69886	187969	8434.3
5	851	47.066	134	345	9	163281	419954	11996.2
6	901	9.774	49	117	9	13008	31060	2389.2
7	911	47.246	48	125	9	44224	167251	12042.1
8	921	47.472	46	117	7	91430	137896	9410.8
9	931	36.759	24	107	5	18188	81086	3789.1
10	941	37.484	12	81	8	12739	83990	8493.6
11	951	69.329	18	37	4	35443	112236	7876.2
12	1001	103.216	37	44	4	108154	128619	11692.3
13	1011	53.506	36	46	4	35398	67703	4041.4
14	1041	15.313	17	43	5	7449	18891	2194.6

LANCARTER, PA. EVENT03 11/24/73

OBS	TIME3	FLOW3	BOD3	TSS3	NO33	LOADBOD3	LOADTSS3	LOADNO33
1	1330	10.43	60	392	13	18043.3	118008	4313.42
2	1330	8.11	52	350	12	11943.1	80384	2754.10
3	1340	6.38	112	202	13	20224.3	34498	2168.18
4	1350	6.31	169	210	13	32774.1	37327	2023.09
5	1400	2.52	151	136	14	11204.0	11575	1038.78
6	1410	3.94	157	100	13	17741.3	11138	1430.33
7	1420	2.92	146	48	17	12073.4	4796	1405.80
8	1430	2.53	120	83	14	11105.7	3947	1003.09
9	1440	3.74	142	1	13	13120.6	104	1384.28
10	1450	2.18	131	60	13	9322.4	3704	802.59

LANCARTER, PA. EVENT04 11/28/73

OBS	TIME4	FLOW4	BOD4	TSS4	NO34	LOADBOD4	LOADTSS4	LOADNO34
1	1328	27.360	187	1172	7.2	434828	908107	5578.81
2	1338	16.481	310	398	6.0	144444	374980	2834.44
3	1348	29.757	147	444	6.2	123796	393443	3221.34
4	1358	10.738	147	336	7.0	44703	138470	2128.78
5	1408	9.322	120	792	8.4	18066	119369	1266.04
6	1418	9.198	110	298	13.3	28434	77435	3316.58
7	1428	5.022	87	292	11.7	11803	35840	1444.01
8	1438	5.633	97	118	12.4	13480	16831	2138.41
9	1448	4.335	83	114	13.0	10460	14641	1926.47

LANCARTER, PA. EVENT06 12/11/74

OBS	TIME5	FLOW5	BOD5	TSS5	NO35	LOADBOD5	LOADTSS5	LOADNO35
1	6	27.827	170	818	9	133970	644434	7092.3
2	16	10.234	70	344	10	20292	163494	2898.8
3	26	10.016	45	234	11	12744	72613	3120.2
4	36	13.444	33	186	10	20479	71870	3844.0
5	46	22.734	32	250	9	22732	142373	5869.4
6	56	44.488	107	878	4	202081	1638194	7534.4
7	106	35.795	100	848	3	101371	879904	3044.6
8	116	41.572	40	370	4	47113	671393	4711.3
9	126	127.633	34	488	3	130124	1743908	10843.7
10	136	124.358	35	534	3	125246	1910897	10723.4
11	146	76.174	14	190	4	30502	409888	8529.2
12	156	22.409	16	220	4	14776	293316	3493.9
13	206	21.491	14	284	4	8931	174047	2434.3
14	216	54.143	12	246	4	18404	377231	6125.3
15	246	22.413	10	238	4	4607	132429	3241.8
16	306	38.704	10	150	9	22893	144423	9885.4
17	346	11.168	50	78	10	16977	24670	3162.8

Figure VII-13. Flow and Quality Data for Stevens Avenue Catchment (Single and Multi-Family Residential, Combined Sewers), Lancaster, Pennsylvania. Parameters are: Flow (cfs); BOD, TSS, NO_3-N concentration (mg/l); BOD, TSS and NO_3-N loads (mg/sec).

Figure VII-14. BOD Concentration Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

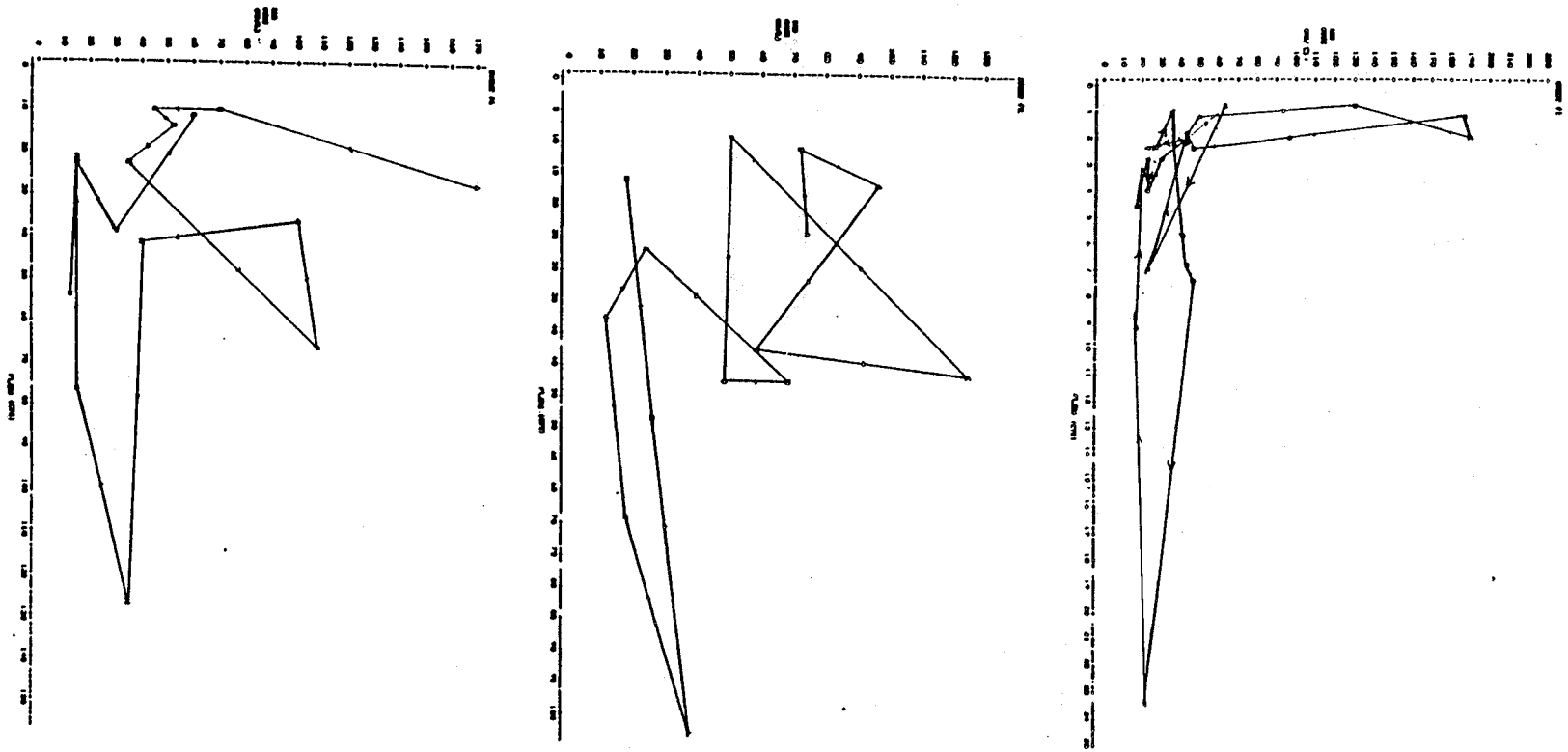


Figure VII-15. TSS Concentration Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

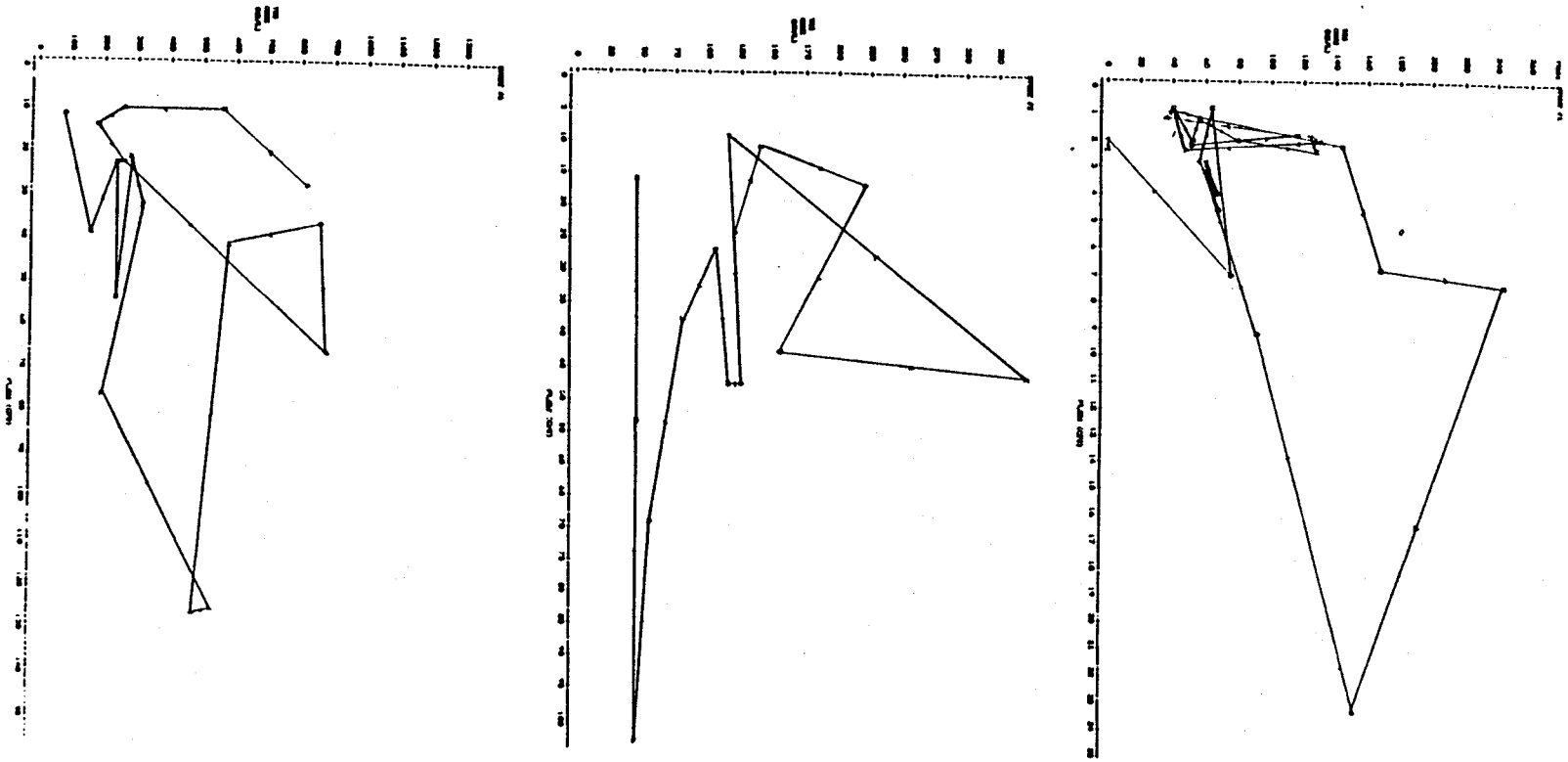


Figure VII-16. NO_3-N Concentration Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

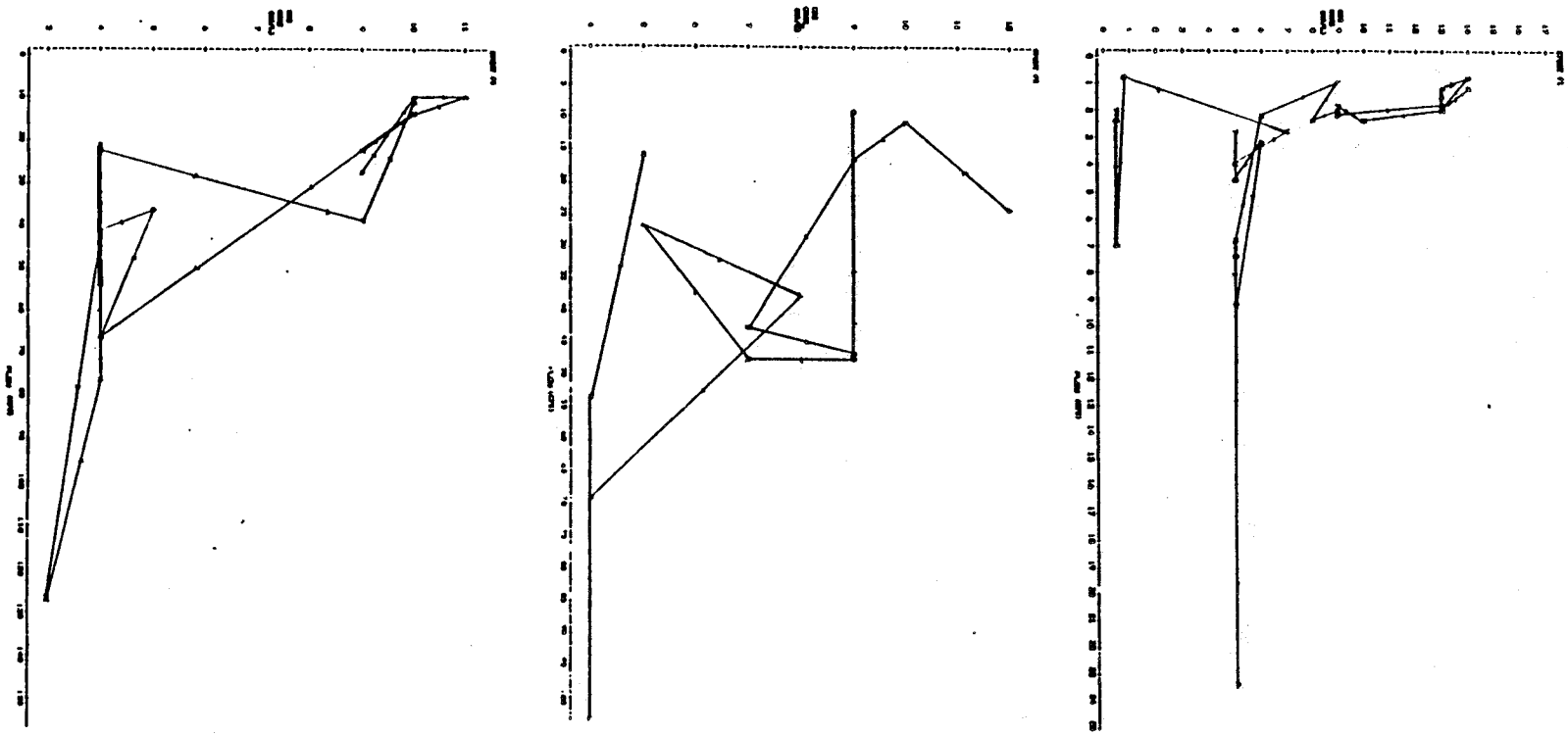


Figure VII-17. BOD Load Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

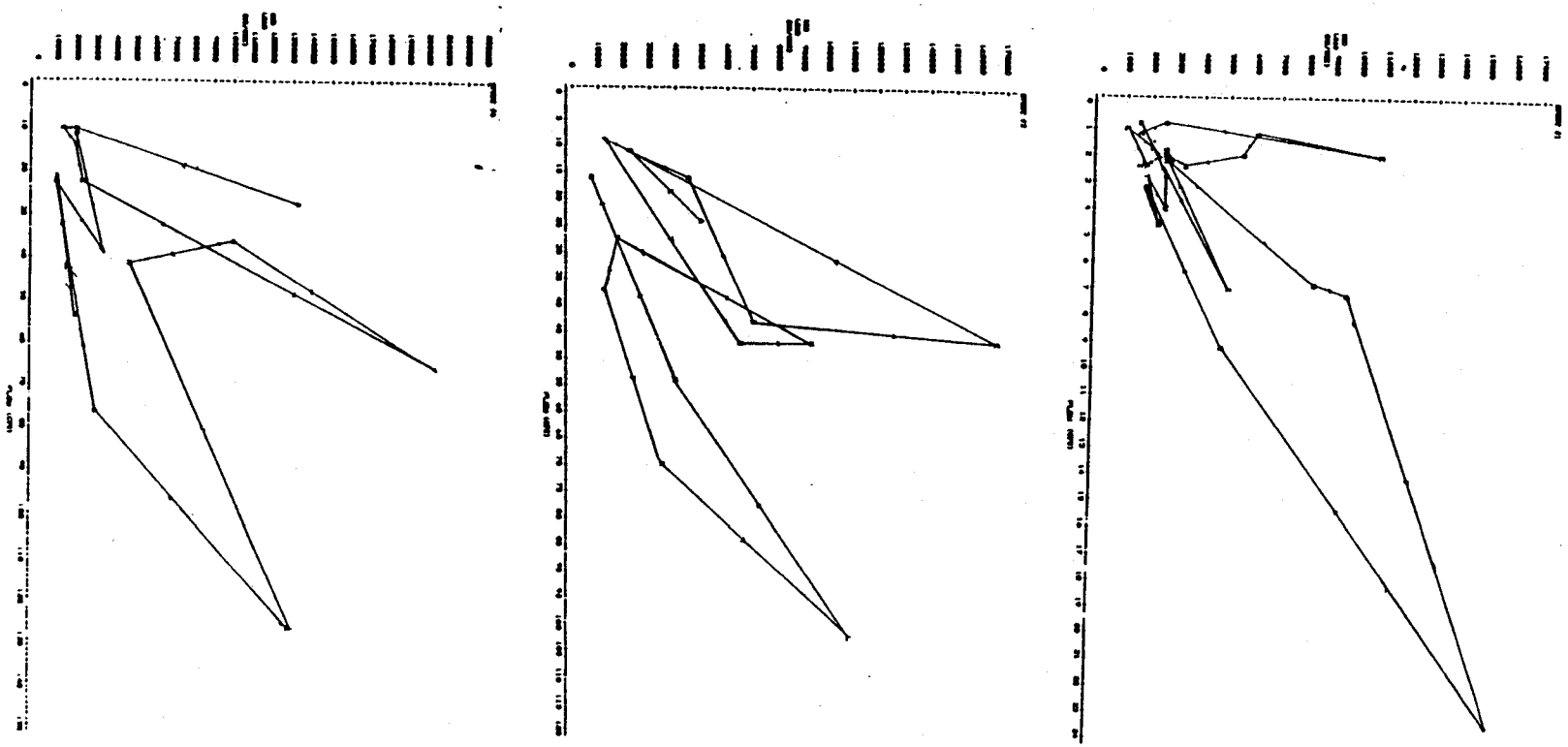


Figure VII-18. TSS Load Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

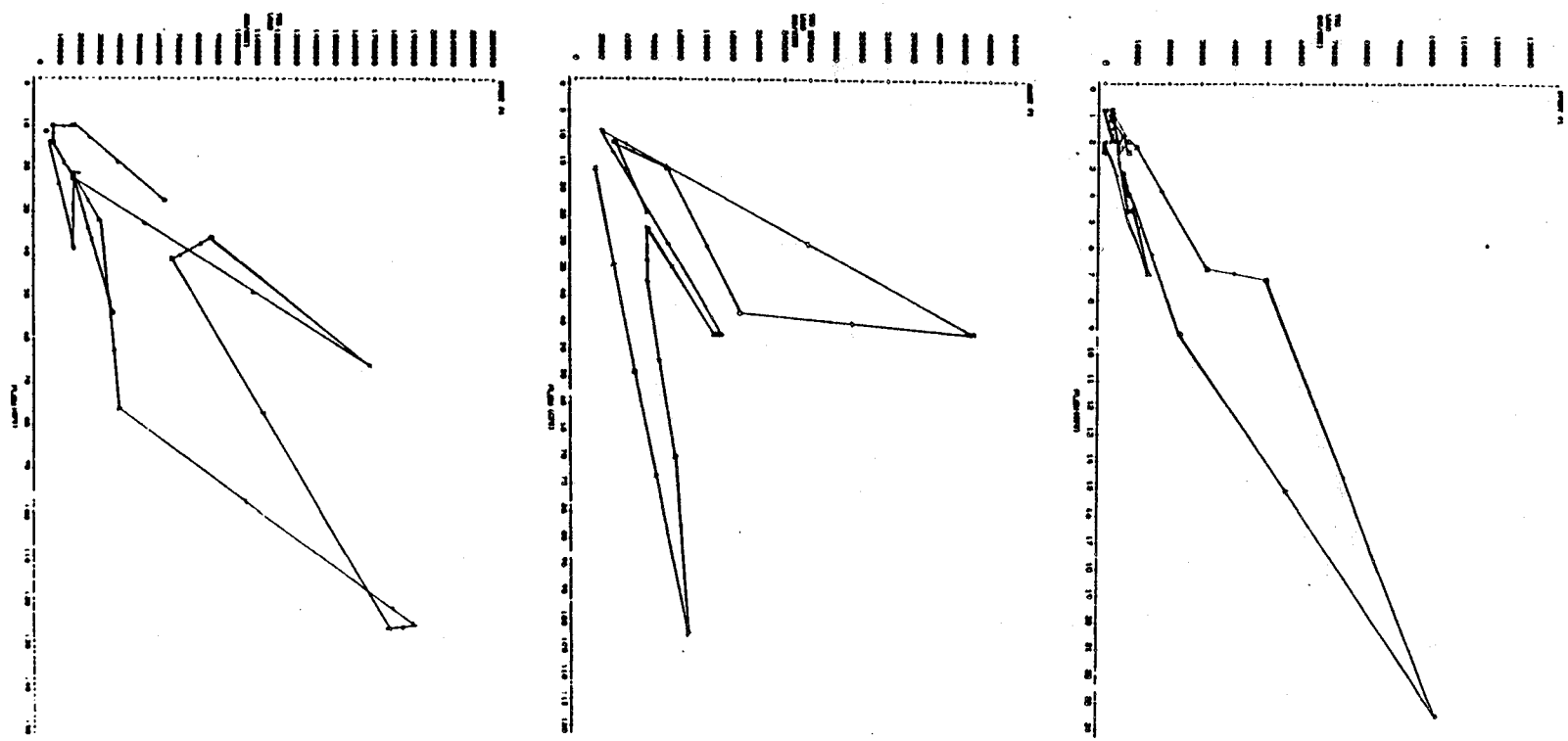


Figure VII-19. NO_3-N Load Vs. Flow, Event 1, Event 2, Event 6. Sequence of letters follows time history.

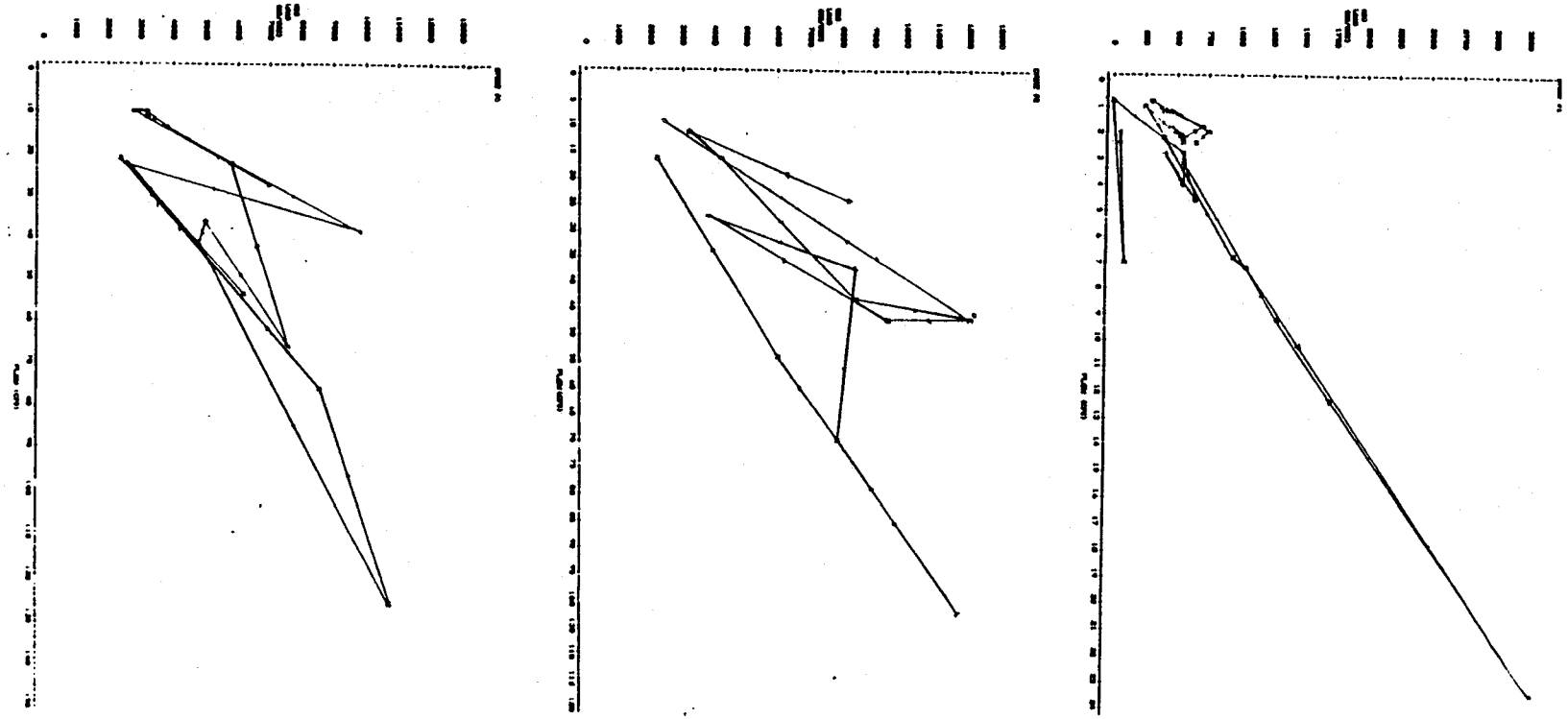


Figure VII-20. Log_{10} Concentration Vs. Log_{10} Flow for All Events, BOD, TSS, NO_3-N.
(1) Event 1, (2) Event 2, (3) Event 3, (4) Event 4, (5) Event 6.

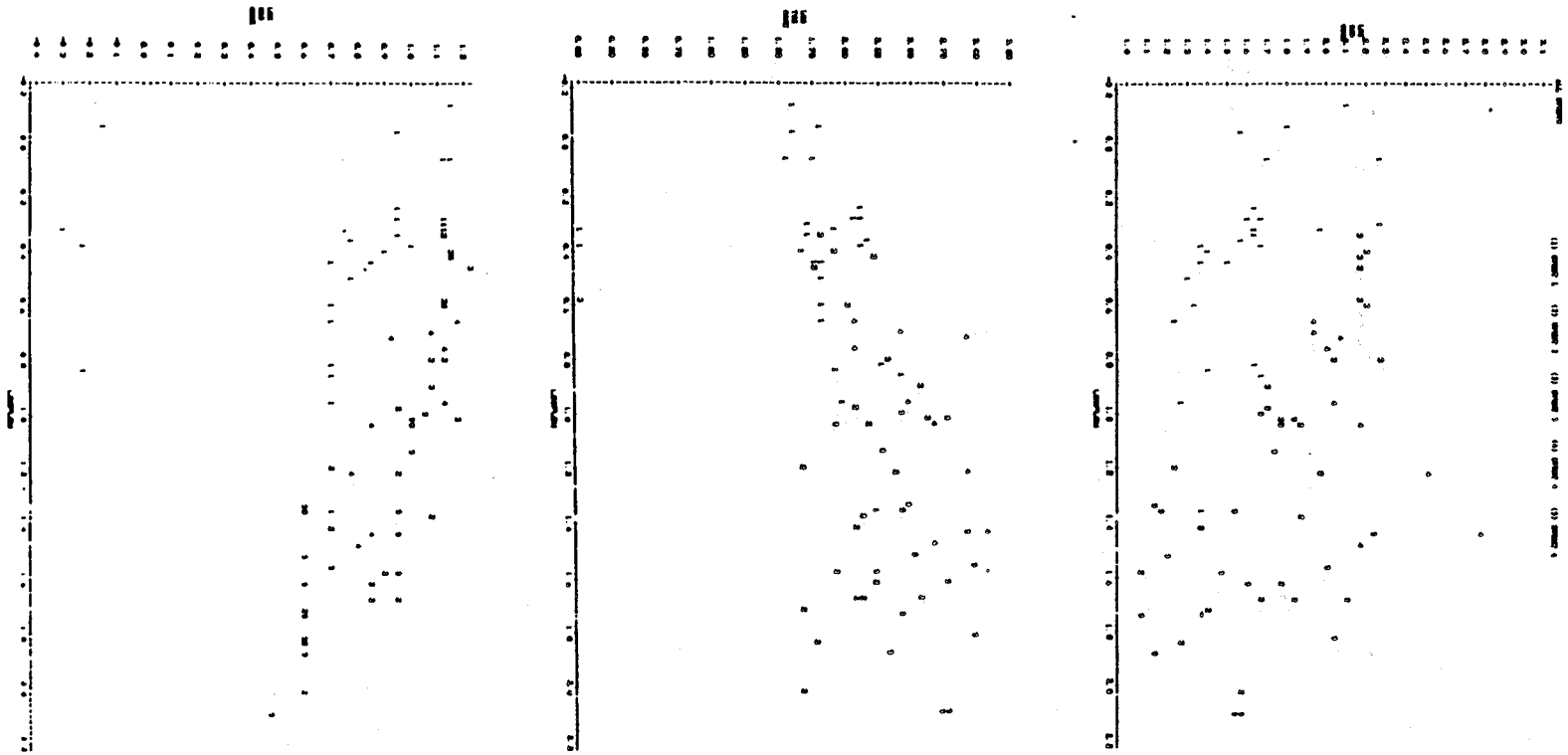
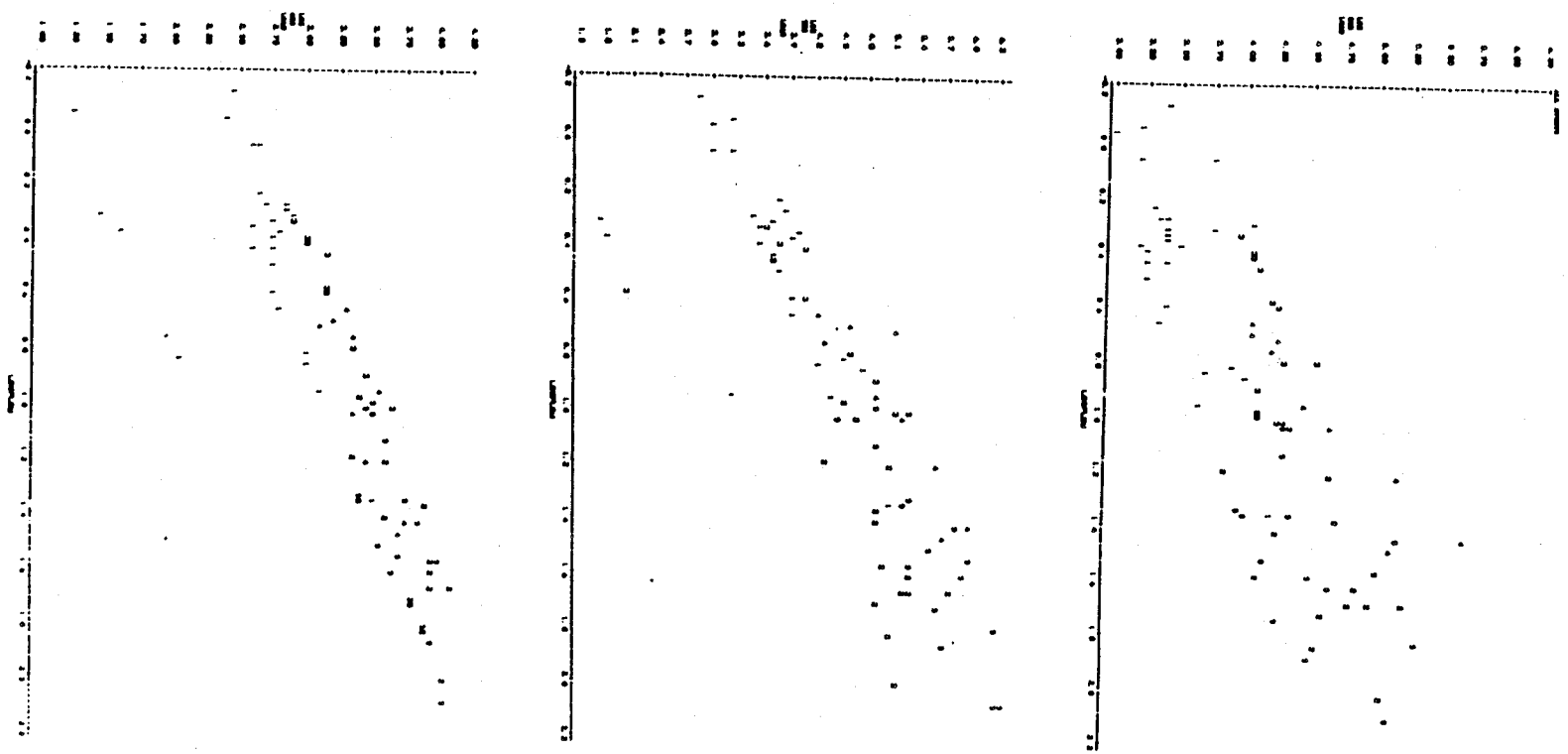


Figure VII-21. Log_{10}Load Vs. Log_{10}Flow for All Events, BOD, TSS, NO_3-N. (1) Event 1, (2) Event 2, (3) Event 3, (4) Event 4, (5) Event 6.



APPENDIX VIII

MISCELLANEOUS TRANSPORT BLOCK TABLES

The following tables provide guidelines for input into the infiltration (subroutine INFIL) and dry-weather flow (subroutine FILTH) routines of the Transport Block. Table VIII-1 gives average degree-days (cumulative deviation below 65°F, summed for the days of each month) for several U.S. cities. Current values are also tabulated in various summary forms by the National Weather Service.

Tables VIII-2 and VIII-3 provide guidelines for relative water use by various commercial establishments and industries. These may be entered as process flows in card groups P1 and Q1, for instance.

Table VIII-1. Average Monthly Degree-days for Cities in the United States (Base 65F).

State	Station	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Ala.	Anniston	0	0	17	118	438	614	614	485	381	128	25	0
	Birmingham	0	0	13	123	396	598	623	491	378	128	30	0
	Mobile	0	0	0	23	198	357	412	290	209	40	0	0
	Montgomery	0	0	0	55	267	458	483	360	265	66	0	0
Ariz.	Flagstaff	49	78	243	586	876	1135	1231	1014	949	687	465	212
	Phoenix	0	0	0	13	182	360	425	275	175	62	0	0
	Yuma	0	0	0	0	105	259	318	167	88	14	0	0
Ark.	Bentonville	1	1	38	216	516	810	879	716	519	247	86	7
	Fort Smith	0	0	9	131	435	698	775	571	418	127	24	0
	Little Rock	0	0	10	110	405	654	719	543	401	122	18	0
Calif.	Eureka	267	248	264	335	411	508	552	465	493	432	375	282
	Fresno	0	0	0	86	345	580	629	400	304	145	43	0
	Independence	0	0	28	216	512	778	799	619	477	267	120	18
	Los Angeles	0	0	17	41	140	253	328	244	212	129	68	19
	Needles	0	0	0	19	217	416	447	243	124	26	3	0
	Point Reyes	350	336	263	282	317	425	467	406	437	413	415	363
	Red Bluff	0	0	0	59	319	564	617	423	336	117	51	0
	Sacramento	0	0	17	75	321	567	614	403	317	196	85	5
	San Diego	11	7	24	52	147	255	317	247	223	151	97	43
	San Francisco	189	177	110	128	237	406	462	336	317	279	248	180
	San Jose	7	11	26	97	270	450	487	342	308	229	137	46
Colo.	Denver	0	5	103	385	711	958	1042	854	797	492	266	60
	Durango	25	37	201	535	861	1204	1271	1002	859	615	394	139
	Grand Junction	0	0	36	333	792	1132	1271	924	738	402	145	23
	Leadville	280	332	509	841	1139	1413	1470	1285	1245	990	740	434
	Pueblo	0	0	74	383	771	1051	1104	865	775	456	203	27
Conn.	Hartford	0	14	101	384	699	1082	1178	1050	871	528	201	31
	New Haven	0	18	93	363	663	1026	1113	1005	865	567	261	52
D. C.	Washington	0	0	32	231	510	831	884	770	606	314	80	0
Fla.	Apalachicola	0	0	0	17	154	304	352	263	184	33	0	0
	Jacksonville	0	0	0	11	129	276	303	226	154	14	0	0
	Key West	0	0	0	0	0	18	28	24	7	0	0	0
	Miami	0	0	0	0	5	48	57	48	15	0	0	0
	Pensacola	0	0	0	18	177	334	383	275	203	45	0	0
	Tampa	0	0	0	0	60	163	201	148	102	0	0	0
Ga.	Atlanta	0	0	8	107	387	611	632	515	392	135	24	0
	Augusta	0	0	0	59	282	494	521	412	308	62	0	0
	Macon	0	0	0	63	280	481	497	391	275	62	0	0
	Savannah	0	0	0	38	225	412	424	330	238	43	0	0
	Thomasville	0	0	2	48	208	361	359	299	178	52	5	1
Idaho	Boise	0	0	135	389	762	1054	1169	868	719	453	249	92
	Lewiston	0	0	133	406	747	961	1060	815	663	408	222	68
	Pocatello	0	0	183	487	873	1184	1333	1022	880	561	317	136
Ill.	Cairo	0	0	28	161	492	784	856	683	523	182	47	0
	Chicago	0	0	90	350	765	1147	1243	1053	868	507	229	58
	Peoria	0	11	86	339	759	1128	1240	1028	828	435	192	41
	Springfield	0	0	56	259	666	1017	1116	907	713	350	127	14
Ind.	Evansville	0	0	59	215	570	871	939	770	589	251	90	6
	Fort Wayne	0	17	107	377	759	1122	1260	1036	874	516	226	53
	Indianapolis	0	0	59	247	642	986	1051	893	725	375	140	16
	Royal Center	11	19	116	373	740	1104	1239	976	860	502	245	54
	Terre Haute	0	5	77	295	681	1023	1107	913	715	371	145	24

Table VIII-1. (continued)

State	Station	July	Aug.	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Iowa	Charles City	17	30	151	444	912	1352	1494	1240	1001	537	256	70
	Davenport	0	7	79	320	756	1147	1262	1044	834	432	175	35
	Des Moines	0	6	89	346	777	1178	1308	1072	849	425	183	41
	Dubuque	8	28	149	444	882	1290	1414	1187	983	543	267	76
	Keokuk	1	3	71	303	680	1077	1191	1025	761	397	136	18
	Sioux City	8	17	128	405	885	1290	1423	1170	930	474	228	54
Kan.	Concordia	0	0	55	277	687	1029	1144	899	725	341	146	20
	Dodge City	0	0	40	262	669	980	1076	840	694	347	135	15
	Iola	0	1	40	236	579	930	1026	817	599	282	98	8
	Topeka	0	0	42	242	630	977	1088	851	669	295	112	13
	Wichita	0	0	32	219	597	915	1023	778	619	280	101	7
Ky.	Louisville	0	0	41	206	549	849	911	762	605	270	86	0
	Lexington	0	0	56	259	636	933	1008	854	710	368	140	15
La.	New Orleans	0	0	0	5	141	283	341	223	163	19	0	0
	Shreveport	0	0	0	53	305	490	550	386	272	61	0	0
Me.	Eastport	141	136	261	521	798	1206	1333	1201	1063	774	524	288
	Greenville	69	113	315	642	1012	1464	1625	1443	1251	842	468	194
	Portland	15	56	199	515	825	1238	1373	1218	1039	693	394	117
Md.	Baltimore	0	0	29	207	489	812	880	776	611	326	73	0
Mass.	Boston	0	7	77	315	618	998	1113	1002	849	534	236	42
	Fitchburg	12	29	144	432	774	1139	1240	1137	940	572	254	70
	Nantucket	22	34	111	372	615	924	1020	949	880	642	394	139
Mich.	Alpena	50	85	215	530	864	1218	1358	1263	1156	762	437	135
	Detroit-Willow Run	0	10	96	393	759	1125	1231	1089	915	552	244	55
	Detroit City	0	8	96	381	747	1101	1203	1972	927	558	251	60
	Escanaba	62	95	247	555	933	1321	1473	1327	1203	804	471	166
	Grand Rapids	0	20	105	394	756	1107	1215	1086	939	546	248	58
	Houghton	70	94	268	582	965	1355	1535	1421	1251	820	474	195
	Lansing	13	33	140	455	813	1175	1277	1142	986	591	287	70
	Ludington	41	55	182	472	794	1135	1271	1183	1056	698	418	153
	Marquette	69	87	236	543	933	1299	1435	1291	1181	789	477	189
	Sault Ste. Marie	109	126	298	639	1005	1398	1587	1442	1302	846	499	224
Minn.	Duluth	66	91	277	614	1092	1550	1696	1448	1252	801	487	200
	Minneapolis	8	17	157	459	960	1414	1562	1310	1057	570	259	80
	Moorhead	20	47	240	607	1105	1609	1815	1555	1225	679	327	98
	St. Paul	12	21	154	459	951	1401	1553	1305	1051	564	256	77
Miss.	Corinth	0	1	13	142	418	669	696	570	396	149	32	1
	Meridian	0	0	0	90	338	528	561	413	309	85	9	0
	Vicksburg	0	0	0	51	268	456	507	374	273	71	0	0
Mo.	Columbia	0	6	62	262	654	989	1091	876	698	326	135	14
	Hannibal	1	3	66	288	652	1037	1139	980	710	374	128	15
	Kansas City	0	0	44	240	621	970	1085	851	666	292	111	8
	St. Louis	0	0	38	202	570	893	983	792	620	270	94	7
	Springfield	0	8	61	249	615	908	1001	790	632	295	118	16
Mont.	Billings	8	20	194	497	876	1172	1305	1089	958	564	304	119
	Harve	20	38	270	564	1023	1383	1513	1291	1076	597	313	125
	Helena	51	78	359	598	969	1215	1438	1114	992	660	427	225
	Kalispell	47	83	326	639	990	1249	1386	1120	970	639	391	215
	Miles City	6	11	187	525	966	1373	1516	1257	1048	570	285	106
	Missoula	22	57	292	623	993	1283	1414	1100	939	609	365	176
Neb.	Drexel	4	6	95	405	788	1271	1353	1096	843	493	219	38
	Lincoln	0	7	79	310	741	1113	1240	1000	794	377	172	32
	North Platte	7	11	120	425	846	1172	1271	1016	887	489	243	59
	Omaha	0	5	88	331	783	1166	1302	1058	831	389	175	32
	Valentine	11	10	145	461	891	1212	1361	1100	970	543	288	83

Table VIII-1. (continued)

State	Station	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Nev.	Reno	27	61	165	443	744	986	1048	804	756	519	318	165
	Tonopah	0	5	96	422	723	995	1082	860	763	504	272	91
	Winnemucca	0	17	180	508	822	1085	1153	854	794	546	299	111
N.H.	Concord	11	57	192	527	849	1271	1392	1226	1029	660	316	82
N.J.	Atlantic City	0	0	29	230	507	831	905	829	729	468	189	24
	Cape May	1	2	38	221	527	852	936	876	737	459	188	33
	Newark	0	0	47	301	603	961	1039	932	760	450	148	11
	Sandy Hook	1	2	40	268	579	921	1016	973	833	499	206	31
	Trenton	0	0	55	285	582	930	1004	904	735	429	133	11
N.M.	Albuquerque	0	0	10	218	630	899	970	714	589	289	70	0
	Roswell	0	0	8	156	501	750	787	566	443	185	28	0
	Santa Fe	12	15	129	451	772	1071	1094	892	786	544	297	60
N.Y.	Albany	0	6	98	388	708	1113	1234	1103	905	531	202	31
	Binghamton	0	36	141	428	735	1113	1218	1100	927	570	240	48
	Buffalo	16	30	122	433	753	1116	1225	1128	992	636	315	72
	Canton	27	61	219	550	898	1368	1516	1385	1139	695	340	107
	Ithaca	17	40	156	451	770	1129	1236	1156	978	606	292	83
	New York	0	0	31	250	552	902	1001	910	747	435	130	7
	Oswego	20	39	139	430	738	1132	1249	1134	995	654	355	90
	Rochester	9	34	133	440	759	1141	1249	1148	992	615	289	54
	Syracuse	0	29	117	396	714	1113	1225	1117	955	570	247	37
N.C.	Asheville	0	0	50	262	552	769	794	678	572	285	105	5
	Charlotte	0	0	7	147	438	682	704	577	449	172	29	0
	Hatteras	0	0	0	63	244	481	527	487	394	171	25	0
	Manteo	0	0	7	113	358	595	642	594	469	249	75	7
	Raleigh	0	0	10	118	387	651	691	577	440	172	29	0
	Wilmington	0	0	0	73	288	508	533	463	347	104	7	0
N.D.	Bismarck	29	37	227	598	1098	1535	1730	1464	1187	657	355	116
	Devils Lake	47	61	276	654	1197	1558	1866	1576	1314	750	394	137
	Grand Forks	32	60	274	663	1160	1681	1895	1608	1298	718	359	123
	Williston	29	42	261	605	1101	1528	1705	1442	1194	663	360	138
Ohio	Cincinnati	0	0	42	222	567	880	942	812	645	314	108	0
	Cleveland	0	9	60	311	636	995	1101	977	846	510	223	49
	Columbus	0	0	59	299	654	983	1051	907	741	408	153	22
	Dayton	0	5	74	324	693	1032	1094	941	781	435	179	39
	Sandusky	0	0	66	327	684	1039	1122	997	853	513	217	41
	Toledo	0	12	102	387	756	1119	1197	1056	905	555	245	60
Okla.	Broken Arrow	0	0	28	169	513	805	881	646	506	212	61	5
	Oklahoma City	0	0	12	149	459	747	843	630	472	169	38	0
Ore.	Baker	25	47	255	518	852	1138	1268	972	837	591	384	200
	Medford	0	0	77	326	624	822	862	627	552	381	207	69
	Portland	13	14	85	280	534	701	791	594	515	347	199	70
	Roseburg	14	10	98	288	531	694	744	563	508	366	223	83
Pa.	Erie	0	17	76	352	672	1020	1128	1039	911	573	273	55
	Harrisburg	0	0	69	308	630	964	1051	921	750	423	128	14
	Philadelphia	0	0	33	219	516	856	933	837	667	369	93	0
	Pittsburgh	0	0	56	298	612	924	992	879	735	402	137	13
	Reading	0	5	57	285	588	936	1017	902	725	411	123	11
	Scranton	0	18	115	389	693	1057	1141	1028	849	516	196	35
R.I.	Block Island	6	21	88	330	591	927	1026	955	865	603	335	96
	Narragansett Pier	1	26	121	366	691	1012	1113	1074	916	622	342	113
	Providence	0	7	68	330	624	986	1076	972	809	507	197	31
S.C.	Charleston	0	0	0	34	214	410	445	363	260	43	0	0
	Columbia	0	0	0	76	308	524	538	443	318	77	0	0
	Due West	0	0	9	142	393	594	651	491	411	158	39	2
	Greenville	0	0	10	131	411	648	673	552	442	161	32	0

Table VIII-1. (continued)

State	Station	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
S.D.	Huron	10	16	149	472	975	1407	1597	1327	1032	558	279	80
	Pierre	4	11	136	438	887	1317	1460	1253	971	516	233	52
	Rapid City	32	24	193	500	891	1218	1361	1151	1045	615	357	148
Tenn.	Chattanooga	0	0	24	169	477	710	725	588	467	179	45	0
	Knoxville	0	0	33	179	498	744	760	630	500	196	50	0
	Memphis	0	0	13	98	392	639	716	574	423	131	20	0
	Nashville	0	0	22	154	471	725	778	636	498	186	43	0
Texas	Abilene	0	0	5	98	350	595	673	479	344	113	0	0
	Amarillo	0	0	37	240	594	859	921	711	586	298	99	0
	Austin	0	0	0	30	214	402	484	322	211	50	0	0
	Brownsville	0	0	0	0	59	159	219	106	74	0	0	0
	Corpus Christi	0	0	0	0	113	252	330	192	118	6	0	0
	Dallas	0	0	0	53	299	518	607	432	288	75	0	0
	Del Rio	0	0	0	26	188	371	419	235	147	21	0	0
	El Paso	0	0	0	70	390	626	670	445	330	110	0	0
	Fort Worth	0	0	0	58	299	533	622	446	308	90	5	0
	Galveston	0	0	0	0	131	271	356	247	176	30	0	0
	Houston	0	0	0	0	162	303	378	240	166	27	0	0
	Palestine	0	0	0	45	260	440	531	368	265	71	0	0
	Port Arthur	0	0	0	8	170	315	381	258	181	27	0	0
	San Antonio	0	0	0	25	201	374	462	293	190	34	0	0
	Taylor	0	0	2	56	234	462	494	375	214	64	8	0
Utah	Modena	6	11	156	499	832	1142	1190	944	816	567	338	97
	Salt Lake City	0	0	61	330	714	995	1119	857	701	414	208	64
Vt.	Burlington	19	47	172	521	858	1308	1460	1313	1107	681	307	72
	Northfield	62	112	283	602	947	1389	1524	1384	1176	754	405	166
Va.	Cape Henry	0	0	0	120	366	648	698	636	512	267	60	0
	Lynchburg	0	0	49	236	531	809	846	722	584	289	82	5
	Norfolk	0	0	5	118	354	636	679	602	464	220	41	0
	Richmond	0	0	31	181	456	750	787	695	529	254	57	0
	Wytheville	7	13	82	352	662	916	945	836	677	410	168	35
Wash.	North Head L.H. Reservation	239	205	234	341	486	636	704	585	598	492	406	285
	Seattle	49	45	134	329	540	679	753	602	558	396	246	107
	Spokane	17	28	205	508	879	1113	1243	988	834	561	330	146
	Tacoma	66	62	177	375	579	719	797	636	595	435	282	143
	Tatoosh Island	295	288	315	406	528	648	713	610	629	525	437	330
	Walla Walla	0	0	93	308	675	890	1023	748	564	338	171	38
	Yakima	0	7	150	446	807	1066	1181	862	660	408	205	53
W.Va.	Elkins	9	31	122	412	726	995	1017	910	797	477	224	53
	Parkersburg	0	0	56	272	600	896	949	826	672	347	119	13
Wis.	Green Bay	32	58	183	515	945	1392	1516	1336	1132	696	347	107
	La Crosse	11	20	152	447	921	1380	1528	1280	1035	552	250	74
	Madison	10	30	137	419	864	1287	1417	1207	1011	573	266	79
	Milwaukee	11	24	112	397	795	1184	1302	1117	961	606	335	100
	Wausau	26	58	216	568	982	1427	1594	1381	1147	680	315	100
Wyo.	Cheyenne	33	39	241	577	897	1125	1225	1044	1029	717	315	100
	Lander	7	23	244	632	1050	1383	1494	1179	1045	687	396	163
	Yellowstone Park	125	173	424	759	1079	1386	1464	1252	1165	841	603	334

Source: American Society of Heating and Air Conditioning Engineers, "Heating, Ventilating, Air Conditioning Guide," Annual Publication.

Table VIII-2. Guide for Establishing Water Usage in Commercial Subareas.

Commercial category	Parameter	Coefficients, mean annual water use, gpd/unit of parameter
Barber Shops	Barber Chair	97.5
Beauty Shops	Station	532.0
Bus-Rail Depots	Sq ft	5.0
Car Washes	Inside Sq ft	4.78
Churches	Member	0.14
Golf-Swim Clubs	Member	33.3-100.0
Bowling Alleys	Alley	200.0
Colleges Resid.	Student	179.0
Hospitals	Bed	150.0-559.0
Hotels	Sq ft	0.256
Laundromats	Sq ft	6.39
Laundries	Sq ft	0.64
Medical Offices	Sq ft	0.62
Motels	Sq ft unit	0.33
Drive-In Movies	Car Stall	8.0
Nursing Homes	Bed	75.0-209.0
New Office Bldgs.	Sq ft	0.16
Old Office Bldgs.	Sq ft	0.27
Jails and Prisons	Occupant Person	10.0-15.0 200.0
Restaurants	Seat	10.0-90.0
Drive-In Restaurants	Car Stalls	109.0

Table VIII-2. (continued)

Commercial category	Parameter	Coefficients, mean annual water use, gpd/unit of parameter
Night Clubs	Person Served	2.0
Retail Space	Sale Sq ft	0.16
Schools, Elementary	Student	6.0-15.0
Schools, High	Student	10.0-19.9
YMCA-YWCA	Person	50.0
Service Stations	Inside Sq ft	0.49
Theaters	Employee	30.0
	Seat	5.0
Apartments	Dwelling Unit	50.0-195.0
Shopping Centers	Sq ft	0.20

Sources: Hittman Associates, Inc., "A System for Calculating and Evaluating Municipal Water Requirements"; and F. P. Linaweaver and J. C. Geyer, "Commercial Water Use Project," Johns Hopkins University, Baltimore, Maryland.

Table VIII-3. Guide for Establishing Water Usage in Industrial Subareas.

Industrial category	Standard Industrial Classification Number	Mean Annual Usage Coefficients gpd/employee
Meat Products	201	903.890
Dairies	202	791.350
Can, Frozen Food	203	784.739
Grain Mills	204	488.249
Bakery Products	205	220.608
Sugar	206	1433.611
Candy	207	244.306
Beverages	208	1144.868
Miscellaneous Foods	209	1077.360
Cigarettes	211	193.613
Weaving, Cotton	221	171.434
Weaving, Synthetics	222	344.259
Weaving, Wool	223	464.439
Knitting Mills	225	273.429
Textile Finish	226	810.741
Floor Covering	227	297.392
Yarn-Thread Mill	228	63.558
Miscellaneous Textile	229	346.976
Whl. Apparel Industry	230	20.000
Saw-Planning Mill	242	223.822
Millwork	243	316.420
Wood Containers	244	238.000
Miscellaneous Wood	249	144.745
Home Furniture	251	122.178
Furniture Fixture	259	122.178
Pulp Mills	261	13494.110
Paper Mills	262	2433.856
Paperboard Mills	263	2464.478
Paper Products	264	435.790
Paperboard Boxes	265	154.804
Building Paper Mills	266	583.355
Whl. Print Industry	270	15.000
Basic Chemicals	281	2744.401
Fibers, Plastic	282	864.892
Drugs	283	457.356
Soap-Toilet Goods	284	672.043
Paint Allied Products	285	845.725
Gum-Wood Chemicals	286	332.895
Agricultural Chem.	287	449.836
Miscellaneous Chemicals	289	984.415

Table VIII-3. (continued)

Industrial category	Standard Industrial Classification Number	Mean Annual Usage Coefficients gpd/employee
Petroleum Refining	291	3141.100
Paving-Roofing	295	829.592
Tires, Tubes	301	375.211
Rubber Footware	302	82.592
Reclaimed Rubber	303	1031.523
Rubber Products	306	371.956
Plastic Products	307	527.784
Leather Tanning	311	899.500
Flat Glass	321	590.140
Pressed, Blown Glassware	322	340.753
Products of Purchased Glass	323	872.246
Cement, Hydraulic	324	279.469
Structural Clay	325	698.197
Pottery Products	326	326.975
Cement, Plaster	327	353.787
Cut Stone Products	328	534.789
Non-Metallic Mineral	329	439.561
Steel-Rolling	331	494.356
Iron, Steel Foundries	332	411.052
Prime Non-Ferrous	333	716.626
Secondary Non-Ferrous	334	1016.596
Non-Ferrous Rolling	335	675.475
Non-Ferrous Foundries	336	969.586
Prime Metal Industries	339	498.331
Metal Cans	341	162.547
Cutlery, Hardware	342	459.300
Plumbing, Heating	343	411.576
Structure, Metal	344	319.875
Screw Machine	345	433.193
Metal Stamping	346	463.209
Metal Service	347	1806.611
Fabricated Wire	348	343.367
Fabricated Metal	349	271.186
Engines, Turbines	351	197.418
Farm Machinery	352	320.704
Construction Equipment	353	218.365

Table VIII-3. (continued)

Industrial category	Standard Industrial Classification Number	Mean Annual Usage Coefficients gpd/employee
Metalwork, Machinery	354	196.255
Special Industry Machinery	355	290.494
General Industrial Machinery	356	246.689
Office Machines	357	138.025
Service Industrial Machine	358	334.203
Miscellaneous Machines	359	238.839
Electric Distribution Products	361	272.001
Electric Industrial Apparatus	362	336.016
Home Appliances	363	411.914
Light-Wiring Fixtures	364	369.592
Radio TV Receiving	365	235.763
Communication Equipment	366	86.270
Electronic Comp.	367	203.289
Electric Product	369	393.272
Motor Vehicles	371	318.233
Aircraft and Parts	372	154.769
Ship and Boat Building	373	166.074
Railroad Equipment	374	238.798
Motorcycle, Bike	375	414.858
Scientific Instruments	381	181.007
Mechanical Measure	383	237.021
Medical Instrument	384	506.325
Photo Equipment	386	120.253
Watches, Clocks	387	164.815
Jewelry, Silver	391	306.491
Toys, Sport Goods	394	213.907
Costume Jewelry	396	423.124
Miscellaneous Manufacturing	398	258.270
Miscellaneous Manufacturing	399	258.270

Source: Hittman Associates, Inc., "A System for Calculating and Evaluating Municipal Water Requirements".

APPENDIX IX

INTEGRATED FORM OF COMPLETE MIXING QUALITY ROUTING

Quality routing in the Transport and Runoff Blocks through conduit segments has long been accomplished by assuming complete mixing within the conduit in the manner of a continuously stirred tank reactor or "CSTR." The procedure is described in the original SWMM documentation (Metcalf and Eddy et al., 1971a, Appendix B) and was very similar to the complete mixing formulation of the Storage/Treatment Block. See, for example, the discussion of equations IV-9, IV-10 and IV-11 in Appendix IV. For the finite difference scheme of equation IV-11, however, it may easily be shown that negative concentrations may be predicted if

$$\Delta t > \frac{2V}{Q} \qquad \text{(IX-1)}$$

where Δt = time step, sec,
V = average volume in the conduit or storage unit, ft^3, and
Q = average flow through the conduit or storage unit, cfs.

This rarely causes a problem for storage unit simulation due to their large volumes. But when long time steps (e.g., 1 hr) are used in Runoff or Transport, instabilities in the predicted concentrations may arise.

These may readily be avoided with minimal loss of accuracy by using the integrated form of the solution to the differential equation. The procedure is described by Medina et al. (1981) and is outlined below as applied to the Runoff and Transport Blocks.

The governing differential equation for a completely mixed volume is

$$\frac{dVC}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} = Q_i C_i - QC - KCV + L \qquad \text{(IX-2)}$$

where C = concentration in effluent and in the mixed volume, e.g., mg/l,
V = volume, ft^3,
Q_i = inflow rate, cfs,
C_i = concentration of influent, e.g., mg/l,
Q = outflow rate, cfs,
K = first order decay coefficient, 1/sec, and
L = source (or sink) of pollutant to the mixed volume, mass/time, e.g., cfs·mg/l.

An analytical solution of this equation is seldom possible when Q, Q_i, C_i, V and L vary arbitrarily with time, as in the usual routing through conduits. However, a simple solution is available to the ordinary, first order differential equation with constant coefficients if parameters Q, Q_i, C_i, V, L and dV/dt are assumed to be constant over the solution time interval, t to t + Δt. In practice, average values over the time interval are used at each time step. Equation IX-2 is then readily integrated over the time interval t to t + Δt with

$$C(0) = C(t) \tag{IX-3}$$

to yield

$$C(t+\Delta t) = \left(\frac{\frac{Q_i C_i + L}{V}}{DENOM}\right)\left(1 - e^{-DENOM \cdot \Delta t}\right) + C(t)\ e^{-DENOM \cdot \Delta t} \tag{IX-4}$$

where $$DENOM = Q/V + K + \frac{1}{V}\, dV/dt \tag{IX-5}$$

Thus, the concentration at the end of the time step is predicted as the sum of a weighted inflow concentration and a decaying concentration from the previous time step.

Equation IX-4 is used in both the Runoff and Transport Block and is completely stable with respect to changes in Δt. It does not reflect rapid changes in volume and flow as well as the finite difference solution (e.g., equation IV-11) but it is updated at each time step. Given the many other uncertainties of quality routing within the sewer system, it should be adequate.

APPENDIX X

SUBSURFACE FLOW ROUTING IN RUNOFF BLOCK

INTRODUCTION

Because SWMM was originally developed to simulate combined sewer overflows in urban catchments, the fate of infiltrated water was considered insignificant. Since its development, however, SWMM has been used on areas ranging from highly urban to relatively undeveloped. Many of the undeveloped and even some of the developed areas, especially in areas like South Florida, are very flat with high water tables, and their primary drainage pathway is through the surficial groundwater aquifer and the unsaturated zone above it, rather than by overland flow. In these areas a storm will cause a rise in the water table and subsequent slow release of groundwater back to the receiving water (Capece et al., 1984). For this case, the fate of the infiltrated water is highly significant. By assuming that the infiltration is lost from the system, an important part of the high-water-table system is not being properly described (Gagliardo, 1986).

It is known that groundwater discharge accounts for the time-delayed recession curve that is prevalent in certain watersheds (Fetter, 1980). This process has not, however, been satisfactorily modeled by surface runoff methods alone. By modifying infiltration parameters to account for subsurface storage, attempts have been made to overcome the fact that SWMM assumes infiltration is lost from the system (Downs et al., 1986). Although the modeled and measured peak flows matched well, the volumes did not match well, and the values of the infiltration parameters were unrealistic. Some research on the nature of the soil storage capacity has been done in South Florida (SFWMD, 1984). However, it was directed towards determining an initial storage capacity for the start of a storm. There remains no standard, widely-used method for combining the groundwater discharge hydrograph with the surface runoff hydrograph and determining when the water table will rise to the surface. For instance, HSPF (Johansen et al., 1980) performs extensive subsurface moisture accounting and works well during average conditions. However, the model never permits the soil to become saturated so that no more infiltration is permitted, limiting its usefulness during times of surface saturation and flooding. Another difficulty with HSPF occurs during drought conditions, since there is no threshold saturated zone water storage (corresponding to the bottom of a stream channel) below which no saturated zone outflow will occur. These difficulties have limited HSPF usefulness for application to extreme hydrologic conditions in Florida (Heaney et al., 1986).

In order to incorporate subsurface processes into the simulation of a watershed and overcome previously mentioned shortcomings, SWMM has been

equipped with a simple groundwater subroutine. The remainder of this appendix will describe the theory, use, and some limitations of the subroutine.

THEORY

Introduction

An effort was made to utilize existing theoretical formulations for as many processes as possible. The purpose was to maintain semblance to the real world while enabling the user to determine parameter values that have meaning to the soil scientist. Also, in the following discussion the term "flow" will refer to water that is passed on to another part of the system, and the term "loss" will refer to water that is passed out of the system. In addition, in the groundwater subroutines, flows and losses have internal units of velocity (flow per unit area).

The groundwater subroutine, GROUND, simulates two zones -- an upper (unsaturated) zone and a lower (saturated) zone. This configuration is similar to the work done by Dawdy and O'Donnell (1965) for the USGS. The flow from the unsaturated to the saturated zone is controlled by a percolation equation for which parameters may either be estimated or calibrated, depending on the availability of the necessary soil data. Upper zone evapotranspiration is the only loss from the unsaturated zone. The only inflow to subroutine GROUND is the calculated infiltration from subroutine WSHED. Losses and outflow from the lower zone can be via deep percolation, saturated zone evapotranspiration, and groundwater flow. Groundwater flow is a user-defined power function of water table stage and, if chosen, depth of water in the discharge channel.

Continuity

The physical processes occurring within each zone are accounted for by individual mass balances in order to determine end-of-time-step stage, groundwater flow, deep percolation, and upper zone moisture. Parameters are shown in Figure X-1 and defined below. Mass balance in the upper (unsaturated) zone is given by,

$$TH2 = \{[(ENFIL-ETU)\cdot PAREA-PERC]\cdot DELT+(D1-D2)\cdot TH2+TH\cdot DWT1\}/(DTOT-D2) \qquad (X-1)$$

In the lower (saturated) zone, for rising water tables,

$$D2 = \{[PERC-ETD\cdot PAREA-.5\cdot(GWFLW+A1\cdot(D2-BC)^{B1}+A3\cdot D2\cdot TW+DEPPRC+DP\cdot D2/DTOT) -TWFLW]\cdot DELT+(D2-D1)\cdot(TH-TH2)\}/(PR-TH2) + D1 \qquad (X-2)$$

and for falling water tables,

$$D2 = \{[PERC-ETD\cdot PAREA-.5\cdot(GWFLW+A1\cdot(D2-BC)^{B1}+A3\cdot D2\cdot TW+DEPPRC+DP\cdot D2/DTOT) -TWFLW]\cdot DELT\}/(PR-TH2) + D1 \qquad (X-3)$$

where TH2 = end-of-time-step upper zone moisture content (fraction),
ENFIL = infiltration rate calculated in subroutine WSHED,
ETU = upper zone evapotranspiration rate,
PERC = percolation rate,

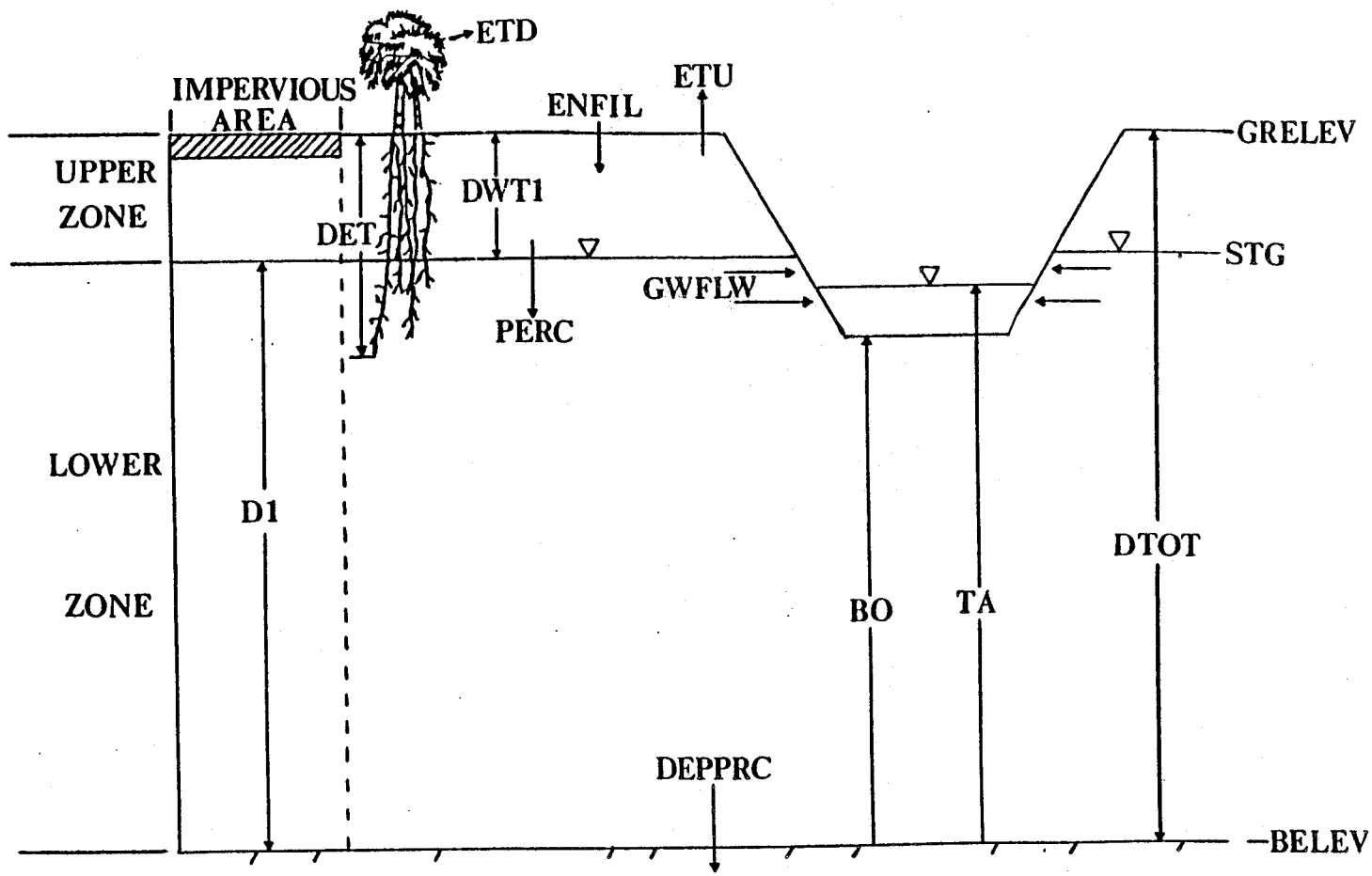


Figure X-1. GROUND Parameters and Conceptualization.

PAREA = pervious area divided by total area,
DELT = time step value,
D1 = beginning-of-time-step lower zone depth (elevation above a datum),
D2 = end-of-time-step lower zone depth,
TH = beginning-of-time-step upper zone moisture content,
DWT1 = beginning-of-time-step upper zone depth,
DTOT = total depth of upper and lower zone = D1+DWT1,
ETD = lower zone evapotranspiration rate,
GWFLW = beginning-of-time-step groundwater flow rate,
A1 = groundwater flow coefficient,
BC = bottom of channel depth (elevation above datum),
B1 = groundwater flow exponent,
DEPPRC = beginning-of-time-step deep percolation rate,
DP = a recession coefficient derived from interevent declines in the water table,
PR = porosity, and
TWFLW = channel water influence rate,
A3 = groundwater flow coefficient, and
TW = depth of water in channel (elevation above datum).

Moisture content (a fraction) is defined as the volume of moisture divided by the volume of solids plus voids. The maximum possible moisture content is the porosity; the minimum is the wilting point (discussed below). Solving equation X-1 for TH2 and using DWT1 = DTOT-D1, yields a much simpler form which is not a function of the unknown D2,

$$TH2 = [(ENFIL-ETU)\cdot PAREA-PERC]\cdot DELT/DWT1 + TH \qquad (X-4)$$

Equation X-4 is solved first, followed by a Newton-Raphson solution of equation X-2 or X-3. The sequencing will be described in more detail in a subsequent section, following a description of the various simulated processes.

Infiltration

Infiltration enters subroutine GROUND as the calculated infiltration from subroutine WSHED. As before in SWMM, either the Horton or Green-Ampt equation can be used to describe infiltration. For time steps where the water table has risen to the surface, the amount of infiltration that cannot be accepted is subtracted from RLOSS (infiltration plus surface evaporation) in subroutine WSHED. In the event that the infiltrated water is greater than the amount of storage available for that time step, the following equation is used to calculate the amount of infiltration that is not able to be accepted by the soil.

$$XSINFL = ENFIL\cdot DELT-AVLVOL/PAREA \qquad (X-5)$$

where XSINFL = excess infiltration over pervious area, and
AVLVOL = initial void volume in the upper zone plus total losses and outflows from the system for the time step.

The second condition exists because of the algebra in equations X-2, X-3 and X-4. As the water table approaches the surface, the end-of-time-step

moisture value, TH2, approaches the value of porosity, which makes the denominator in equations X-2 and X-3 go towards zero. Since a denominator close to zero could result in an unrealistic value of D2, a different way of handling the calculations had to be implemented. When the initial available volume in the upper zone plus the volume of total outflows and losses from the system minus the infiltration volume is between zero and an arbitrary value of 0.0001 ft, several assumptions are made. First, end-of-time-step groundwater flow and deep percolation, which are normally found by iteration, are assumed to be equal to their respective beginning-of-time-step values. This step is taken to ensure that the final available volume remains in the previously mentioned range. Second, TH2 is set equal to an arbitrary value of 90% of porosity. It is believed that this will allow the TH2 value in this special case to be reasonably consistent with the TH2 values juxtaposed to it in the time series. Third, D2 is set close to the total depth -- the actual value of D2 depends on the value of porosity. Fourth, the amount of infiltration that causes the final available volume to exceed 0.0001 ft is calculated in the following equation and sent back to the surface in the form of a reduction in the term RLOSS in subroutine WSHED.

```
XSINFL = ENFIL*DELT+(.0001-AVLVOL)/PAREA                    (X-6)
```

Because of the way this special case is handled, it is possible for a falling water table to have the calculated excess infiltration be greater than the actual amount of infiltration. It is not desirable for the ground to pump water back onto the surface! Hence, the difference between the calculated excess infiltration and the actual infiltration is added to the infiltration value of the next time step. The number of occurrences of this situation in a typical run is very small, as is the computed difference that is passed to the next time step, so no problems should occur because of this solution.

Upper Zone Evapotranspiration

Evapotranspiration from the upper zone (ETU) represents soil moisture lost via cover vegetation and by direct evaporation from the pervious area of the subcatchment. No effort was made to derive a complex formulation of this process. The hierarchy of losses by evapotranspiration is as follows: 1) surface evaporation, 2) upper zone evapotranspiration, and 3) lower zone transpiration. Upper zone evapotranspiration is represented by the following equations,

```
ETMAX = VAP(MONTH)                                          (X-7)
ETAVLB = ETMAX-EVAPO                                        (X-8)
ETU = CET*ETMAX                                             (X-9)
IF(TH.LT.WP.OR.ENFIL.GT.0.) ETU = 0.                       (X-10)
IF(ETU.GT.ETAVLB) ETU = ETAVLB                             (X-11)
```

where ETMAX = maximum total evapotranspiration rate (input on card F1),
VAP(MONTH) = input maximum evapotranspiration rate for month MONTH,
ETAVLB = maximum upper zone evapotranspiration rate,
EVAPO = portion of ETMAX used by surface water evaporation,
CET = fraction of evapotranspiration apportioned to upper zone, and
WP = wilting point of soil.

The two conditions that make ETU equal to zero in equation X-10 are believed to simulate the processes actually occurring in the natural system. The first condition (moisture content less than wilting point) relates to the soil science interpretation of wilting point -- the point at which plants can no longer extract moisture from the soil. The second condition (infiltration greater than zero) assumes that vapor pressure will be high enough to prevent additional evapotranspiration from the unsaturated zone.

Lower Zone Evapotranspiration

Lower zone evapotranspiration, ETD, represents evapotranspiration from the saturated zone over the pervious area. ETD is the last evapotranspiration removed, and is determined by the following depth-dependent equation and conditions.

```
ETD = (DET-DWT1)*ETMAX*(1-CET)/DET                          (X-12)
IF(ETD.GT.(ETAVLB-ETU)) ETD = ETAVLB-ETU                    (X-13)
IF(ETD.LT.0.) ETD = 0.                                      (X-14)
```

where ETD = lower zone evapotranspiration rate, and
DET = depth over which evapotranspiration can occur.

Since ETD is typically very small compared to other terms and has to be checked for certain conditions, it is assumed constant over the time step and not solved for in the iterative process.

Percolation

Percolation (PERC) represents the flow of water from the unsaturated zone to the saturated zone, and is the only inflow for the saturated zone. The percolation equation in the subroutine was formulated from Darcy's Law for unsaturated flow, in which the hydraulic conductivity, K, is a function of the moisture content, TH. For one-dimensional, vertical flow, Darcy's Law may be written

$$v = -K(TH) \cdot dh/dz \qquad \text{(X-15)}$$

where v = velocity (specific discharge) in the direction of z,
z = vertical coordinate, positive upward,
K(TH) = hydraulic conductivity,
TH = moisture content, and
h = hydraulic potential.

The hydraulic potential is the sum of the elevation (gravity) and pressure heads,

$$h = z + PSI \qquad \text{(X-16)}$$

where PSI = soil water tension (negative pressure head) in the unsaturated zone.

Equating vertical velocity to percolation, and differentiating the hydraulic potential, h, yields

$$\text{Percolation} = -K(TH)\cdot(1+ dPSI/dz) \qquad \text{(X-17)}$$

A choice is customarily made between using the tension, PSI, or the moisture content, TH, as parameters in equations for unsaturated zone water flow. Since the quantity of water in the unsaturated zone is identified by TH in previous equations, it is the choice here. PSI can be related to TH if the characteristics of the unsaturated soil are known. Thus, for use in equation X-17, the derivative is

$$dPSI/dz = dPSI/dTH \cdot dTH/dz \qquad \text{(X-18)}$$

The slope of the PSI versus TH curve should be obtained from data for the particular soil under consideration. Relationships for a sand, sandy loam and silty loam are shown in Figures X-2, X-3 and X-4 (Laliberte et al., 1966). The data are based on laboratory tests of disturbed soil samples and illustrate only the desaturation (draining) characteristics of the soil. The relationship during the saturation (wetting) phase will ordinarily be different; when both the wetting and draining relationships are shown the curves usually illustrate a hysteresis effect. The figures also show the relationship between the hydraulic conductivity of the unsaturated soils and the moisture content. In some cases (e.g., sand), K(TH) may range through several orders of magnitude. Soils data of this type are becoming more readily available; for example, soil science departments at universities often publish such information (e.g., Carlisle et al., 1981). The data illustrated in Figures X-2, X-3 and X-4 are also useful for extraction of parameters for the Green-Ampt infiltration equations.

Equation X-17 may be approximated by finite differences as

$$\text{Percolation} = -K(TH)\cdot[1+(\Delta TH/\Delta z)\cdot(\Delta PSI/\Delta TH)] \qquad \text{(X-19)}$$

For calculation of percolation, it is assumed that the gradient, $\Delta TH/\Delta z$, is the difference between moisture content TH in the upper zone and field capacity at the boundary with the lower zone, divided by the average depth of the upper zone, DWT1/2. Thus,

$$\text{Percolation} = -K(TH)\cdot\{1+[(TH-FD)\cdot 2/DWT1]\cdot PCO\} \qquad \text{(X-20)}$$

where FD = field capacity, and
PCO = $\Delta PSI/\Delta TH$ in the region between TH and FD.

PCO is obtained from data of the type of Figures X-2, X-3 and X-4.

Finally, the hydraulic conductivity as a function of moisture content is approximated functionally in the moisture zone of interest as

$$K(TH) = HKTH = HKSAT\cdot EXP[(TH-PR)\cdot HCO] \qquad \text{(X-21)}$$

where HKTH = hydraulic conductivity as a function of moisture content,

Touchet Silt Loam

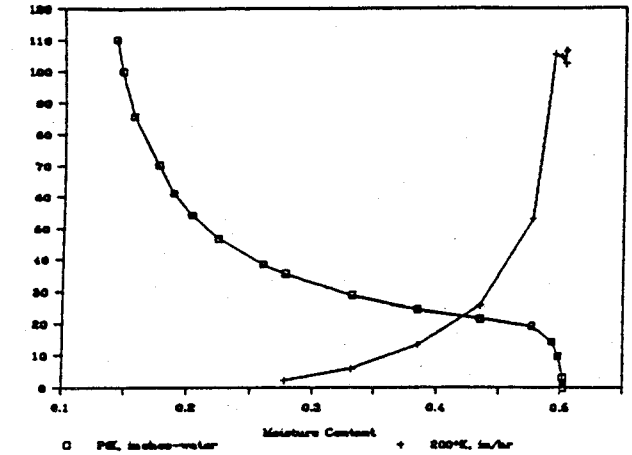


Figure X-2.

Tension, PSI (squares, in. of water) and hydraulic conductivity, K (crosses, in/hr, K multiplied by 200) versus moisture content. Derived from data of Laliberte et al (1966), Tables B-5 and C-3. Porosity = 0.503, temp. = 26.5 °C, saturated hyd. conductivity = 0.53 in/hr.

Columbia Sandy Loam

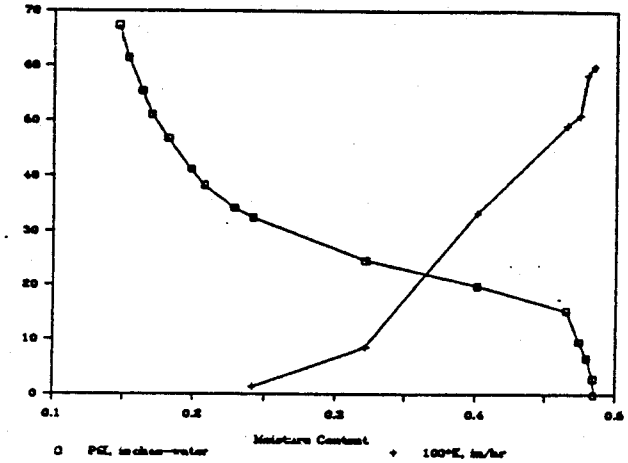


Figure X-3.

Tension, PSI (squares, in. of water) and hydraulic conductivity, K (crosses, in/hr, K multiplied by 100) versus moisture content. Derived from data of Laliberte et al. (1966), Tables B-8 and C-5. Porosity = 0.485, temp. = 25.1 °C, saturated hyd. conductivity = 0.60 in/hr.

Unconsolidated Sand

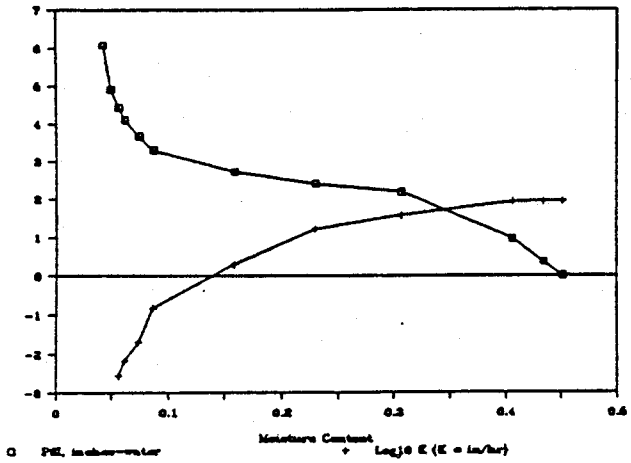


Figure X-4.

Tension, PSI (squares, in. of water) and log-10 of hydraulic conductivity, K (crosses, K in in/hr) versus moisture content. Derived from data of Laliberte et al. (1966), Tables B-14 and C-11. Porosity = 0.452, temp. = 25.1 °C, saturated hyd. conductivity = 91.5 in/hr.

HKSAT = saturated hydraulic conductivity, and
HCO = calibration parameter.

HCO can be estimated by fitting the HKTH versus TH curve to the hydraulic conductivity versus moisture content curve, if such data are available (e.g., Figures X-2, X-3, X-4); three fits are shown in Figure X-5. The fits are not optimal over the entire data range because the fit is only performed for the high moisture content region between field capacity and porosity. If soils data are not available, HCO can be estimated by model calibration.

Combining equations X-20 and X-21 gives the resulting percolation equation for the model,

$$PERC = HKTH \cdot [1 + PCO \cdot (TH - FD)/(DWT1/2)] \qquad (X\text{-}22)$$

where PERC = percolation rate (positive downward) and is only nonzero when TH is greater than FD.

If data sources for parameters PCO and HCO are lacking, they may be estimated through the calibration process. On the basis of preliminary runs, the groundwater subroutine is relatively insensitive to changes in PCO and HCO, so a lack of extensive soils data should not discourage one from using the model.

If moisture content is less than or equal to field capacity, percolation becomes zero. This limit is in accordance with the concept of field capacity as the drainable soil water that cannot be removed by gravity alone (Hillel, 1982, p. 243). Once TH drops below field capacity, it can only be further reduced by upper zone evapotranspiration (to a lower bound of the wilting point).

The percolation rate calculated by equation X-22 will be reduced by the program if it is high enough to drain the upper zone below field capacity or make the iterations for D2 converge to an unallowable value. Also, since checks must be made on PERC, it is assumed to be constant over the time step and therefore not determined through an iterative process.

Field Capacity and Wilting Point

These parameters are used for demarcations for percolation and ET. Field capacity, FC, is usually considered to be the amount of water a well-drained soil holds after free water has drained off, or the maximum amount it can hold against gravity (SCS, 1964; Linsley et al., 1982). This occurs at soil moisture tensions (see further discussion below) of from 0.1 to 0.7 atmospheres, depending on soil texture. Moisture content at a tension of 1/3 atmosphere is often used. The wilting point (or permanent wilting point), WP, is the soil moisture content at which plants can no longer obtain enough moisture to meet transpiration requirements; they wilt and die unless water is added to the soil. The moisture content at a tension of 15 atmospheres is accepted as a good estimate of the wilting point (SCS, 1964; Linsley et al., 1982). The general relationship among soil moisture parameters is shown in Figure X-6 (SCS, 1964).

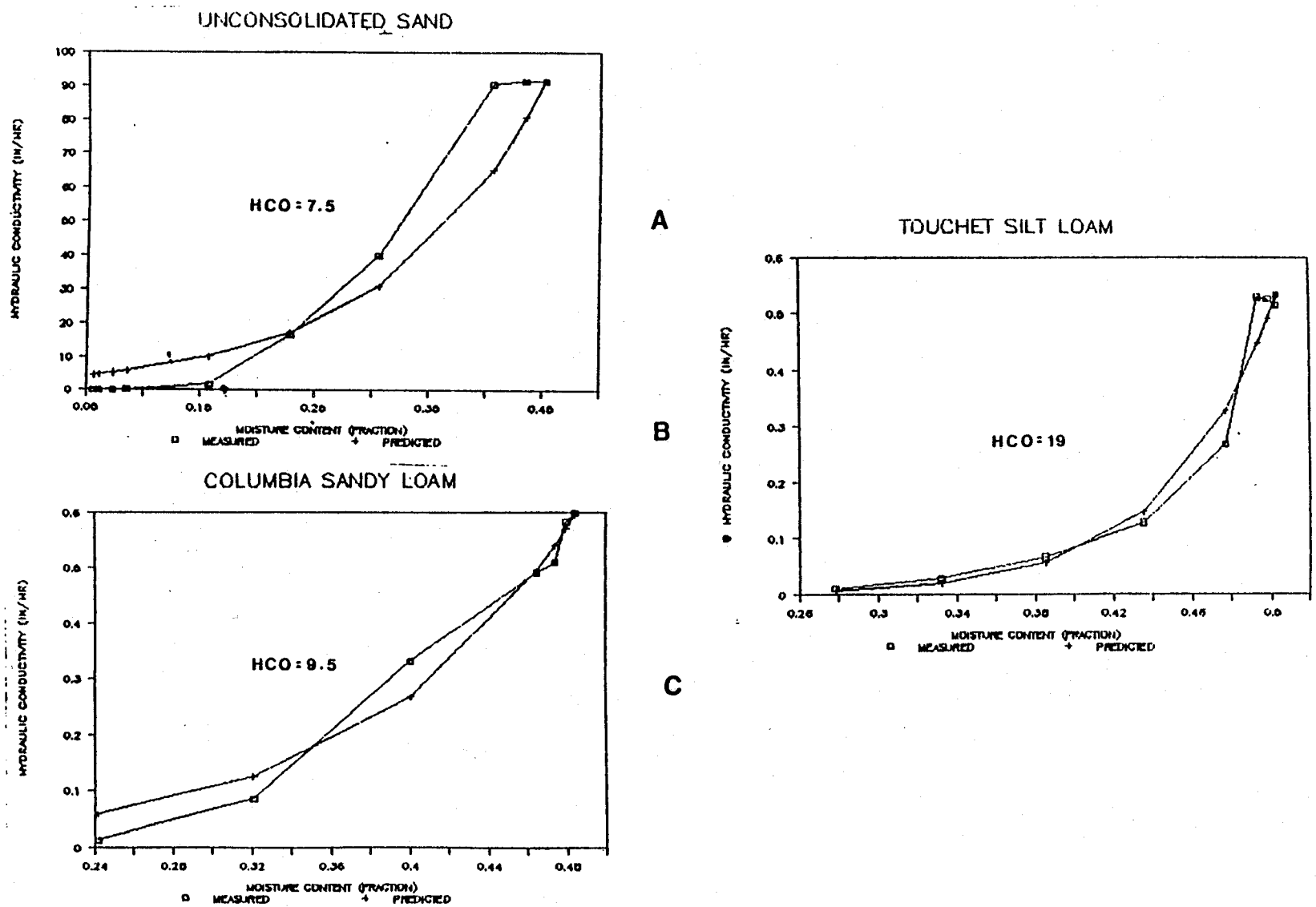


Figure X-5. Model Representation and Measured Hydraulic Conductivity Curves for Three Types of Soil.

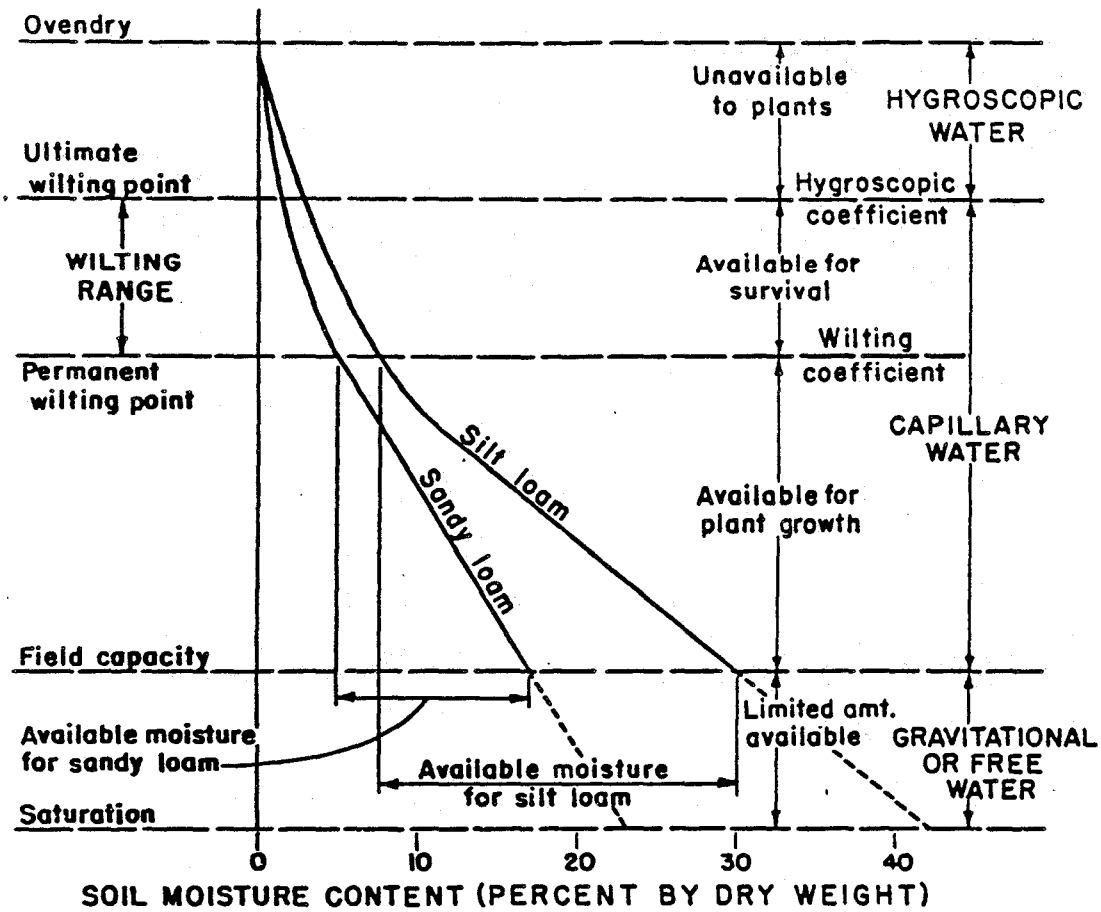


Figure X-6. Kinds of Water in Soil (SCS, 1964). Note that Silt Loam Contains more than Twice as Much Readily Available Water than Sandy Loam.

Data for FC and WP are available from the SCS, agricultural extension offices and university soil science departments. Generalized data are shown in Table X-1, as derived from Linsley et al. (1982, p. 179).

Table X-1. Volumetric Moisture Content at Field Capacity and Wilting Point (Derived* from Linsley et al., 1982, Table 6-1.)

Soil Type	Field Capacity	Wilting Point
Sand	0.08	0.03
Sandy loam	0.17	0.07
Loam	0.26	0.14
Silt Loam	0.28	0.17
Clay loam	0.31	0.19
Clay	0.36	0.26
Peat	0.56	0.30

*Fraction moisture content = fraction dry weight x dry density / density of water.

Deep Percolation

Deep percolation represents a lumped sink term for unquantified losses from the saturated zone. The two primary losses are assumed to be percolation through the confining layer and lateral outflow to somewhere other than the receiving water. The arbitrarily chosen equation for deep percolation is

$$DEPPRC = DP \cdot D1/DTOT \qquad \text{(X-23)}$$

where DEPPRC = beginning-of-time-step deep percolation rate, and
DP = a recession coefficient derived from interevent water table recession curves.

The ratio of D1 to DTOT allows DEPPRC to be a function of the static pressure head above the confining layer. Although DEPPRC will be very small in most cases, it is included in the iterative process so that an average over the time step can be used. By doing this, large continuity errors will be avoided should DEPPRC be set at a larger value.

Groundwater Discharge

Functional Form --

Groundwater discharge represents lateral flow from the saturated zone to the receiving water. The flow equation takes on the following general form:

$$GWFLW = A1 \cdot (D1-BC)^{B1} - TWFLW + A3 \cdot D1 \cdot TW \qquad \text{(X-24)}$$

and

$$TWFLW = A2 \cdot (TW-BC)^{B2} \qquad \text{(X-25)}$$

where GWFLW = beginning-of-time-step groundwater flow rate (per subcatchment

area,

TWFLW = channel water influence flow rate (per subcatchment area),
A1,A2 = groundwater and channel water influence flow coefficients,
A3 = coefficient for cross-product,
B1,B2 = groundwater and tailwater influence flow exponents,
BC = elevation of bottom of channel, and
TW = elevation of water in channel.

If D1 is less than BC or TW, GWFLW is set equal to zero. In addition, if TW = BC and B2 = 0, then the indeterminant form of zero raised to the zero power in equation X-25 is set equal to 1.0 by the program. The functional form of equations X-24 and X-25 was selected in order to be able to approximate various horizontal flow conditions, as will be illustrated below.

Since groundwater flow can be a significant volume, an average flow each time step is found by iteration using equation X-2 or X-3. Groundwater flows can be routed to any previously defined inlet, trapezoidal channel, or pipe, allowing the user to isolate the various components of the total hydrograph, as shown in Figure X-7. That is, the groundwater flow does not have to be routed to the same destination as the overland flow from the subcatchment.

The effects of channel water on groundwater flow can be dealt with in two different manners. The first option entails setting TW (elevation of water surface in the channel) to a constant value greater than or equal to BC (bottom-of-channel elevation) and A2, B2 and/or A3 to values greater than zero. If this method is chosen, then the user is specifying an average tailwater influence over the entire run to be used at each time step.

The second option makes the channel water elevation, TW, equal to the elevation of water in an actual channel (trapezoidal channel or circular pipe). For this option, the groundwater must be routed to a trapezoidal channel or pipe -- not an inlet. The depth of water in the channel (TW - BC) at each time step is then determined as the depth in the channel or pipe from the previous time step. (It is assumed that the bottom of the channel is at the elevation BC.) The beginning-of-time-step depth must be used to avoid complex and time-consuming iterations with the coupled channel discharge equations in subroutine GUTTER. Unfortunately, because of this compromise the groundwater flow may pulsate as D1 oscillates between just above and just below elevation TW. This pulsing may introduce errors in continuity and is, of course, unrepresentative of the actual system. Shorter time steps and larger or less steep channels (reducing the response of the channel) can be used to reduce the pulses. Also, caution must be taken when selecting A1, B1, A2, B2 and A3 so that GWFLW cannot be negative. Although this may occur in the actual system and represent recharge from the channel, there is currently no means of representing this reverse flow and subtracting it from the channel. One way of assuring that this cannot happen is to make A1 greater than or equal to A2 and B1 greater than or equal to B2, and A3 equal to zero.

Because of the general nature of the equation, it can take on a variety of functional forms. For example, a linear reservoir can be selected by setting B1 equal to one and A2 and A3 equal to zero. Two drainage examples are illustrated below.

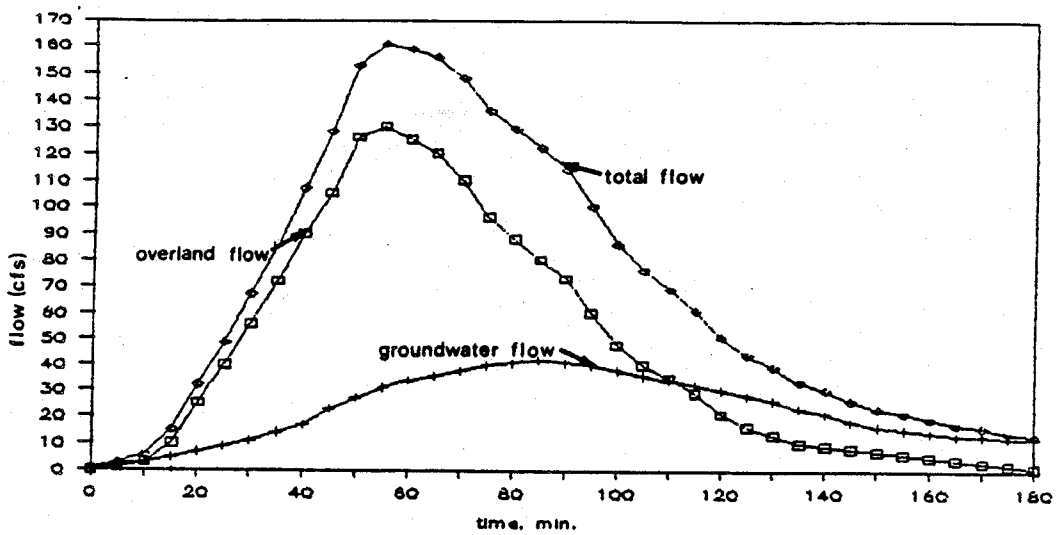


Figure X-7. Hydrograph of total flow and its two major components.

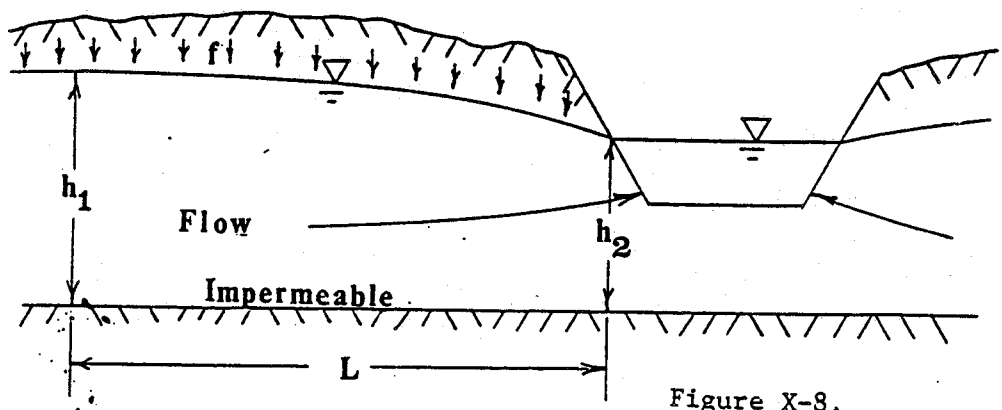


Figure X-8.
Definition sketch for Dupuit-Forcheimer approximation for drainage to adjacent channel.

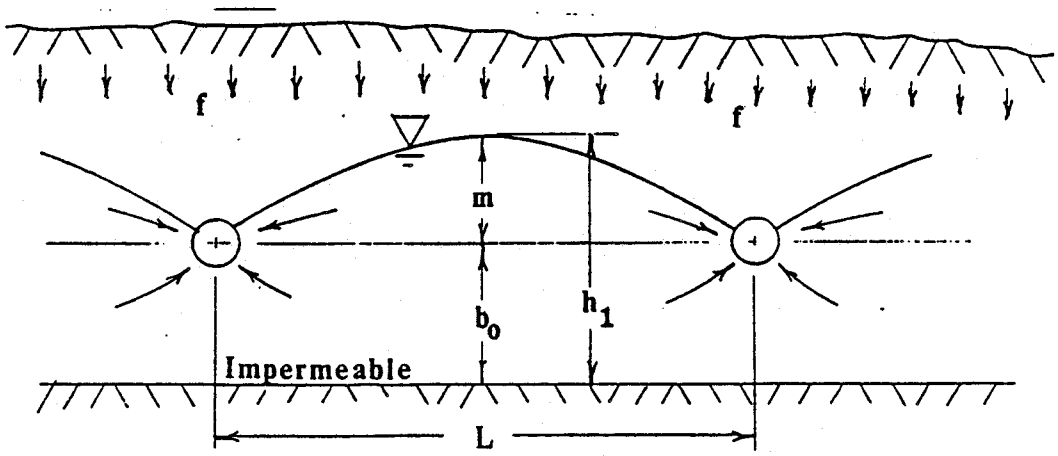


Figure X-9. Definition Sketch for Hooghoudt's Method for Flow to Circular Drains.

Example: Infiltration and Drainage to Adjacent Channel --

Under the assumption of uniform infiltration and horizontal flow by the Dupuit-Forcheimer approximation, the relationship between water table elevation and infiltration for the configuration shown in Figure X-8 is (Bouwer, 1978, p. 51)

$$K(h_1^2 - h_2^2) = L^2 f \qquad \text{(X-26)}$$

where f = infiltration rate,
K = hydraulic conductivity, and other parameters are as shown on Figure X-8.

Before matching coefficients of equations X-24 and X-25 to equation X-26, it should be recognized that the water table elevation in SWMM, D1, represents an average over the catchment, not the maximum at the "upstream" end that is needed for h_1 in equation X-26. Let D1 be the average head,

$$D1 = (h_1 + h_2)/2 \qquad \text{(X-27)}$$

Substituting $h_1 = 2\ D1 - h_2$ into equation X-26 gives, after algebra

$$(D1^2 - D1\ h_2)\ 4K/L^2 = f \qquad \text{(X-28)}$$

from which a comparison with equations X-24 and X-25 yields $A1 = A3 = 4K/L^2$, $A2 = 0$, and $B1 = 2$. Note that GWFLW has units of flow per unit area, or length per time, which are the units of infiltration, f, in equation X-28.

Example: Hooghoudt's Equation for Tile Drainage --

The geometry of a tile drainage installation is illustrated in Figure X-9. Hooghoudt's relationship (Bouwer, 1978, p. 295) among the indicated parameters is

$$f = (2D_e + m)\ 4Km/L^2 \qquad \text{(X-29)}$$

where D_e = effective depth of impermeable layer below drain center, and other parameters are defined in Figure X-9. D_e is less than or equal to b_o in Figure X-9 and is a function of b_o, drain diameter, and drain spacing, L; the complicated relationship is given by Bear (1972, p. 412) and graphed by Bouwer (1978, p. 296). The maximum rise of the water table, $m = h_1 - b_o$. Once again approximating the average water table depth above the impermeable layer by $D1 = 2h_1 - b_o$, equation X-29 can be manipulated to

$$f = [(h_1 - b_o)^2 + 2D_e(h_1 - b_o)]\ 4K/L^2 =$$

$$= [(D1 - b_o)^2 + D_e D1 - D_e b_o]\ 16K/L^2 \qquad \text{(X-30)}$$

Comparing equation X-30 with equations X-24 and X-25 yields

$$A1 = 16K/L^2,$$

$B1 = 2$

$A2 = 16KD_e b_o/L^2$

$B2 = 0$

$A3 = 16KD_e / TW\ L^2$

and $TW = BC = b_o$ = constant during the simulation. The equivalent depth, D_e, must be obtained from the sources indicated above. The mathematics of drainage to ditches or circular drains is complex; several alternative formulations are described by van Schilfgaarde (1974).

LIMITATIONS

Since the moisture content of the unsaturated zone is taken as an average over the entire zone, the shape of the moisture profile is totally obscured. Therefore, infiltrated water cannot be modeled as a diffusing slug moving down the unsaturated zone, as is the case in the real system. Furthermore, water from the capillary fringe of the saturated zone cannot move upward by diffusion or "suction" into the unsaturated zone.

The simplistic representation of subsurface storage by one unsaturated "tank" and one saturated "tank" limits the ability of the user to match nonuniform soil columns. Another limitation is the assumption that the infiltrated water is spread uniformly over the entire catchment area, not just over the pervious area. In addition, just as for surface flow, groundwater may not be routed from one subcatchment to another. The tendency of the tailwater influence to cause pulses if TW-BC is equated to the dynamic water depth in the adjacent channel is a limitation that will remain until the channel flow and subsurface flow are solved simultaneously using a set of coupled equations. Such a solution would also permit reverse flow or recharge from the channel to be simulated.

Finally, water quality is not simulated in any of the subsurface routines. If water quality is simulated in RUNOFF and the subsurface flow routines activated, any loads entering the soil will "disappear," as if the soil provides 100 percent treatment.

SUBROUTINE CONFIGURATION

A flowchart of the subroutine configuration is presented in Figure X-10. Initial values and constants used in subroutine GROUND come mostly from subroutine GRIN, designed specifically to read in these values. Subroutine GRIN is called by RHYDRO. Other necessary values are transferred during the CALL statement and from previously calculated values stored in COMMON.

Subroutine GROUND first initializes pertinent parameters, then calculates fluxes that are constant over the time step. Beginning-of-time-step fluxes are calculated next, and the value of percolation is checked to ensure that it will not raise the water table above the ground surface.

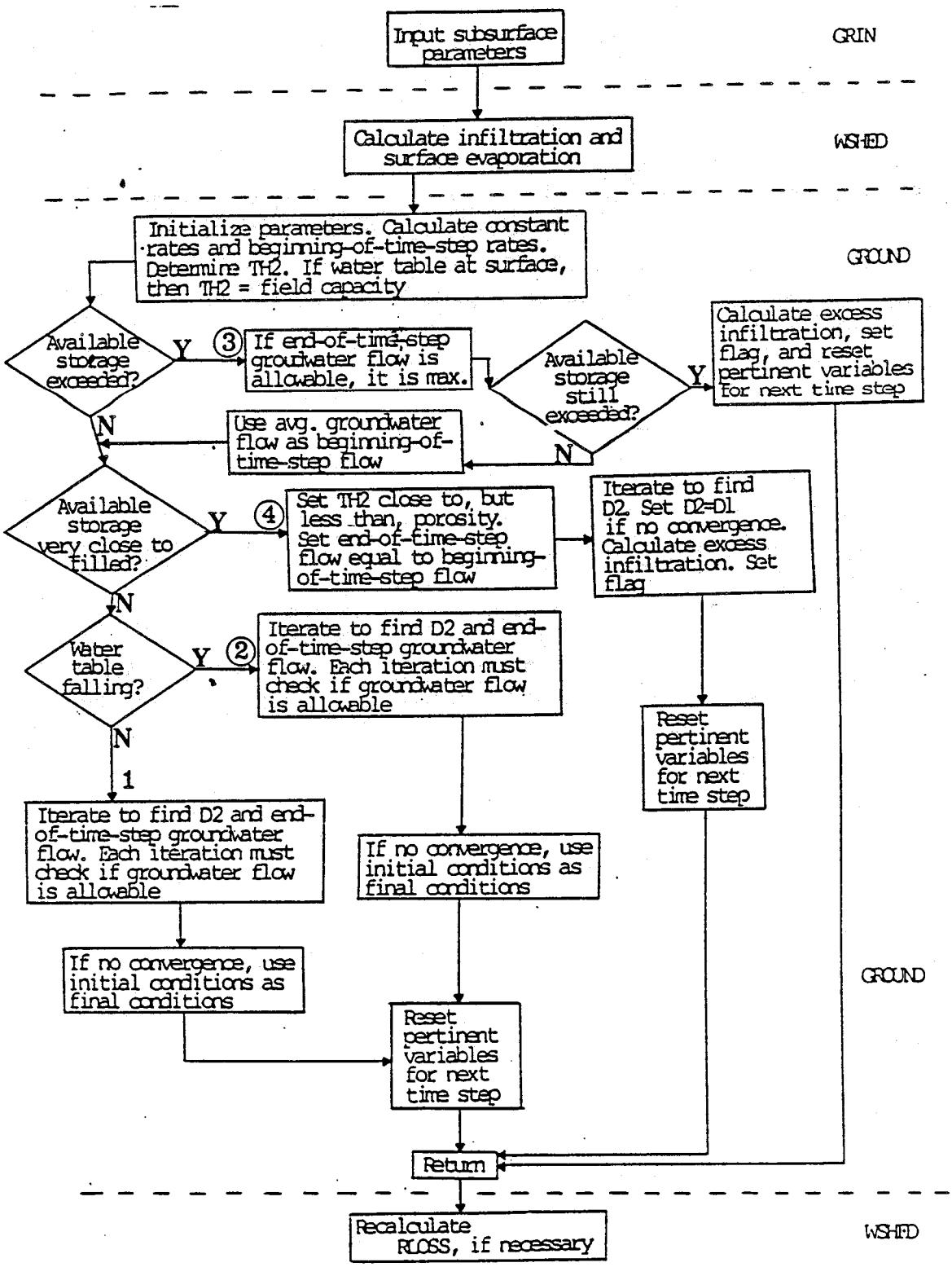


Figure X-10. Flowchart of Subsurface and Directly-connected Surface Calculations.

After other constants are calculated and TH2 is determined from equation X-4, the program branches to one of four areas. The first and second areas are for rising and falling water tables, equations X-2 and X-3, respectively. In both cases, Newton-Raphson iteration is used to solve simultaneously for the final groundwater flow, depth of lower zone, and deep percolation. Each iteration checks whether or not groundwater flow is possible (D1 greater than or equal to TW and BC). After the iterations converge, final conditions are set as the next time step's initial conditions.

In the event of saturation (D1 = DTOT), the third area sets D2 equal to DTOT, sets final groundwater flow equal to the maximum possible (D2 = DTOT), and assumes DEPPRC remains constant over the time step. Any excess infiltration is then routed back to the surface for overland flow calculations, and final conditions are set for the next initial conditions. However, if the maximum groundwater flow and DEPPRC rates permit some infiltration into the subsurface zone, the initial and final groundwater flow are averaged to be used as the new initial groundwater flow, and the program branches back to iterate for the solution. This pathway will rarely, if ever, be taken, but must be included to minimize possible continuity errors.

In the event the available storage in the unsaturated zone is less than 0.0001 ft, the fourth area sets TH2 equal to 90% of porosity and D2 close to DTOT, and returns any infiltration to the surface that causes the final unfilled upper zone volume to be greater than 0.0001 ft. This is to avoid oscillations as the water table hovers near the ground surface. Again, final conditions are then set as the next time step's initial conditions.

EXAMPLES

Cypress Creek Calibration and Verification

Two examples will illustrate the use of the new subroutine. The first example is a year-long simulation of a 47 mi^2 portion of the 117 mi^2 Cypress Creek Watershed in Pasco County, Florida, about 30 miles north of Tampa (Figure X-11). The region has been studied in relation to the interaction of surface water and ground water under the stress of heavy pumping and drainage activities in the area (Heaney et al., 1986). The watershed is characterized by sandy soils in which most water movement follows subsurface pathways. For this example, only a single 47 mi^2 area above State Road 52 (Figure X-11) and tributary to the USGS gage at San Antonio has been simulated.

Twenty-four parameters on three additional H-cards are required for each subsurface subcatchment. (Many of these can be ignored or set to zero during most runs; not all parameters are required for all runs.) Input parameters are echoed on two new pages of output that immediately follow the surface subcatchment information. Figure X-12 is an example of these two new pages; the values in Figure X-12 are from the calibration run on Cypress Creek. In addition to the new output just mentioned, a subsurface continuity check is provided in addition to the existing surface continuity check. An example of this amended page is shown in Figure X-13.

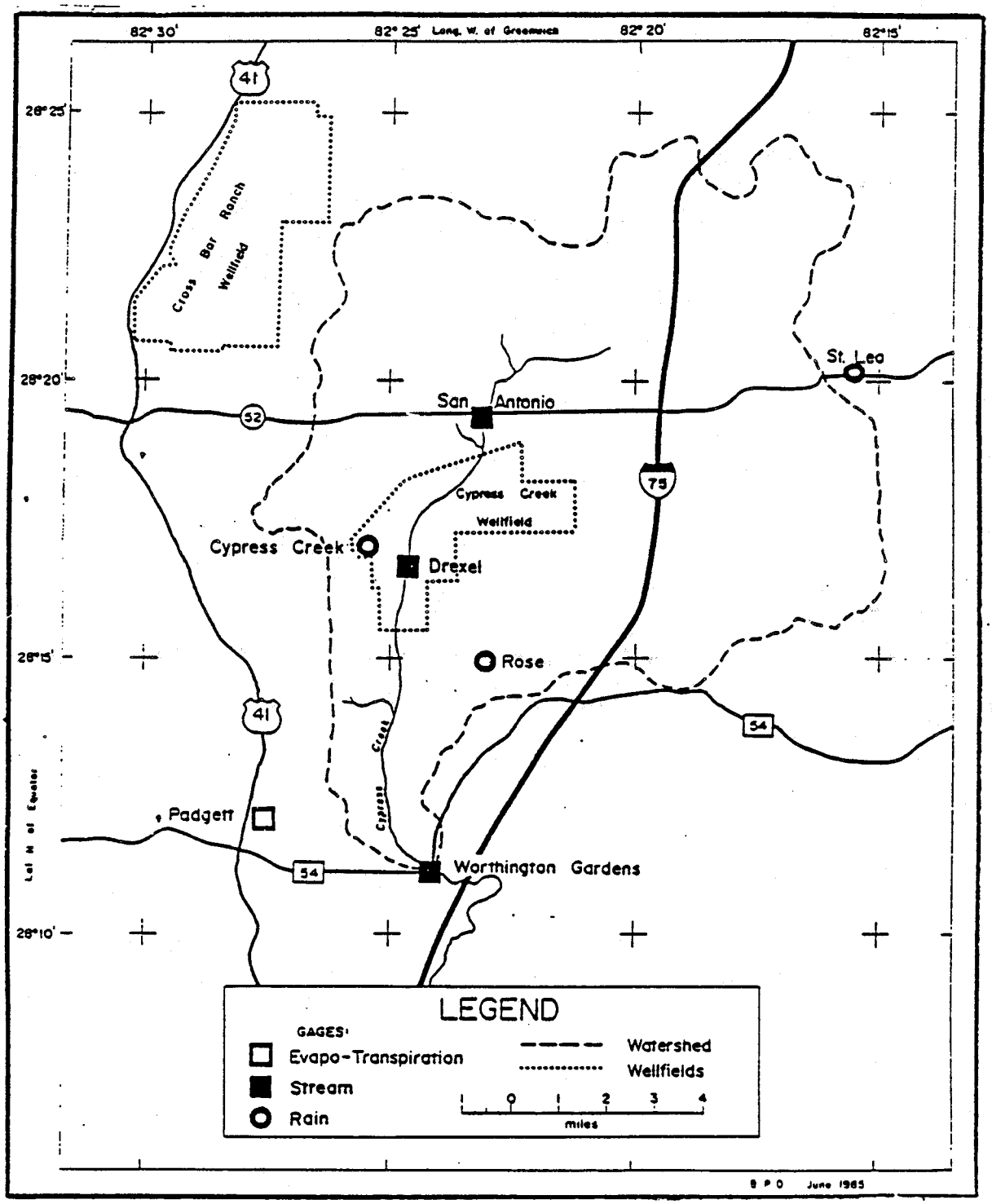


Figure X-11. Map of Cypress Creek Watershed in Pasco County, Florida. (Heaney et al., 1986)

* * * * * G R O U N D W A T E R I N P U T D A T A * * * * * *

SUBCAT. NO.	GUTTER OR INLET	ELEVATIONS GROUND (FT)	BOTTOM (FT)	INITIAL STAGE (FT)	BC (FT)	TW (FT)	FLOW CONSTANTS A1 (IN/HR-FT**B1)	B1	A2 (IN/HR-FT**B2)	B2
21	22	20.00	0.00	7.20	8.55	8.55	4.500E-05	2.600	0.000E+00	1.000

* * * * * G R O U N D W A T E R I N P U T D A T A (CONTINUED) * * * * * *

SUBCAT. NO.	SOIL PROPERTIES POROSITY	SATURATED HYDRAULIC CONDUCTIVITY (IN/HR)	WILTING POINT	FIELD CAPACITY	INITIAL MOISTURE	MAX. DEEP PERCOLATION (IN/HR)	PERCOLATION PARAMETERS HCO *	PCO ** (FT)	ET PARAMETERS DEPTH OF ET (FT)	FRACTION OF ET TO UPPER ZONE
21	.4600	5.000	.1500	.3000	.3010	2.000E-03	10.00	15.00	14.00	0.350

HYD. CONDUCTIVITY = SAT. HYD. COND. * EXP((UPPER Z MOISTURE CONTENT - POROSITY) * HCO)
* PERCOLATION RATE = HYD. COND. * (1 + PCO * (UPPER ZONE MOISTURE CONTENT - FIELD CAPACITY)/(UPPER ZONE DEPTH/2))

Figure X-12. Subsurface Input Data for Cypress Creek Calibration.

```
$ $ $ --- CONTINUITY CHECK FOR QUANTITY --- $ $ $
                                                          CUBIC FEET     INCHES OVER
                                                                         TOTAL BASIN
TOTAL PRECIPITATION (RAIN PLUS SNOW)                     3.434232E+09      30.518
TOTAL INFILTRATION                                       2.878862E+09      25.583
TOTAL EVAPORATION                                        5.298000E+08       4.708
TOTAL GUTTER/PIPE/SUBCAT FLOW AT INLETS                  2.559983E+07       0.227
TOTAL WATER REMAINING IN GUTTER/PIPES                    0.000000E+00       0.000
TOTAL WATER REMAINING IN SURFACE STORAGE                 0.000000E+00       0.000
INFILTRATION OVER THE PERVIOUS AREA...                   2.878862E+09      25.841

INFILTRATION + EVAPORATION +
SNOW REMOVAL + INLET FLOW +
WATER REMAINING IN GUTTER/PIPES +
WATER REMAINING IN SURFACE STORAGE +
WATER REMAINING IN SNOW COVER.........                   3.344122E+09      29.718

*** CONTINUITY CHECK FOR SUBSURFACE WATER ***
                                                          CUBIC FEET     INCHES OVER
                                                                         TOTAL BASIN
TOTAL INFILTRATION                                       2.878862E+09      25.583
TOTAL UPPER ZONE ET                                      1.149578E+09      10.216
TOTAL LOWER ZONE ET                                      6.667578E+08       5.925
TOTAL GROUNDWATER FLOW                                   9.013922E+07       0.801
TOTAL DEEP PERCOLATION                                   4.816257E+08       4.280
INITIAL SUBSURFACE STORAGE                               9.675055E+09      85.978
FINAL SUBSURFACE STORAGE                                 1.016489E+10      90.330

UPPER ZONE ET OVER PERVIOUS AREA                         1.149578E+09      10.319
LOWER ZONE ET OVER PERVIOUS AREA                         6.667578E+08       5.985


THE ERROR IN CONTINUITY IS CALCULATED AS

****************************************
* PRECIPITATION + INITIAL SNOW COVER   *
*       - INFILTRATION -               *
*EVAPORATION - SNOW REMOVAL -          *
*INLET FLOW - WATER IN GUTTER/PIPES -  *
*WATER IN SURFACE STORAGE -            *
*WATER REMAINING IN SNOW COVER         *
*--------------------------------------*
* PRECIPITATION + INITIAL SNOW COVER   *
****************************************


ERROR.............................                                  2.624 PERCENT

*****************************************
* INFILTRATION + INITIAL STORAGE - FINAL *
* STORAGE - UPPER AND LOWER ZONE ET -    *
* GROUNDWATER FLOW - DEEP PERCOLATION    *
* -------------------------------------- *
* INFILTRATION + INITIAL STORAGE -       *
* FINAL STORAGE                          *
*****************************************

ERROR ............................                                  0.039 PERCENT
```

Figure X-13. Continuity Check for Surface and Subsurface for Cypress Creek Calibration. The Relatively Large Surface Continuity Error does not Actually Exist; it Comes from a Double Accounting of the Groundwater Flow -- a Problem that Has Been Fixed.

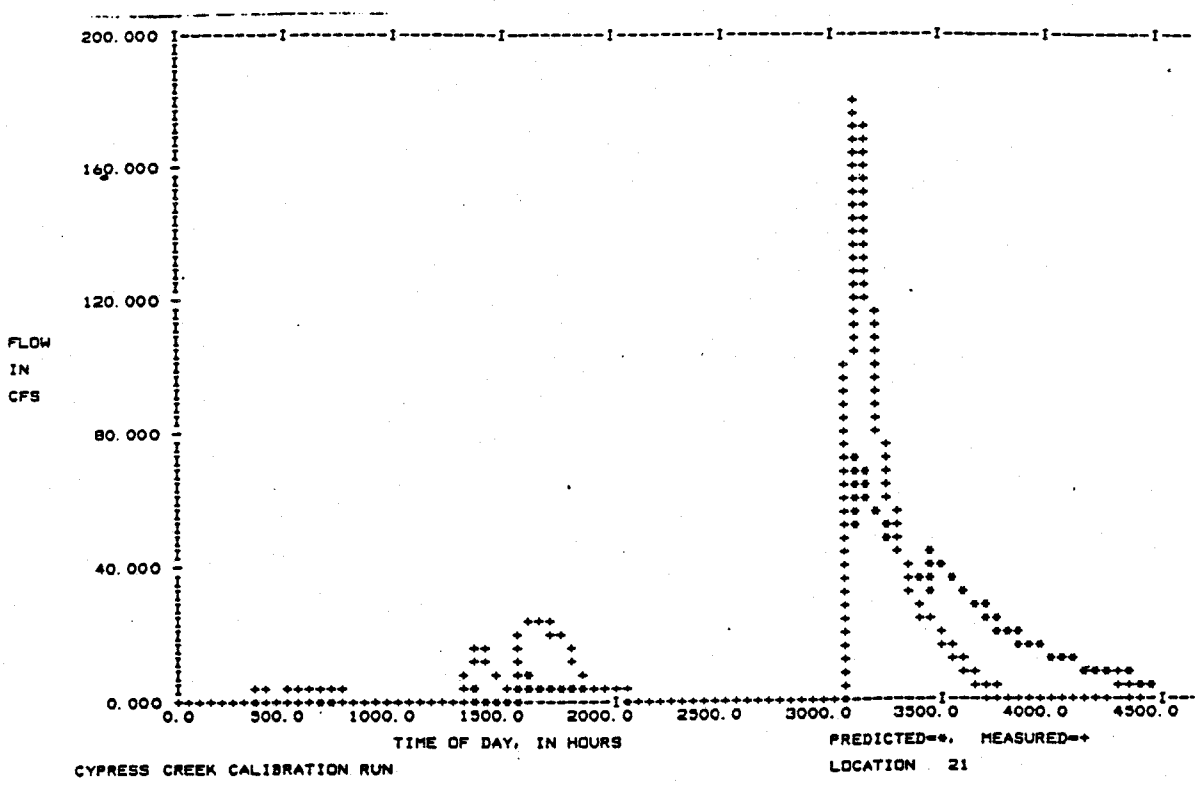
The simulation is divided into two six-month runs: the first six months for calibration, and the second six months for verification. Since Cypress Creek is a very flat, pervious area with well-drained soils and very little surface flow, it was modeled in a manner that would allow groundwater flow to account for most of the flow in the channel. In other words, the groundwater parameters represented by far the most critical part of the calibration. The only complete rainfall data for the calibration period are for the gage at St. Leo, out of the catchment to the east. Although these data are in daily increments, the calibration process was relatively simple because of the existence of both flow and shallow-well stage data. In addition, only one subcatchment (surface and subsurface) was used, since the purpose of this example was only to illustrate the use of subroutine GROUND, not to provide a thorough simulation.

Figure X-14 shows the predicted groundwater flow hydrograph and the measured total flow hydrograph for the calibration run, and Figure X-15 shows a comparison of the predicted total flow hydrograph to the measured total flow hydrograph for the calibration run. Predicted and measured stages for the calibration can be seen in Figure X-16. The calibration is not especially remarkable in light of the lack of detailed rainfall data for the 47 mi^2 area. The predicted stage hydrograph does not exhibit the short-term variations that are measured, primarily because of the lack of spatial detail in the rain. In addition, the measured stages are at one well near the center of the modeled area and would be expected to show more variation than would the average water table over the 47 mi^2 simulated by SWMM. The existence of more than one gage in the 47 square miles of the catchment and shorter increment rainfall data would have improved the fit seen in Figure X-16. Figures X-17, X-18 and X-19 show similar results for the verification runs. In general, the average recession of the water table is simulated accurately, but not the fluctuations.

Hypothetical Catchment with High Water Table

The second example is a 100 ac hypothetical subcatchment with the same soil properties as Cypress Creek and a water table that is initially one foot from the surface. The 10-yr SCS Type II design storm for Tallahassee, Florida is used for the rainfall input (Figure X-20). This storm is characterized by very high rainfall between hours 11 and 12.

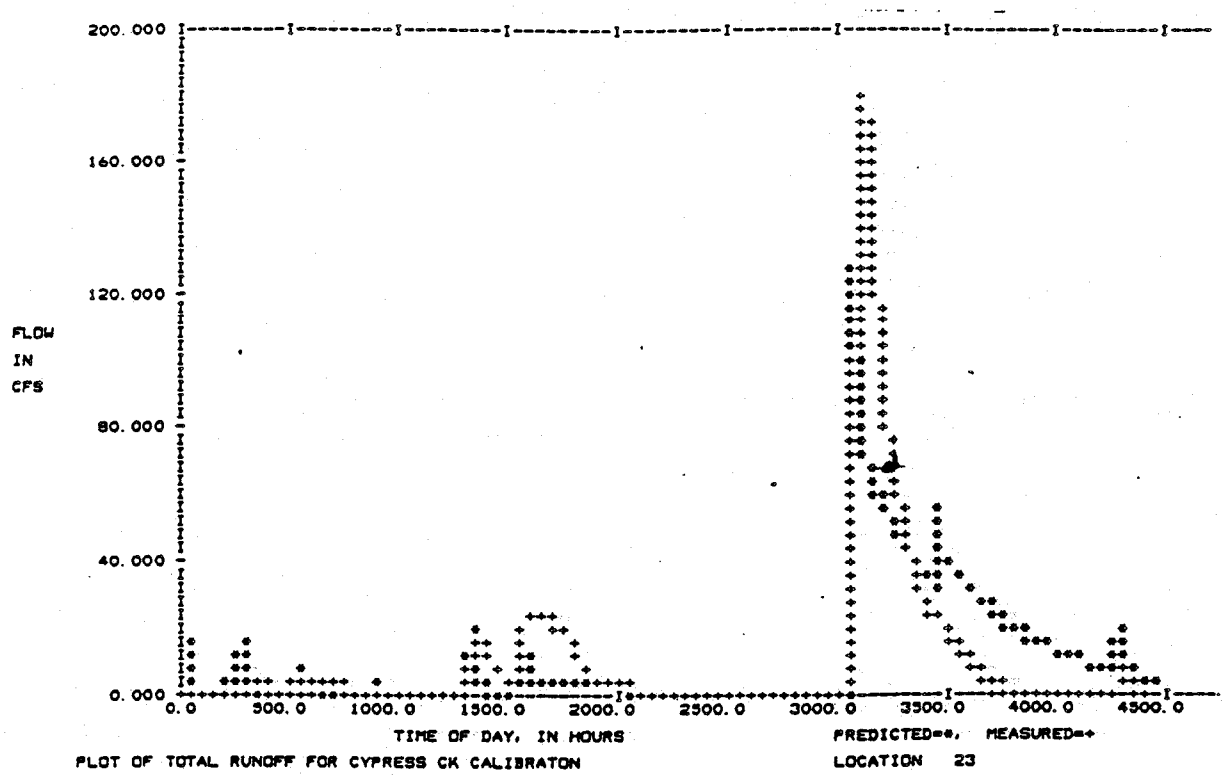
In order to illustrate the influence of a high water table, runs were made with and without the groundwater subroutine. Table X-2 shows the disposition of the rainfall when a high water table is simulated as opposed to when it is ignored. Note that evaporation is about the same, and the difference in the amount of infiltrated water shows up as a direct difference in surface runoff. (The runs were halted before all water had run off.) The two hydrographs and the corresponding water table (for the run in which it is simulated) are shown in Figure X-21. A larger difference in peak flows would have resulted if the flows had not been routed to a very large channel. Also, note that the two hydrographs are identical until about hour eleven into the simulation, when the simulated water table rises to the surface.



HYDROGRAPH STATISTICS FOR LOCATION 21

	VOLUME CUBIC FEET	VOLUME INCHES	PEAK FLOW TIME, HR	PEAK FLOW FLOW, CFS	DURATION START, HR	DURATION END, HR	DURATION LENGTH, HR	NO. POINTS
PREDICTED, TOTAL TIME	0.14547E+09	1.293	3105.000	73.242	0.000	4430.000	4430.000	194
MEASURED, TOTAL TIME	0.16359E+09	1.454	3120.000	180.000	0.000	4392.000	4392.000	184
PREDICTED, OVERLAPPING TIME	0.14463E+09	1.285	3105.000	73.242	0.000	4393.000	4393.000	195
MEASURED, OVERLAPPING TIME	0.16359E+09	1.454	3120.000	180.000	0.000	4392.000	4392.000	18
DIFFERENCES, ABSOLUTE	0.18964E+08	0.169	15.000	106.758				
% OF MEAS		11.592		59.310				

Figure X-14. Predicted Groundwater Flow Hydrograph and Total Measured Flow Hydrograph for Cypress Creek Calibration.



HYDROGRAPH STATISTICS FOR LOCATION 23

	VOLUME CUBIC FEET	VOLUME INCHES	PEAK FLOW TIME, HR	PEAK FLOW FLOW, CFS	DURATION START, HR	DURATION END, HR	DURATION LENGTH, HR	NO. POINTS
PREDICTED, TOTAL TIME	0.17127E+09	1.522	3059.000	128.228	0.000	4430.000	4430.000	194
MEASURED, TOTAL TIME	0.16359E+09	1.454	3120.000	180.000	0.000	4392.000	4392.000	184
PREDICTED, OVERLAPPING TIME	0.17042E+09	1.514	3059.000	128.228	0.000	4393.000	4393.000	192
MEASURED, OVERLAPPING TIME	0.16359E+09	1.454	3120.000	180.000	0.000	4392.000	4392.000	184
DIFFERENCES, ABSOLUTE	-0.68276E+07	-0.061	61.000	51.772				
% OF MEAS		-4.174		28.762				

Figure X-15. Total Predicted Flow Hydrograph and Total Measured Flow for Cypress Creek Calibration.

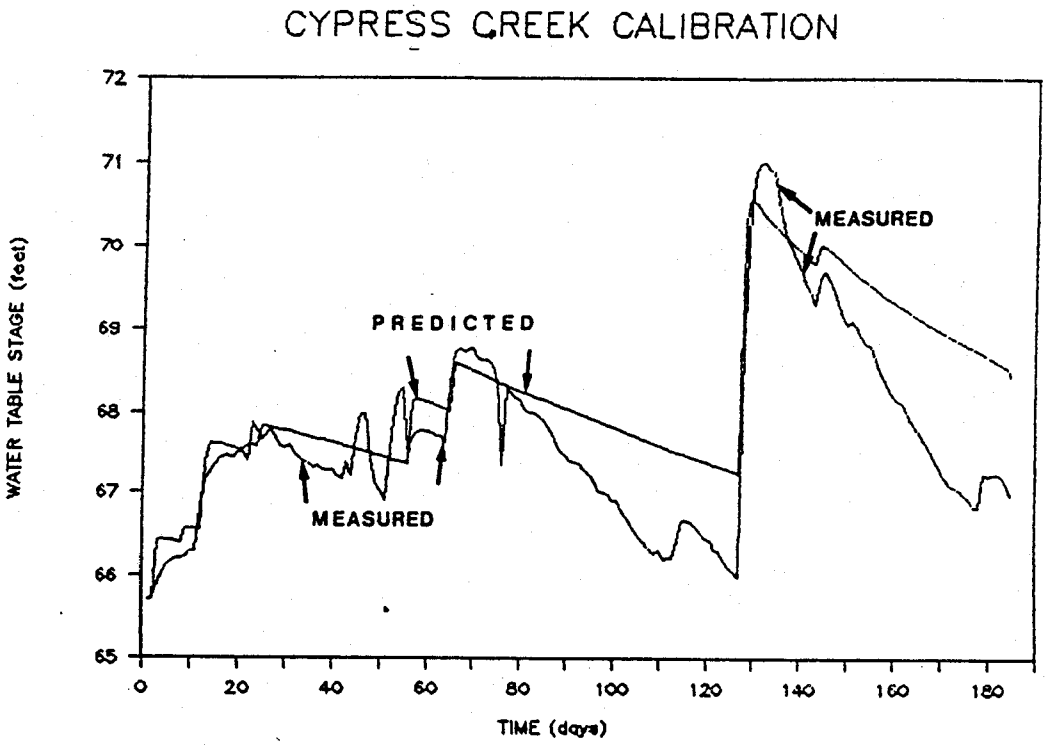


Figure X-16. Predicted and Measured Stages for Cypress Creek Calibration.

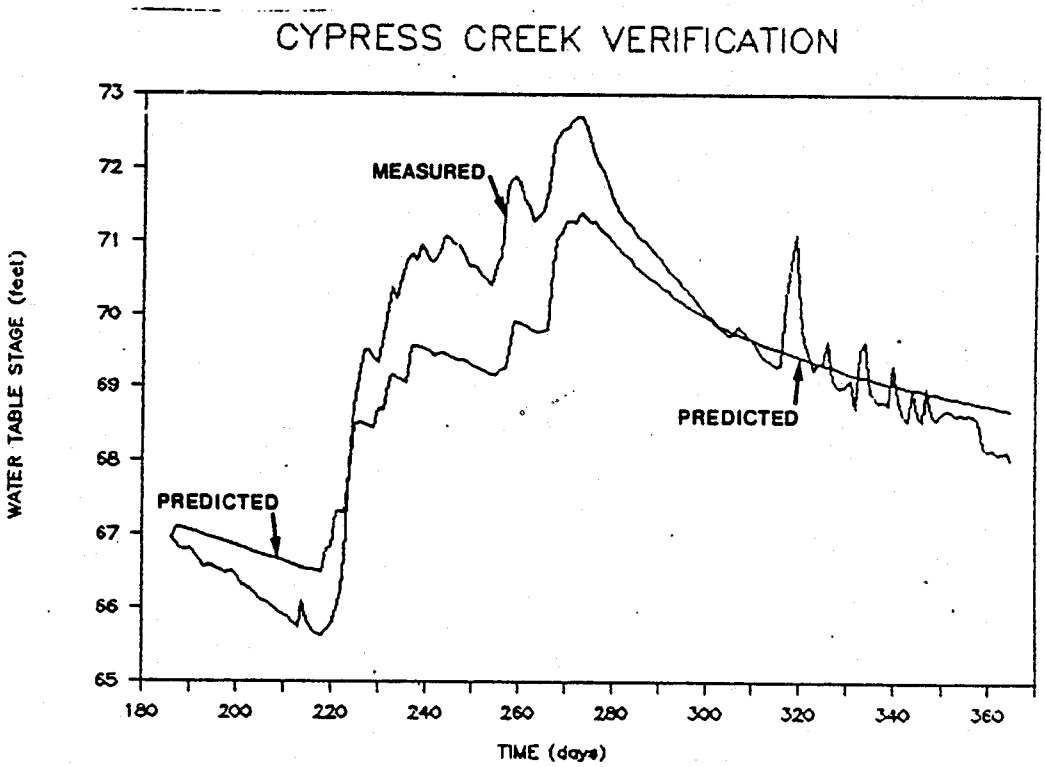
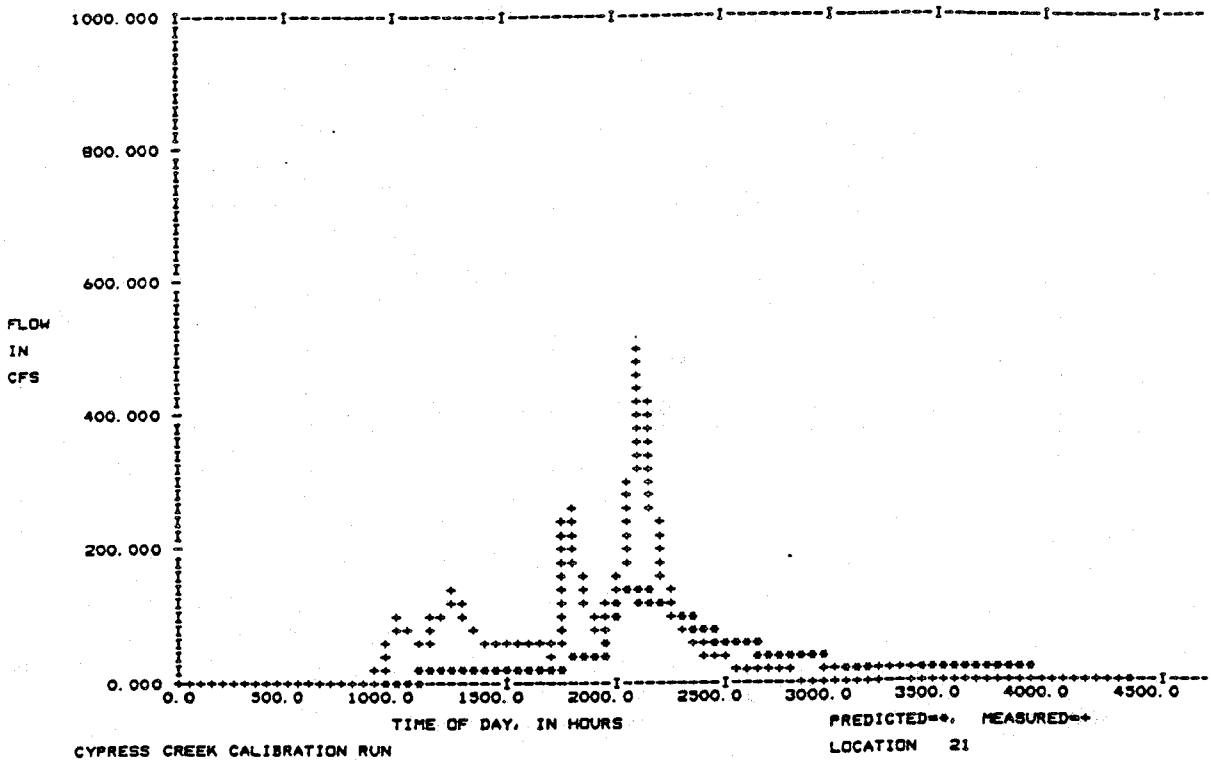


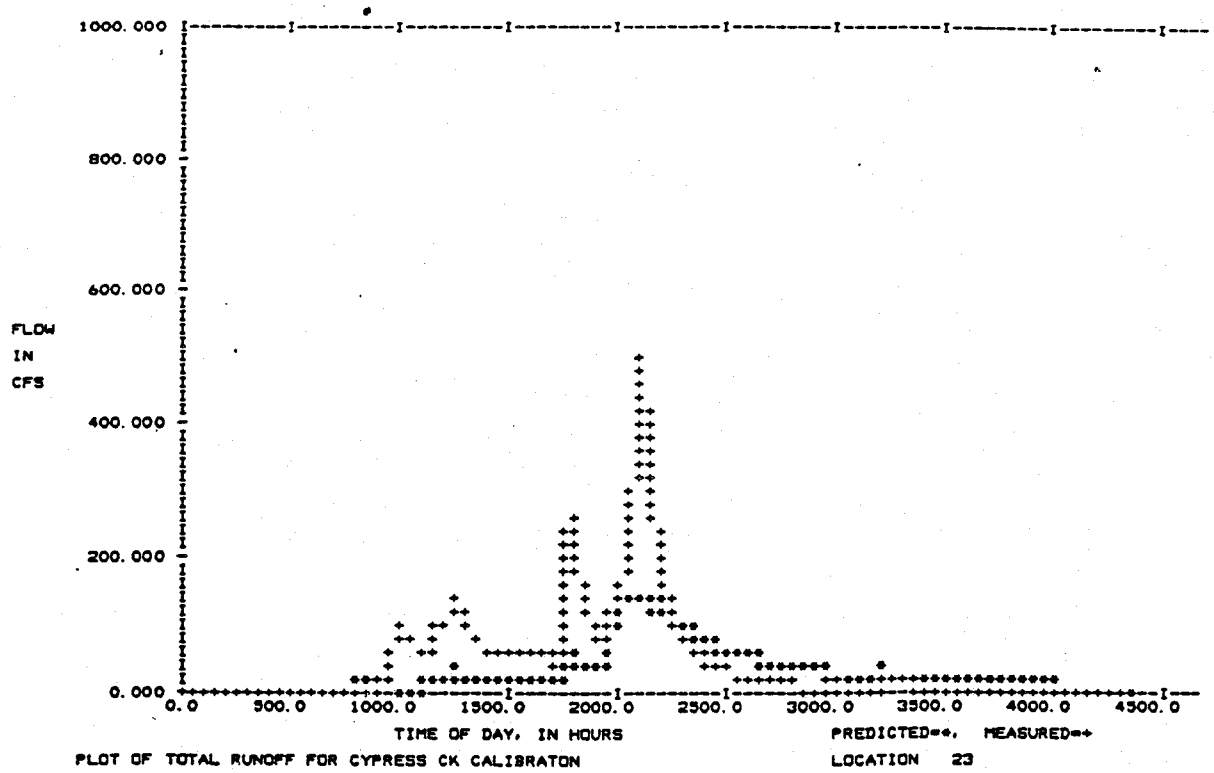
Figure X-17. Predicted and Measured Stages for Cypress Creek Verification.



HYDROGRAPH STATISTICS FOR LOCATION 21

	VOLUME CUBIC FEET	VOLUME INCHES	PEAK FLOW TIME, HR	PEAK FLOW FLOW, CFS	DURATION START, HR	DURATION END, HR	DURATION LENGTH, HR	NO. POINTS
PREDICTED, TOTAL TIME	0.42533E+09	3.780	2112.000	144.583	0.000	4350.000	4350.000	199
MEASURED, TOTAL TIME	0.71232E+09	6.330	2112.000	500.000	0.000	4320.000	4320.000	181
PREDICTED, OVERLAPPING TIME	0.42426E+09	3.770	2112.000	144.583	0.000	4312.000	4312.000	197
MEASURED, OVERLAPPING TIME	0.71232E+09	6.330	2112.000	500.000	0.000	4320.000	4320.000	181
DIFFERENCES, ABSOLUTE	0.28806E+09	2.560	0.000	355.417				
% OF MEAS		40.440		71.083				

Figure X-18. Predicted Groudwater Flow Hydrograph and Total Measured Flow Hydrograph for Cypress Creek Verification.



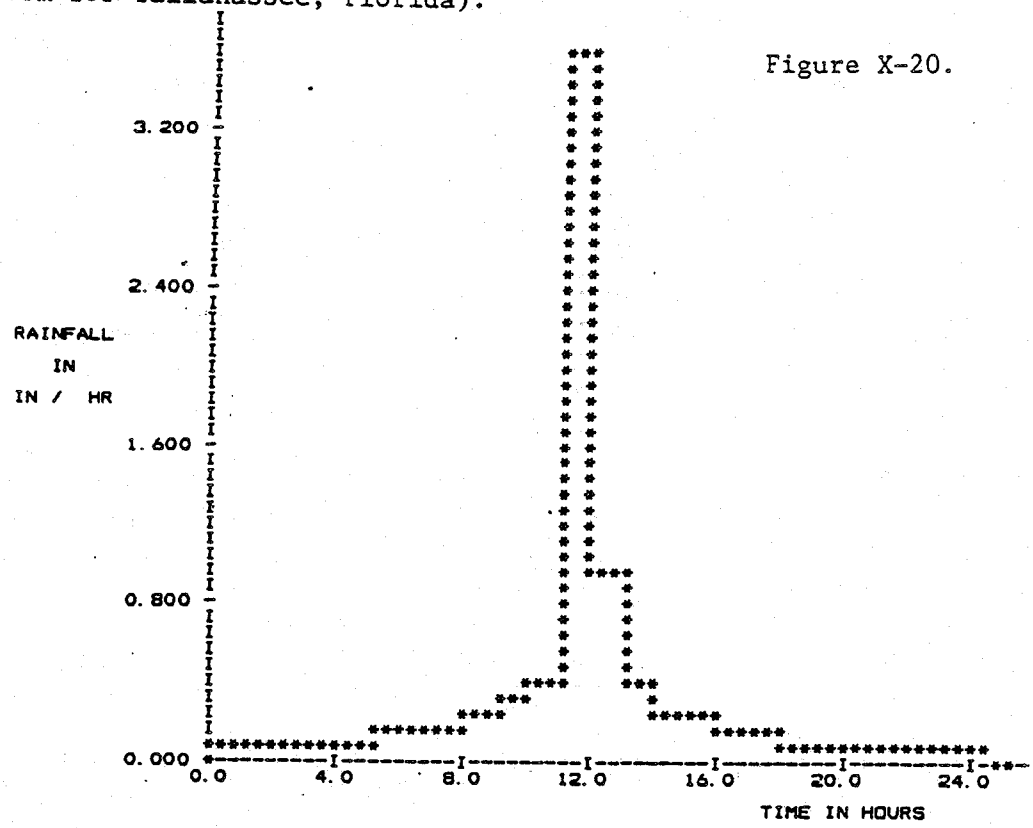
HYDROGRAPH STATISTICS FOR LOCATION 23

	VOLUME CUBIC FEET	VOLUME INCHES	PEAK FLOW TIME, HR	PEAK FLOW FLOW, CFS	DURATION START, HR	DURATION END, HR	DURATION LENGTH, HR	NO. POINTS
PREDICTED, TOTAL TIME	0.44397E+09	3.943	2112.000	149.908	0.000	4350.000	4350.000	199
MEASURED, TOTAL TIME	0.71232E+09	6.330	2112.000	500.000	0.000	4320.000	4320.000	181
PREDICTED, OVERLAPPING TIME	0.44289E+09	3.936	2112.000	149.908	0.000	4312.000	4312.000	197
MEASURED, OVERLAPPING TIME	0.71232E+09	6.330	2112.000	500.000	0.000	4320.000	4320.000	181
DIFFERENCES, ABSOLUTE	0.26943E+09	2.394	0.000	350.092				
% OF MEAS		37.824		70.018				

Figure X-19. Total Predicted Flow Hydrograph and Total Measured Flow for Cypress Creek Verification.

Hydrograph for Hypothetical Subcatchment (10-yr SCS Type II Design Storm for Tallahassee, Florida).

Figure X-20.



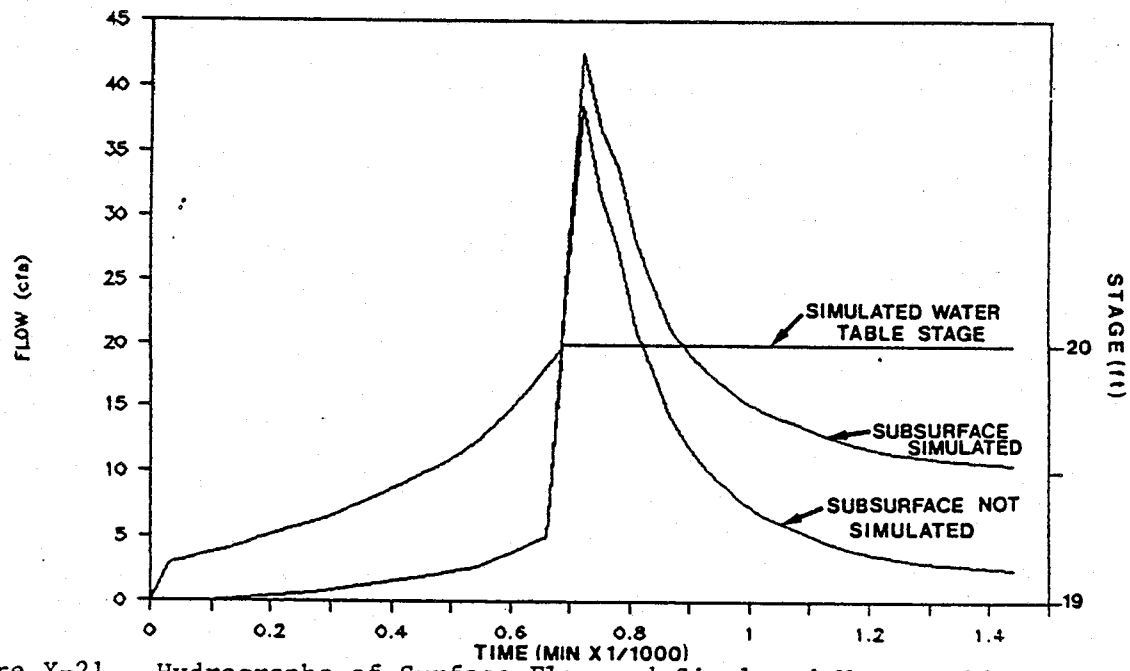


Figure X-21. Hydrographs of Surface Flow and Simulated Water Table Stage from Hypothetical Subcatchment. The Hydrographs are Identical Until the Water Table Reaches the Surface (20 ft).

Table X-2. Fate of Runoff With and Without High Water Table Simulation

Water Budget Component	Inches Over Total Basin	
	With Water Table Simulation	Without Water Table Simulation
Precipitation	8.399	8.399
Infiltration	6.637	1.731
Evaporation	0.103	0.104
Channel flow at inlet	1.495	2.407
Water remaining in channel	0.015	0.038
Water remaining on surface	0.150	4.124
Continuity error	0.001	0.005

Execution time on the IBM 3033 mainframe increased from 0.32 CPU seconds without the groundwater simulation to 0.42 CPU seconds with the groundwater simulation. Thus, some additional computational expense can be expected.

CONCLUSIONS

Although the subroutine is fairly simple in design and has several limitations, the new groundwater subroutine should increase the applicability of SWMM. Preliminary test runs have determined it to be accurate in the simulation of water table stage and groundwater flow. Further calibration and verification tests need to be done on other areas to confirm these preliminary results. Also, estimation of parameters, although fairly numerous, appears to be relatively uncomplicated. In addition, parameters are physically-based and should be able to be estimated from soils data. The flexible structure of the algorithm should permit a more realistic simulation of catchments in which a major hydrograph component is via subsurface pathways.