US Army Corps of Engineers

December 1981

FINAL REPORT TO CONGRESS

THE STREAMBANK EROSION CONTROL EVALUATION AND DEMONSTRATION ACT OF 1974 SECTION 32, PUBLIC LAW 93-251

Appendix C - Geotechnical Research

Rock Toe With Tie-Backs

Precast Block Paving

Board Fence Dikes

FINAL REPORT TO CONGRESS

THE STREAMBANK EROSION CONTROL
EVALUATION AND DEMONSTRATION ACT OF 1974
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APPENDIX C
GEOTECHNICAL RESEARCH

Consisting of

A SUMMARY REPORT OF LABORATORY RESEARCH AND FIELD EXPERIMENTS ON STREAM STABILITY AND IDENTIFICATION OF CAUSES OF STREAMBANK EROSION

U.S. ARMY CORPS OF ENGINEERS
December 1981

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ABSTRACT

Geotechnical research conducted by the WES addressed three specific topics in the Section 32 Program: (a) identify the causes and mechanisms of streambank erosion, specifically the influence of alluvial geology, and determine the techniques for monitoring the natural erosion processes and changes caused by human activities; (b) conduct research on soil stability, specifically the influence of soil properties on bank stability and the development of procedures for evaluating bank stability; and (c) investigate new methods and techniques for bank protection and river training structures either as part of a restoration system or as preventive measures. Geomorphological and waterborne geophysical studies indicate that most instances of extensive streambank erosion have been caused by complex interactions between hydrologic events, channel materials, and the effects of human activities along or in the affected channels. At given sites, the rates, characterization, and causes of streambank erosion were often determined using historical aerial photographic data, waterborne geophysical data, and river mechanics principles. The capability for laboratory measurement of soil erosion characteristics under hydraulic flows was attempted by an experimental flume for applying hydraulic shear stress to a soil sample; however, laboratory test results require field validation before application of these results in a predictive mode. Soil erodibility can be estimated using laboratory relationships among critical tractive shear stress, soil pore water and eroding (river) water chemistry, and electrical dispersion of the soil. A conceptual procedure combining erosion characteristics and slope stability analyses was developed for evaluating streambank stability. In the area of geotechnical research for new methods and techniques for bank protection, experimental prefabricated panels of coated fabrics were emplaced with hand-labor methods and light construction equipment to provide lower bank protection; upper bank protection was achieved by spraying liquid polymers on denuded areas to control erosion from rains until vegetation was reestablished.

PREFACE

This appendix summarizes research conducted during the period July 1975 through July 1981 by the Geotechnical Laboratory (GL), U. S. Army Engineer (USAE) Waterways Experiment Station (WES), under the auspices of the Corps of Engineers (CE) Steering Committee authorized by the Secretary of the Army through the Chief of Engineers pursuant to the Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251 (as amended by Public Law 94-587, Section 155 and Section 161, October 1976).

Research to address geotechnical elements inherent in the erosional processes was conducted by an ad hoc research team of the GL, WES. The Principal Investigators conducting the research were Dr. E. B. Perry, Dr. D. M. Patrick, and Mr. S. G. Tucker under the general direction of Mr. C. L. McAnear, Team Leader and Representative on the CE Steering Committee.

The research team was assisted in the investigation by Messrs. L. M. Smith, C. B. Whitten, J. R. May, W. J. Farrell, W. L. Murphy, J. C. Oldham, C. R. Styron, and D. W. White, GL, WES; Mr. T. J. Pokrefke, Hydraulics Laboratory, WES; and Mr. B. R. Winkley, USAE District, Vicksburg. Geophysical consultants providing expertise on systems and applications of seismic subbottom profiling were Mr. D. E. Abert, Ocean Seismic Electronics, Inc., Houston, Tex.; Mr. James McQuay, Marine Technical Services, Inc., Houston, Tex.; and Mr. Roger Caron, EG&G, Inc., Waltham, Mass. Academic researchers and advisors were Dr. K. Arulanandan, University of California, Davis; Dr. C. S. Alexander, University of Illinois; Dr. S. A. Schum, Colorado State University; and Dr. C. R. Thorne, University of East Anglia, United Kingdom. The technical support and coordination for the waterborne geophysical experiments provided by the geotechnical and hydraulics staffs of USAE Districts, Vicksburg, Pittsburgh, Omaha, St. Louis, and Memphis, and USAE Division, Missouri River, are gratefully acknowledged. Many valuable comments and suggestions contributed through informal liaisons, both in the United States and in the international community,

are acknowledged and appreciated. Technical information on products and applications of manufactured and/or processed materials provided by representatives of industry and trade associations is appreciated.

Conceptual guidance for the research was initiated by Messrs. J. P. Sale, Chief; S. J. Johnson, Special Assistant for Civil Works Research; R. G. Ahlvin, Assistant Chief; and R. L. Hutchinson, Pavement Systems Research Program Manager (all retired, formerly of GL, WES).

The research was conducted and this report was prepared by the research team under the general guidance of Mr. C. L. McAnear, Chief, Soil Mechanics Division, GL; Dr. D. C. Banks, Chief, Engineering Geology and Rock Mechanics Division, GL; and Mr. A. H. Joseph, Chief, Pavement Systems Division, GL. The report was reviewed by Mr. Woodland G. Shockley, Consultant to the GL. Mr. J. P. Sale was Chief of the GL during the initial research, July 1975-January 1980. Mr. C. L. McAnear and Dr. D. C. Banks were alternately Acting Chief, GL, during the final phase of the research and preparation of this report.

COL Tilford C. Creel, CE, was the Commander and Director of the WES during preparation of this report. Mr. Fred R. Brown was the Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.873	square metres
cubic feet per second	0.02831685	cubic metres per second
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
Fahrenheit degrees per minute	5/9	Celsius degrees or Kelvins* per minute
feet	0.3048	metres
feet per mile	0.0018939	metre per metre
feet per second	0.3048	metres per second
gallons	0.01	metre per second squared
gallons (U. S. liquid) per minute	0.00006309	cubic metre per second
horsepower	745.6999	watts
inches	25.4	millimetres
miles (U. S. statute)	1.609347	kilometres
ounces	28.34952	grams
ounces per square yard	0.03390575	kilograms per square metre
pounds (mass)	0.4535924	kilograms
pounds (mass) per square feet	4.882428	kilograms per square metre
square feet	0.09290304	square metres
square miles (U. S. statute)	2.589998	square kilometres
tons (2,000 lb mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

SUMMARY

Introduction

Engineering geologic and waterborne geophysical studies improved the understanding of fluvial geomorphological processes on streambank erosion. The understanding of the erosion resistance or susceptibility of various soils and the effects of those characteristics on streambank stability was increased. Materials and construction methods previously developed in surface stabilization research were adapted to bank protection structures using laboratory modeling techniques and experimental field installations.

Description of Tasks

The technical tasks specified in the legislation were the development of new materials and techniques for bank protection, research on soil stability, and identification of the causes of erosion. These have been implemented into three research tasks as follows: Identify the Causes and Mechanisms of Streambank Erosion, specifically the influence of fluvial geology and the techniques for monitoring the natural processes and the changes caused by human activities; Conduct Research on Soil Stability, specifically the influence of soil properties on bank stability and the development of procedures for evaluating bank stability; and Investigate New Methods and Techniques for Bank Protection, specifically recent developments in materials usage and soil treatments that may be applicable to bank protection and river training structures either as part of a restoration system or as preventive measures.

To accomplish these tasks and other related activities under the Section 32 Program, the Geotechnical Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) established an ad hoc research team combining specialized technologies in geology, soil mechanics, soil stabilization, data-gathering systems, and materials development. Active liaison was maintained with related research tasks in other disciplines, notably hydraulics. In addition to the research team, well-known consultants in the academic and private communities were engaged to effectively utilize and demonstrate the state of the art.

Objectives and Approach

Influences of fluvial geology on causes and mechanisms of streambank erosion

Objectives. The objectives were to define the causes and mechanisms of streambank erosion in terms of the influence of fluvial geology and to develop techniques for monitoring fluvial conditions in stream channels.

Approach. Approximately 20 representative river sites nationwide where erosion is occurring were studied to identify factors relative to site characteristics that may cause or affect erosion. This investigation included streams exhibiting diverse geologic, hydraulic, and hydrologic conditions. A partial list of general data elements collected and analyzed included stream depth, channel and valley geometry, meander configuration, climatic influences, and material properties. Historical changes in fluvial geomorphology were studied at selected sites, using aerial photography and topographic maps to interpret the causes of geomorphic changes and to determine the mechanisms involved in bank erosion. The historical analyses were used to aid in the formulation of a working hypothesis for the causes and mechanisms of streambank erosion and to develop a systematic approach to identifying erosion-susceptible banks.

Four river reaches were chosen for examination by side-scanning sonar and continuous seismic reflection profiling techniques to determine the feasibility of using such methods to monitor features and events occurring on channel beds and subaqueous portions of channel banks. The methods were validated and technical guidelines for their use were prepared. These methods provide general data on the effect of sediment transport on the streambed and may also give some indication of changes taking place along the banks.

The products of these studies were the identification of some site-specific factors that may cause or contribute to streambank erosion and the evaluation of erosion or accretion occurring under various conditions. The aim of this work was to develop a sound basis for prediction of erosion problems in diverse geologic, hydraulic, and hydrologic regimes by identifying factors contributing to erosion. The geophysical program contributed to the understanding of relations between sediment transport accretion and erosion and provided additional site data to the inventory.

Research on soil properties affecting bank stability

Objectives. The erosion characteristics of cohesionless soils, which are controlled by gravitational forces, are fairly well understood. However, the development of a procedure for streambank stability analysis has been stymied, in part, by a lack of understanding of the erosive characteristics of cohesive soils, which are controlled by physical and electrical surface phenomena. Thus, the objectives were to develop laboratory equipment and test procedures for measuring erosion rate versus local hydraulic (tractive) shear stress for natural or remolded cohesive soils; to conduct laboratory tests on representative samples of natural cohesive soils and river water to develop generalized procedures for predicting critical tractive shear stress and rate of erosion caused by current action along streambanks; to develop a procedure for evaluating streambank stability using erosion and shear strength properties determined from laboratory tests conducted on undisturbed samples of natural cohesive soil; and to estimate bank recession at selected time intervals resulting from erosion and slope failure of similar natural soils for flows at normal water level and for rapid drawdown.

Approach. Based on the state-of-the-art capability in soil testing and liaison with current research investigators, a rationale was conceived for a method to estimate the erodibility of natural undisturbed cohesive soils. Testing samples representative of a geographical distribution of uniform natural soils and the respective river water yielded empirical evidence of the influence of various parameters on the erosion susceptibility of soils. The capability for laboratory measurements of soil erosion characteristics under hydraulic flows was expanded by an experimental self-contained laboratory recirculating tilting flume for applying hydraulic shear stresses to a soil sample. A procedure for evaluating streambank stability was developed that utilizes laboratory- or field-measured soil erosion as well as conventional soil parameters in simulated field conditions.

Geotechnical research on new methods and techniques for bank protection

Objectives. The objective was to study the application of new materials and construction techniques in geotechnical engineering to streambank protection. Additionally, materials and methods developed for other applications, such as expedient pavement surfacings and waterproofers, were investigated as to their applicability for streambank protection and restoration.

Approach. Fabricated metal panels developed for use as landing surfaces for aircraft were investigated for lower bank protection. Many panels of different materials and configurations have been developed, and extensive studies of various panel joints, connectors, and anchoring devices have been conducted. A vast amount of experience and technology exists for this type of material. Concepts also were considered for the use of prefabricated membranes such as medium-weight and lightweight impervious membranes as well as perforated membranes and double-walled membranes that can be filled with soil or grout. Various applications of membranes were evaluated with attention directed to anchoring configurations, construction techniques, and cost analysis. Chemical soil stabilization techniques were investigated for upper bank protection where liquid polymers are sprayed on denuded areas to protect the bank until vegetation becomes established and provides protection.

Two fabricated metal panels were simulated using aluminum plates and placed along the bank of a scale model of a curving sand channel. The panels were placed with and without filter cloth and anchoring systems while several flow regimes were investigated. Several prefabricated membranes were tested concurrently, and their ability to sustain the various flow regimes without erosion and movement of the underlying sand particles was noted. Five materials were sprayed on a local hillside for study as upper bank protectors. These materials were a polyvinyl acetate emulsion, a copolymer emulsion of acrylate and methacrylates, a penetrating grade of cutback asphalt, an acrylate resin emulsion, and a resinous material processed from oil shale and organic materials. Automated data recording devices collected and recorded meteorological data and soil temperatures periodically.

Concepts for bank protection were investigated at two field experimental test sites using membrane blankets, the membrane-encapsulated soil layer (MESL), and the stepped MESL. Additional soil stabilizing materials that appeared to be potentially suitable for retarding streambank erosion also were evaluated in the field experiments. Technical guidelines for all practicable bank protection systems studied have been prepared as instructional reports and technical papers.

Summary of Findings

Findings resulting from the research conducted under Work Unit 4 are summarized below.

Influences of fluvial geology on causes and mechanisms of streambank erosion

Rivers are complex, dynamic systems, which exist in a state of quasi-equilibrium in terms of flow, sediment discharge, hydraulic geometry, climate, and geomorphic development. A state of dynamic, quasi-equilibrium also exists between a river and its upstream and downstream tributaries.

Geologic materials in channels and banks are important factors controlling fluvial behavior. Bedrock occurrence in channels and along banks is of more importance in controlling the location of erosion than soils. Generally, the occurrence of bedrock in a streambank will lessen the chances of erosion of that bank but may deflect currents against other bank areas which are not formed in bedrock and may, therefore, be susceptible to erosion. Bedrock in channels of degrading streams will result in steep gradients and high velocities at the bedrock locations producing extensive erosion of soils in the banks. Soils control the location and rates of erosion on the basis of their relative erodibility and on the basis of the stability of the soil mass. Sliding, slumping, and general slope instability are probably as common as soil erodibility. Once a channel bank has reached its long-term stable slope, slope instability generally should not be a problem except as it is caused by erosion and other external processes.

Conventional aerial photography provides a relatively rapid and inexpensive means of studying and monitoring bank erosion sites. The examination of historic photography is particularly important in identifying trends and baselines. River mechanics provide a methodology for quantification of the information derived from the aerial photography. On large streams waterborne geophysical techniques are useful for monitoring fluvial behavior and identifying causes of adverse fluvial behavior.

Generally, the occurrence of streambank erosion at many, if not most, sites can be related to both natural and accelerated (human-induced) causes. The evidence suggests that accelerated erosion is significant at many sites. Those human activities that appear to most often affect fluvial behavior and contribute to massive bank loss are: channelization, existence of dams on streams having large bed loads, agricultural and forestry practices, and urbanization. In many areas, streams have reacted to more than one of these activities. Among these general human activities, channelization and overintensive land use are potentially the most adverse.

Research on soil properties affecting bank stability

Procedures were developed for measuring erosion of soil samples using a laboratory recirculating tilting flume. Methods were developed to predict soil erosion in the field. Analyses of laboratory test results obtained using a flume and rotating cylinder apparatus at the University of California, Davis, revealed relationships among critical tractive shear stress, electrical properties of the soils, and rates of erosion for saturated remolded soils using distilled water as the eroding fluid. Correction factors were obtained for the effects of remolding and salt concentrations of the eroding fluid. The laboratory relationships can be adjusted by the correction factors to estimate erodibility of saturated undisturbed soil subjected to current induced tractive shear stress by river water for use in bank stability analyses.

The analysis of streambank changes caused by soil erosion is analogous to conventional stability analysis of an excavated slope. Bank recession with time can be estimated by using a conceptual procedure that combines erosion characteristics and conventional soil parameters used in limit equilibrium slope stability analyses. Erosional changes in geometry, such as toe recession or bed degradation, can precipitate slope failure with resulting top retreat of the streambank. The bank recession with time is equal to the cumulative bank recession caused by erosion and slope failures. The analysis of a generalized streambank section evaluated for bank and bed erosion and slope stability under normal flow conditions and during the passage of flood is illustrated by an example problem in Part II of this Appendix.

To evaluate streambank stability, it is necessary to estimate changes in geometry due to erosion and slope movements. Bank recession or bed degradation estimated from the laboratory relationships developed for tractive (current) erosion is an approximation because it does not take into account such things as accretion along the banks, secondary currents, freeze-thaw, and bed aggradation as eroded soil from upstream is deposited at the reach of the river under consideration. A sediment transport analysis that includes hydraulic sorting and armoring would be necessary to include the effects of deposition. In addition to changes in geometry due to current erosion, bank failure causes changes in geometry. Bank failure results when the induced shear stresses exceed the shear strength of the bank soils. Increases in shear stress can result from increase in slope height or steepness, increase in external loads (surcharge), and rapid drawdown of the river. Decreases in shear strength of the soil can result from an increase in pore water pressure, soil expansion, or shear movements.

Simple homogeneous banks are most easily handled by the suggested procedure for evaluating streambank stability. Simplifying procedures common in conventional soil mechanics practice permits complex heterogeneous banks to be evaluated. The suggested procedures are slightly more complex and unique only in that the erodibility of the bank soils is incorporated into the assessment of equilibrium and potential bank failure.

The research developed theoretical approaches and the use of experimental laboratory equipment and procedures. Field validation is highly desirable and, in fact, required to establish the credibility of the laboratory results and the conceptual approaches.

Geotechnical research on new methods and techniques for bank protection

Potential applications of new materials, construction methods, and techniques for protecting streambanks were investigated in model, small test plots and prototype field tests. The materials and innovative methods found suitable for placement on streambanks are cost-effective, as well as readily available from commercial sources, and can be used by private landowners having only limited resources available such as hand labor and light equipment.

Spray-on soil stabilizers proved satisfactory for upper bank erosion control and aided in establishment of a vegetation cover. Aluminum honeycomb grids used to confine denuded soil provided erosion protection against rainfall and wind until vegetation could be reestablished. Impervious membranes provided erosion protection when placed as blankets and are most suitable for rapid placement as temporary protection. The MESL constructed as slabs or steps are more durable when heavier protection is needed. These materials can be used on stable banks without expensive grading and shaping of severely eroded banks. Riprap used as edge and toe restraints and filter fabrics used for drainage control were effective. Jute bags filled with sand failed when used as edge and toe protection, but bags filled with concrete mix performed satisfactorily.

All of the test materials provided good erosion protection under normal and bank-full stream conditions and were only damaged when deep-seated bank failures occurred during rapid drawdowns.

Technology Transfer

The research results will be incorporated into Corps technical guidance, such as engineer manuals and technical letters, and will be included in related training courses for engineering and design personnel. A training course dealing specifically with streambank erosion and the results of the Section 32 Program will be offered.

The laboratory recirculating tilting flume developed in this research has been used to examine the erodibility of rock downstream of the spillways at two Corps of Engineers (CE) dams.

Methodologies and geomorphological and geophysical data derived from these studies were provided to the Lower Mississippi Valley Division (LMVD) on the White and Mississippi Rivers and in the Yazoo River basin; similar support was provided to the Missouri River Division for stretches of the Missouri River. Geomorphological data derived from studies conducted in the Yazoo River basin have been provided to the Soil Conservation Service. Support has been provided to the North Pacific Division during the aftermath of Mt. St. Helen's eruption and to the South Pacific Division for beach erosion studies. The effectiveness of waterborne geophysical techniques demonstrated under this Section 32 program has expanded the use of this technology by CE Districts to monitor channel processes.

Technical guidelines for all practical bank protection systems have been prepared as instructional reports and technical papers.

Results of research emanating from this work unit and reported in technical documents and professional presentations to professional, technical, and trade organizations, and to the academic and private practice communities, and the public sector are summarized in Exhibit 1.

Recommendations

The following recommendations are derived from the research conducted under Work Unit 4.

Influences of fluvial geology on causes and mechanisms of streambank erosion

Proposed hydraulic structures and other hydrologic projects should include, as a part of their designs, increased evaluation of the potential influence of the structure or project on the fluvial geomorphology. Those projects involving dams or channelization should receive careful study.

To the extent practicable, comprehensive, interdisciplinary basin-wide studies should be conducted for the purposes of establishing detailed data bases and determining the relations between water resource requirements and the impact of these requirements on fluvial geomorphology as well as on environmental quality.

The operation and maintenance of existing projects should include a periodic review of upstream and downstream fluvial conditions for the purpose of identifying potential adverse effects and for planning remedial actions, if necessary. On large, navigable streams, periodic waterborne geophysical surveys should be made.

Research on soil properties affecting bank stability

The laboratory equipment and relationships developed in this research for predicting the critical tractive shear stress and erosion rate for saturated undisturbed cohesive soils subjected to tractive shear stresses from river water should be field validated to establish the credibility of the conceptual approaches. Analytical procedures should be expanded to include variable hydraulic regimes and geomorphic processes. Additional laboratory and field research should be conducted to better simulate the whole erosion processes which influence bank stability.

Geotechnical research on new methods and techniques for bank protection

Spray-on soil stabilizers, particularly the synthetic latex and emulsion materials that were the most effective, should be considered for use to aid the initial establishment of vegetation on denuded top bank areas. Aluminum grids in conjunction with induced vegetation are recommended when more expensive erosion control measures are not justified, but where something more substantial than vegetation alone is required.

Impervious membrane materials, such as laminated vinyl-coated nylon, are easily constructed with hand labor and light equipment, are readily available from commercial sources, are cost-effective, and should be considered suitable for erosion protection by private landowners and others having limited resources available. The blanket method should be considered where the banks require a light protective surface to prevent erosion by current and wave action and the MESL slabs as a medium-type protection when loose surface conditions exist on banks. The stepped MESL can be used as heavy duty protection in areas where severely eroded and caved banks are nearly vertical as this method eliminates extensive grading and shaping of the banks.

Exhibit 1

Research Reports, Publications, and Presentations

Influence of fluvial geology on causes and mechanisms of streambank erosion

May, J. R. 1981. "Engineering Geology and Geomorphology of Streambank Erosion; Report 3, Application of Waterborne Geophysical Techniques in the Fluvial Environment," Technical Report GL-79-7, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Patrick, D. M. and Whitten, C. B. 1981 (Mar). "Geomorphic Studies of Tillatoba Creek, Mississippi," Abstracts with Programs, Southeastern Section, Geological Society of America Annual Meeting.

__________. 1981 (May). "Aerial Photographic Studies of Tillatoba Creek Basin, Mississippi," Abstract, Mississippi Section, American Society of Civil Engineers Annual Meeting.

Patrick, D. M., Smith, L. M., and Whitten, C. B. 1981. "Methodologies for Studying Accelerated Fluvial Change," Proceedings of the International Workshop on the Engineering Management of Gravel Bed Rivers, Wales, Wiley Publishing Co., New York.

Smith, L. M. and Patrick, D. M. 1979. "Engineering Geology and Geomorphology of Streambank Erosion; Report 1, Eel River Basin, California," Technical Report GL-79-7, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Whitten, C. B. and Patrick, D. M. 1981. "Engineering Geology and Geomorphology of Streambank Erosion; Report 2, The Yazoo Basin Uplands, Mississippi," Technical Report GL-79-7, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Research on soil properties and bank stability

Arulanandan, K., Gillogley, E., and Tully, R. 1980. "Development of a Quantitative Method to Predict Critical Shear Stress and Rate of Erosion of Natural Undisturbed Cohesive Soils," Technical Report No. GL-80-5, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Oswalt, N. R., Mellema, W. J., and Perry, E. B. 1981 (May). "New Means for the Protection of Banks and Bottom of Waterways Against the Attack by Currents and Waves, Including Those Generated by Ships," 25th Permanent International Association of Navigation Congresses, Edinburgh, Scotland.

Perry, E. B. 1979. "Development of a Quantitative Method to Predict Critical Shear Stress and Rate of Erosion of Natural Undisturbed Cohesive Soil," Engineering and Scientific Research at WES, U. S. Army Corps of Engineers Information Exchange Bulletin, Vol 0-79-3.

_________. 1981 (Feb). "Bank Protection I," Presentation to Course on Hydraulic Design of Flood Control Channels, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

_________. 1981 (Aug). "Streambank Protection Using Used Auto Tires," American Society of Civil Engineers Specialty Conference Water Forum, San Francisco, Calif.

Perry, E. B. and Maynard, S. T. 1979 (Nov). "Corps of Engineers Bank Stabilization Demonstration Projects," Presentation to Conference on Arroyo Stabilization in Erosive Soil, Albuquerque, N. Mex.

Geotechnical research on new methods and techniques for bank protection

Oldham, Jessie C. 1979. "Section 32 Program, Streambank Erosion Control, Evaluation and Demonstration, Work Unit 4, Research on Soil Stability and Identification of Causes of Streambank Erosion; Evaluation of Spray-On Stabilizers for Bank Protection," Investigation Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Spivey, Alston C., Jr., and Styron, Clarence R., III. 1979. "Section 32 Program, Streambank Erosion Control, Evaluation and Demonstration, Work Unit 4, Research on Soil Stability and Identification of Causes of Streambank Erosion; Investigation of a Grid for Bank Protection," Investigation Report 3, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Styron, Clarence R., III. 1979. "Section 32 Program, Streambank Erosion Control, Evaluation and Demonstration, Work Unit 4, Research on Soil Stability and Identification of Streambank Erosion; Evaluation of Rigid and Flexible Materials for Bank Protection," Investigation Report 2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Webster, Steve L. 1974. "Construction of MESL Demonstration Road at Fort Hood, Texas, May 1972," Miscellaneous Paper No. S-74-13, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

White, Dewey W., Jr. 1981. "Evaluation of Membrane-Type Materials for Streambank Erosion Protection," Miscellaneous Paper No. GL-81-4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Steering committee

McAnear, C. L. and Grace, J. L. 1981 (Jan). "Overview of Use of Stone for Erosion Control," Presentation for Workshop on Stone for Erosion Control at the 64th Annual Convention of the National Crushed Stone Association, New Orleans, La.

APPENDIX C: RESEARCH ON SOIL STABILITY AND IDENTIFICATION OF CAUSES OF STREAMBANK EROSION (WORK UNIT 4)

PART I: INFLUENCES OF FLUVIAL GEOLOGY ON CAUSES AND MECHANISMS OF STREAMBANK EROSION

Research Plan

1. The objective of this research task was to define causes and mechanisms of streambank erosion in terms of the influence of fluvial geology and to develop techniques for monitoring sedimentological conditions in stream channels. Representative river sites were studied to identify factors relative to site characteristics that may cause or affect erosion. This investigation included historical analyses of streams exhibiting diverse geologic, hydraulic, and hydrologic conditions. A partial list of general data elements collected and analyzed included stream depth, channel and valley geometry, meander configuration, climatic influences, and material properties.

2. Selected sites were chosen for examination by waterborne geophysical methods consisting of sidescanning sonar and acoustical subbottom profiling techniques to determine the feasibility of using such methods to monitor features and events on channel beds and subaqueous portions of channel banks. Basically, these methods are capable of providing data on the effect of sediment transport on the streambed and data on changes taking place along the banks.

3. The products of these studies are the identification of site-specific factors that cause or contribute to streambank erosion and the evaluation of erosion or accretion occurring under various field conditions. This work lends itself to the development of a sound basis for prediction of erosion problems in diverse geologic, hydraulic, and hydrologic regimes by identifying the factors contributing to erosion. The geophysical monitoring program contributes to the understanding of relations between sediment transport, accretion and erosion, and provides additional site data on bottom and subsurface conditions.

Essential Elements of Fluvial Geomorphology

General

4. The identification of the causes of streambank erosion and the development of plans for the mitigation of bank erosion require a rather detailed understanding of natural and human-altered fluvial processes in general and detailed information on the fluvial geology of the area in question. The interrelations between the fluvial processes and geology comprise the discipline of fluvial geomorphology. Fluvial geology in a broad sense includes all aspects of the regional geologic environment which may control or affect fluvial processes at a given site or area. Specifically, it includes the nature of the valley alluvium and of the material upon which the alluvium rests. The geologic or geomorphic information developed for a given site or reach of river must be integrated with geotechnical and hydraulic information relevant to the design of erosion control structures. This same integration of data is also necessary in the planning of new hydraulic projects in order to consider the effects of new structures on local or regional bank erosion. In the past, integrated interdisciplinary planning has not been the usual approach.

5. The understanding of specific causes of streambank erosion must involve several elements; namely, the relations between fluvial geomorphology and river mechanics, the relations between upstream and downstream tributaries within the drainage basin, the significance of temporal relations, and the actual or potential impact of human activities. The use of these elements in understanding the causes of bank erosion as well as ancillary considerations will be presented later in this section as well as subsequent sections.

Classification and characterization of streams

6. Streams may be classified on the basis of either the morphology of the individual stream (or reach) and on the stream pattern within the drainage basin. Also, streams may be categorized as either alluvial or bedrock depending upon the presence or absence

of alluvium within the stream channel. Streams may be classified morphologically as straight, braided, or meandering; if meandering, classifications may include the size of the meander bends. Stream pattern classifications are based upon the arrangement of the drainage within a drainage basin and usually reflect structures and discontinuities in the rocks underlying the channel. Parallel, rectangular, radial, and trellis are types of drainage patterns which are controlled by structures and discontinuities; whereas, dendritic patterns often occur in structureless, homogeneous rock.

7. In alluvial channels the bottom of the channel is situated in alluvium, some of which is being transported by the flowing water. On the other hand, bedrock channels are those in which little or no alluvium is present. Alluvial streams may be classified on the basis of the grain size of their channel or bed material, for example, clay-, sand-, or gravel-bed streams. The bed material of alluvial streams is usually characteristic of the mode of sediment transport. Two principal modes are suspended load and bed load. Suspended load streams are those in which the channels are predominately fine grained, and much fine-grained material is being transported in suspension. On the other hand, bed load streams exhibit predominately sandy or gravel channels with similar material being transported on the streambed. Schumm (1971) has presented a useful classification of alluvial channels on the basis of sediment transport mode and channel stability. Schumm recognized three transport modes: suspended load, mixed load, and bed load for which he gave three possible conditions of relative stability; namely, a stable channel (graded stream) in which neither erosion nor deposition predominate, a depositing channel exhibiting an excess of load, and an eroding channel exhibiting a deficiency of load. Any transport mode could exhibit any stability condition.

8. Schumm's alluvial channel classification is important in the analysis of streambank erosion because it emphasizes the significance of sediment load (which will be discussed in later sections) and because it points out the fact that streams exhibit natural erosion. Schumm's classification, in fact, may be more applicable to relatively

short reaches or to exclusively natural conditions. This results from the fact that the classification scheme does not associate erosion with excess load. Later sections will show that excessive sediment load can be associated with erosion.

9. Channel stability is difficult to define. Obviously, a particular short reach of river which has remained in place with unchanged channel geometry and pattern over many years or generations would be considered stable. A longer reach, perhaps 10 miles long, may exhibit segments in which significant changes (erosional or depositional) are occurring; however, the net change over the entire length may be zero; i.e., the amount of material removed by erosion equals the amount deposited. In the second case, a riparian owner on an eroding segment would not consider his segment stable; however, the longer reach would have to be considered stable in a technical sense. On the other side of the spectrum are the "wild" streams, those which over many miles exhibit either an excess or a deficiency in sediment load. The results of either excess or deficiency in sediments may, either directly or indirectly, lead to bank erosion as well as other fluvial modifications.

10. In discussing the characterization of streams, it is important to realize that erosion is an expected and necessary part of natural, fluvial processes. The erosion may occur on the channel bed or banks and is generally caused by changing flow conditions resulting from changing meteorological (precipitation) events within the basin. Examples of natural fluvial change accompanied by erosion are the cutoff of meander loops by high or flood stage flows and the downstream migration of meander bends during normal flow conditions in meandering, alluvial streams. While a natural stream is in a state of dynamic equilibrium, the equilibrium may be altered by human activities that may also result in erosion. Erosion produced by human causes is called accelerated erosion (see paragraph 38). The distinction between accelerated erosion and natural erosion should be an important element of site-specific or general studies of streambank erosion.

Channel materials

11. The nature and type of bed and bank materials will affect the location and rate of erosion. Usually, the materials forming banks and beds of streams are quite variable, particularly for large meandering, alluvial streams. The variability includes both the types of materials, i.e., clays, sands, and gravels, and the shapes of the deposits. The variability results from different environments of deposition which characterize fluvial processes on a large floodplain. Common environments of deposition include: (a) point bar deposits, which are sandy materials on the inside of meander loops; (b) backswamp deposits, which are clayey, fine-grained materials originating from overbank (flood) flows; and (c) clay plugs, which are fine-grained materials deposited in oxbow lakes. Other environments of deposition may also be present. Ordinarily, erosion will be most likely to occur in materials that are granular and possess minor amounts of clay-size particles. Krinitzsky (1965) has shown the relations between bank erosion and environments of deposition on the lower Mississippi River. Also, the possible influence of bedrock on erosion potential both under the channel and at the banks should be considered.

12. The analysis of actual or potential bank erosion requires that considerable geologic information be obtained. For the valley alluvium, information on the type of material, its thickness and stratigraphy, and environment of deposition must be known. The age, stratigraphy, lithology, structure as well as strength, and other geotechnical properties should be determined for rock underlying the alluvium or exposed in the bed and banks.

River mechanics

13. The concepts and principles of river mechanics are important tools which provide semiquantitative information on the causes of fluvial modification. Basically, the river mechanics theory explains observed morphological changes in channel characteristics in terms of changes in water discharge (flow) and sediment discharge. Five empirical proportionalities, shown below, illustrate these relations.

$$W \alpha Q Q_s$$

$$W/d \alpha Q_s$$

$$d \alpha Q$$

$$S_c \alpha \frac{Q_s D_{50}}{Q}$$

$$S \alpha \frac{S_v}{Q_s}$$

where

W = stream width

Q = flow

Q_s = sediment

d = stream depth

S_c = channel slope

D_{50} = mean sediment size

S = sinuosity

S_v = valley slope

14. These relationships, given as proportionalities, are actually complex power functions and should, therefore, be considered to represent approximations. Even so, they are important in quantifying data and in determining the magnitude and possible cause of fluvial change whether natural or accelerated (Leopold and Maddock 1953, Lane 1955, and Simons 1979).

15. The use of these relations involves the application of methodologies for measuring fluvial change and consideration of temporal relations both of which will be addressed in later sections. However, it is helpful here to give an example of the use of these relations. Suppose that observation of a particular reach over a period of time has revealed an increase in stream width (W). Such an increase would involve erosion of one or both banks. River mechanics relations (proportionality 1) would indicate that the erosion has been

caused by an increase in either flow (Q) or sediment discharge (Q_s) or both. With this information, it is possible to investigate causes for increased Q and Q_s . Possible natural causes for increased Q and Q_s would include prolonged, atypically high precipitation events within the drainage basin producing larger runnoff and, consequently, larger channel flows. On the other hand, increased sediment discharge could result from intensive upland land use and subsequent erosion in some portions of the basin.

Temporal relations

16. Temporal relations consist of identifying the significance or meaning of observed fluvial changes in terms of the time frame over which the changes have been observed. There are several considerations, including dynamic equilibrium, time scale, and expected changes with time. Dynamic equilibrium means that streams will respond to changes in flow or sediment discharge in accordance with the principles of river mechanics (as explained previously) and will attain morphologies in equilibrium with these flows or sediment discharges. On the other hand, there may be a more-or-less continuous and long-term change in flow or sediment discharge which will result in continually changing morphologies. Examples of changes which have occurred on river systems during and since the Pleistocene are abundant. A relationship between channel gradient and geologic time is illustrated by Figure C1 (Schumm 1971). If the change in channel gradient is considered over a long period of time, perhaps thousands of years, the change appears to be approximately uniform. However, if the change in channel gradient is examined over a much shorter (and nonspecified) duration of time essentially no change is observed (see insert on Figure C1). Thus, natural fluvial systems should be expected to change with time; however, the changes may occur slowly. A further complication is that certain fluvial changes which are observed to occur relatively rapidly may not be natural but may be caused by human activities. A final implication which is derived from a consideration of temporal relations is the need for long-term monitoring or observation of fluvial systems of interest in order to measure fluvial change and the causes thereof.

Climate

17. The driving force contributing to the development of a particular geomorphic condition is the local and regional climate. Climate is a stochastic (or probabilistic) and periodic process, meaning that inferences about the process are based upon an incomplete set of data and the process appears to repeat itself in a more-or-less regular and predictable fashion.

18. Climate affects geomorphology by defining the hydraulic conditions (particularly flows) and by defining (or at least influencing) weathering and soil formation which control sediment yield in the basin. The significance of climatic controls on long-term fluvial geomorphology has been shown in some detail by Schumm (1971) in studies of the changes that have occurred in certain streams since the Pleistocene. These changes are important aspects of fluvial geomorphology, and they include channel width, depth, and sinuosity.

19. Granted that the climatic changes occurring since the Pleistocene have changed the nature of certain streams, it is necessary to consider to what extent smaller scale, gradual climatic changes occurring over a few score years might change stream characteristics, particularly if accompanied by extensive change in the regional land use. No doubt small-scale climatic changes would play a role, but it seems unlikely that such changes would result in extensive stream modification.

20. On the other hand, the periodically occurring extreme climatic event such as a flood would be expected to contribute, at least locally, to stream morphology modification. The cutting off of meander loops during floods in sinuous alluvial streams is an example of such fluvial modification. However, the flood does not necessarily alter the entire meander system, which must exist in such a configuration as to most expeditiously transport the stream load. These local changes may be quite significant, but it is questionable whether, in a natural system, the extreme event could produce extensive and massive stream modification alone since, at least to a certain extent, the natural stream would also be adjusted to extreme conditions.

21. Perhaps of more importance would be those situations in which the periodicity of extreme climatic events became more frequent such as extended periods of heavy rains, extended periods of drought, or repetitive flood and drought. These extreme circumstances would appear as miniclimatic changes and could affect changes in stream morphology. The common phenomena of fairly extensive bank failure associated with rapidly changing water level are indicative of the results of changes in climatic periodicity. As will be shown, these climatically induced problems may be aggravated by human activities.

Drainage basin

22. An individual stream or reach of stream is in dynamic equilibrium not only with respect to flow and sediment discharge along the stream or reach, but also with both upstream and downstream tributaries within the drainage basin. Thus, an observed fluvial modification occurring at one site may be caused by conditions or events practically anywhere within the basin. Furthermore, analyses and studies of bank erosion problems cannot be limited to the site in question but must include (in varying degrees of detail) basin-wide evaluations. Studies of drainage basins should include geologic conditions that could contribute to instability such as landslide susceptibility, seismicity, and erosion susceptible soils. The studies also should include human activities such as dams, channelization and meander cutoffs, mining, quarrying, and agriculture and forestry operations. Historic meteorological events also should be considered.

Mechanisms and Causes of Streambank Erosion

23. Previous discussions have described theoretical and practical aspects that must be considered in order to properly understand the causes and types of streambank erosion. In this section, the geotechnical and geomorphic mechanisms and causal relations will be described.

Geotechnical mechanisms

24. Material failures result from either or both increased shear

stress or decreased shear strength. Changes in stress and strength usually result from changes in flow or hydraulic geometry. For example, increased flow may result in a higher and more critical shear stress at the soil-water interface, which results in the removal of the soil particles in the banks of the channel. The degradation or erosion of channel bottoms and the toes of channel walls (a change in hydraulic geometry) may result in overstressing the soil mass in the banks, slope instability, and failure of the banks. Decreased strengths may result from liquefaction produced by earthquakes or other processes, from drawdown and weathering of exposed channel materials, and from changes in water table conditions in the banks. The identification of stress-strength parameters and other geological and geotechnical characteristics of the soil and soil mass are necessary for the implementation of remedial measures for bank protection; however, knowledge of these parameters may not necessarily provide insight into sequential conditions beyond the site in question.

25. A categorization of increased stress and decreased strength mechanisms of streambank erosion has been prepared by the American Society of Civil Engineers (ASCE) Task Committee on Channel Stabilization and is summarized below (Keown et al. 1977).

- a. Attack of the toe of the underwater slope, leading to bank failure and erosion. The period of greatest bank failure normally occurs in a falling river at the medium stage or lower.
- b. Erosion of soil along the bank caused by current action.
- c. Sloughing of saturated, cohesive banks, i.e., banks incapable of free drainage, due to rapid drawdown.
- d. Flow slides (liquefaction) in silty and sandy soil.
- e. Erosion of the soil by seepage out of the bank (piping).
- f. Erosion of upper bank, river bottom, or both due to wave action caused by wind or passing boats.

26. The six erosion types given above include most situations and provide meaningful information for the design of bank protection structures. In four of the six types (a, c, d, and e) the loss of material is caused by either modified slope geometry (a) or by the

nature of slope materials (c, d, and e), underscoring the need for geological and geotechnical data for preventive design. The main disadvantage of the ASCE erosion types is that there is no identifiable relation to the geomorphic and hydraulic conditions of the channel. Also, these erosion types lend no information as to channel stability in general.

Geomorphic erosion mechanisms

27. Streambank erosion may be manifested by three geomorphic processes or mechanisms: channel widening, channel deepening (both involve changing profile and cross section), and changing planform. These processes relate to the hydraulic geometry (or morphology), provide an indication of probable causes, and may be quantified.

28. Channel widening. Widening is a process which is evidenced by an increase in channel width, with or without a corresponding increase in channel depth. Previous discussion of the mechanics of rivers indicated that widening occurs because of the adjustment of the channel to an increased sediment discharge, or to an increased sediment discharge accompanied by an increase in flow. When both sediment discharge and flow increase, widening and deepening occur. When only sediment load increases, width increases and depth may decrease. If the process involves mainly an increase in sediment load, the type corresponds to Schumm's depositing channel. Another name for this process or type is an aggrading channel, implying that the channel has aggraded or filled in because of an excess of sediments.

29. Channel deepening. Channel deepening is a process of channel degradation with which the depth of the channel is increased. The increased channel depth may cause instability of the higher and possibly steeper banks and thus further losses by channel widening. Whether or not instability actually occurs is a function of the geotechnical properties of the bank materials and of the bank geometry. The degradation or deepening results from increased flow without appreciable increase in sediment discharge. The increased flow may result from an overall increase in the volume of water moving through the channel or an increase in channel slope.

30. Changing planform. Changing planform includes changes in the location of the channel. Examples of changing planform are shifting of channels, cutting off of meander bends, downstream migration of meander bends, and changes in the sinuosity or shape of meander bends. Generally, these changes represent an adjustment of channel slope to conform with changes in flow or sediment discharge.

31. These three mechanisms or processes are often dependent to the extent that a given site or reach may exhibit successive stages of, for example, deepening followed by changing planform. Also, the initiation of a given process at a particular site may initiate another different process either upstream or downstream.

Causes of streambank erosion

32. The causes of natural phenomena such as streambank erosion cannot be categorically stated in terms of one or two specific and limited events, conditions, or circumstances. Ordinarily, natural phenomena are caused by several conditions operating concurrently or a sequence of interrelated events or circumstances. The sequentiality of events is of prime importance, and each specific event must be understood. The causative sequence also may pertain to space as well as time. For example, an extremely high-intensity meteorologic event occurring in a restricted part of a drainage basin may contribute to a flood event of short duration in the downstream portion of the basin that results in localized bank loss. In such an example, the solution to the bank erosion downstream involves information on flow characteristics at the site in question as well as particulars on the catchment in which the event occurred and data on the stream system between the catchment and the site that was eroded.

33. The meaning attached to the word "cause" is often dependent upon the scale at which the problem is viewed and upon the discipline of the individual studying the problem. For example, a rather narrow, albeit accurate, explanation of cause would be the occurrence of lift and critical shear stresses at the soil-water interface. Upon quantification this explanation is satisfactory and provides necessary input to the design of protective structures. However, this cause fits all

erosion types with the exception of the slope or material failures previously mentioned. On the other hand, a cause could be considered to be waves generated by passing vessels. Generally, to be meaningful, the cause must include the following considerations which proceed from a small-scale toward a large-scale examination of the problem.

a. The occurrence and identification of lift and critical shear stresses at the soil-water interface.

b. The manifestation of a geomorphic process and analysis of the process.

c. The identification of factors contributing to the geomorphic process.

d. An examination of upstream or downstream areas in order to determine specific reasons.

34. The completion of the study will result in the identification of the cause of erosion. Of course, the study steps outlined above would also include geotechnical evaluation of the site in order to obtain design information. The complete examination of the erosion problem will result in the conclusion that the erosion is either natural or accelerated.

Natural Versus Accelerated Erosion

General

35. Streambank erosion, as well as other types of fluvial erosion, is either natural or accelerated. By natural, it is meant that the type and amount of erosion which is experienced is usual and expected and the site or reach in question has, in fact, experienced this type and amount of erosion over many years. Accelerated erosion is characterized, generally, as being atypically high in magnitude and of a different nature than that which would be expected based upon previous experience. Obviously, the distinction between natural and accelerated erosion must be based upon previous experience or historical information on the site or locale in question. For example, erosion produced by earthquakes and volcanism would be great in magnitude and extent but would be natural but atypical. Accelerated

erosion may be caused by human activities and may involve many miles of stream channel throughout a basin. Natural erosion would usually be considerably less widespread and smaller in magnitude than accelerated erosion.

36. Overall, our knowledge and experience with accelerated streambank erosion is considerably less well documented than that of accelerated upland or hill-slope erosion. With respect to the latter, much is known of the adverse effects of overintensive agricultural land use and the resulting sheet erosion and gullying that has occurred in many parts of the south. Although the nature of upland erosion is considerably different from streambank erosion, the magnitude and scope of channel modifications which have been undertaken on the nation's rivers strongly suggest that accelerated streambank erosion may be as common as accelerated upland erosion.

Natural erosion

37. The downstream migration of meander loops, avulsions, i.e. the change of channel distributary, and the effects of extreme precipitation occurrences (either flood or drought), are the primary examples of natural channel modifications which are accompanied by streambank erosion. Ordinarily, natural channel behavior is characterized by an overall balance between erosion and deposition within rather short reaches. Thus, the amount of material eroded at the outside of a meander loop will approximately equal the amount deposited on the inside of the next loop downstream. If river stages do not change appreciably, the meander pattern will slowly shift downstream without a singular change of sinuosity or size of meander loops. During avulsions, flows shift, either totally or in part, from one distributary to another producing effects similar to those caused by climatic events. Atypically high intensity or prolonged precipitation events will produce atypical flows and sediment discharges which, in turn, will enlarge the channel by widening and deepening in order to accommodate the higher stages. During falling stages, bank erosion may occur because of piping, sloughing, or liquefaction, particularly when the high stages have been maintained for considerable time. During

extremely low stages, piping, sloughing, or liquefaction may occur if local groundwater tables remain high. Also, the bank exposed during low stage conditions may experience sheet erosion caused by local, over-bank flows. Generally, the nature of the bank and bed material will control the magnitude of natural bank erosion.

Accelerated erosion

38. The impact of human activities upon fluvial systems may be considered as either site or nonsite specific. Site specific impacts are direct and usually result from river engineering projects (construction of dams and stream channel modification). Nonsite specific impacts are predominantly indirect and cause modification of geomorphic processes which control the hydraulic geometry of streams (agricultural practices and interbasin transfers). The relations between site and nonsite impacts are shown in Table C1. Ironically, site impact activities are often carried out to ameliorate the adverse effects of nonsite activities.

39. Site specific impacts. Probably one of the most disruptive practices of river engineering has been the direct modification of natural channels in an effort to "train" the river. Channelization, which usually involves straightening and clearing of stream channels, has the primary effect of shortening channel length. Decreased channel lengths, usually accompanied by decreased channel roughness, create increased channel velocities and peak discharges and decreased basin response times and minimum (base flow) discharge. The usual result is local streambank erosion due to channel entrenchment, bank over-steepening, bank failure, and downstream bank erosion from channel aggradation and widening. As the entrenchment moves upstream, a wave of streambank erosion moves through the river system until it is assimilated in first order stream channels in the headwaters of the basin. However, improved designs and the use of grade control structures may preclude such adverse conditions.

40. Construction of reservoirs also has a direct impact upon the ability of a stream channel to transport water and sediment. As reservoirs temporarily interrupt the downstream transport of basin

runoff, sediment is trapped behind dams, creating relatively sediment-free streamflow downstream from the dam. In an effort to reattain the previous relationships between discharge and sediment transport, the stream, lacking sediment, scours the channel. Temporary storage of streamflow diminishes peak discharges, those flows which are largely responsible for channel geometry maintenance. Consequently, after an initial period of active streambank erosion, downstream channel flows are reduced.

41. Nonsite specific impacts. Unlike river engineering practices that have a direct and immediate impact upon fluvial systems, nonsite specific impacts may be more difficult to analyze. Their influence upon natural fluvial systems is often masked by spatial and temporal variability of occurrence within the drainage basin and by the simultaneous influence of natural phenomena upon the fluvial system. Theoretically, any human activity that modifies the magnitude, frequency, and duration of production of water or sediment discharge from a drainage basin will ultimately (if of sufficient magnitude) have an effect upon all subsystems of the basin. The impact of the human activities upon the fluvial system depends upon the nature of the mechanics of the system, especially the development of the system toward a state of quasi-equilibrium, the existence of geomorphic thresholds, and the character of external variables (climate, topography, geology). Consequently, one type of human activity will not impact upon all fluvial systems to equal extents. However, the impact of a nonsite human activity is similar enough to make broad generalizations about its effect on fluvial systems.

42. Whereas the natural characteristics of a drainage basin dictate the mechanics of the fluvial system, they also dictate human activity in the basin in the form of resource utilization. Resource utilization is usually manifested in the form of agriculture (soil and climate), timber harvesting and grazing (vegetation), mining (geology), and recreation (topography and climate). All of these activities have an important nonsite specific impact upon fluvial systems.

43. Agricultural practices have long been considered a primary

cause of stream channel modification (Chorley 1969). The relative impact of cropping practices varies widely, depending upon types of crops, procedures used, and natural characteristics of the area. However, the removal of natural vegetative cover and cultivation of relatively "exotic" vegetation usually results in increased sediment production and increased runoff. The impact on the stream channel environment is to increase peak discharges and sediment storage and transport. The ultimate result is streambank erosion, locally caused by oversteepened banks, increased channel widths, and possibly sinuosity changes as the channel adjusts to a new sediment/water discharge regime. Certain timber harvesting practices and overgrazing will have a similar effect on downstream channels by increasing runoff and sediment yield. The excavation of surface mines may drastically increase sediment production, if the excavation is adjacent to a stream channel. Recreation activities may be locally significant in increasing runoff and sediment yield through soil compaction.

44. Human activities associated with urbanization may have a substantial impact upon local streams. As areas of natural vegetation are developed for residential, commercial, or industrial use, runoff and sediment production are increased tremendously, frequently doing severe damage to local stream channels. As construction is completed, sediment production is greatly reduced but runoff is further accelerated. The result is streambank erosion from channel volume adjustments to increased discharges with frequent overbank discharges (floods) occurring in the interim. The construction of roads in urban areas, associated with previously mentioned activities (timber harvesting, surface mines), may also have a similar effect upon stream channels.

Methodology for Studying Streambank Erosion

45. The methodologies necessary for the successful solution of streambank erosion problems must include interdisciplinary approaches utilizing hydraulic, hydrologic, soil mechanics, and geological techniques. This section addresses applicable geological techniques.

These techniques are important because they provide not only information on the materials and physical characteristics of the site or reach, but also data on baseline conditions, the amount of erosion expected at the site or reach, and the possible influence of human activities (Patrick, Smith, and Whitten 1981).

General geological studies

46. Geological studies of actual or potential bank erosion problems should include the examination of fluvial and other types of geologic maps, the conduct of land and waterborne geophysical surveys, and field examinations. Existing geologic, soils, and other special purpose maps and reports, contain information concerning the nature of bed, bank, and channel materials and thus provide inferences of their erodibility as well as provide information on subsurface structure that may influence channel alignment. Geophysical techniques provide information about the subsurface and give indications of the stratification and homogeneity of these materials. Field observations may be made by walking stream channels or banks during both high and low flow conditions, if possible. During low stages, the observer should examine channels for evidence of degradation, bedrock, or other materials which may influence stream behavior. Particular attention should be given to streambanks; evidence of instability, such as piping, slumping, sliding, or sloughing, should be noted. These field examinations may be conducted in conjunction with field surveys. Aerial overflights may be useful in some circumstances for the rapid evaluation of large areas of the basin and for selecting reaches for further ground study. Attention should also be given to examination of streams which are tributary to the reach in question. In some cases, tributary streams may more readily show evidence of instability than the larger streams (Krinitzsky 1965, Saucier 1967 and 1969, Smith and Saucier 1971, Smith and Russ 1974, Smith 1979, and Murphy (in preparation)).

Historical analysis

47. Historical analysis consists of collecting and examining historical data pertinent to the site, reach, or basin of interest and comparing these data with current data. The purposes of these analyses

are to identify established trends of behavior of the river, to identify times of and explanations for significant fluvial changes, and to determine possible future changes. These studies may be made for existing projects and should be a part of the analysis for proposed projects. Generally, historical analyses may be conducted using aerial imagery, topographic maps, waterborne geophysical techniques, as well as available engineering data. The information derived from these studies provide input to new designs by characterizing the fluvial behavior. For existing projects, the information indicates the impact of the project on the river and, if required, contributes to remedial efforts. The data collected during these analyses should include, to the extent possible, width, depth, slopes, sinuosity, flow, and sediment discharge, as well as other hydraulic information for the purpose of establishing cause and effect relations in terms of river mechanics and the geomorphology of the area. Often, flow, sediment discharge, and other hydraulic data are expensive to procure and, at some sites, may not be available. In such situations, geometric or morphological information must be obtained from aerial imagery and topographic maps and the flow and sediment discharge inferred from this information (Simons, Schumm, and Stevens 1974).

Imagery and topographic maps

48. Remotely sensed imagery and topographic maps are the data bases for historical analyses of geomorphic change, as well as the analysis of overall basin conditions. With respect to imagery, the type used will be dependent upon the scale requirements which, in turn, are a function of the project or reach size and the amount of detail that is necessary. For general basin studies, particularly those covering large areas or for large rivers and estuaries, LANDSAT imagery and high-altitude aerial photography would be most useful. Furthermore, LANDSAT imagery may be computer enhanced for the purpose of refining particular hydrologic, geologic, or sedimentologic characteristics of the basin. For detailed studies, several scales of imagery beginning with small scales and progressing through large-scale, low-altitude conventional panchromatic aerial photography is

recommended. In the United States, aerial photographic coverage provided by the Department of Agriculture is generally available, and for many regions, several vintages of coverage exist (May 1978, and Dept. of the Army 1979). Topographic map coverage, in some cases, can be used in the absence of or as a supplement to imagery. Such maps are particularly useful if periodic revisions are available.

Waterborne geophysical techniques

49. Waterborne geophysical techniques can, in many cases, provide useful information on geological influences along and beneath stream channels. These techniques are acoustical in nature and include continuous seismic profiling and side-scan sonar. Seismic profiling can provide data with respect to the character, thickness, and stratification of the channel material as well as the stratification and structure in the underlying bedrock. This technique is particularly useful for detecting rock hard points which may be controlling river behavior; also, the technique may provide information on sand-wave forms, scour channels, and other bottom conditions. Side-scan sonar is used primarily for detailed mapping of the channel bottom. Bottom mapping will yield information on wave forms, rock outcrops, slump or slide zones, and other indications of channel instability. Waterborne geophysical methods may be used to identify the causes of existing erosion and to provide information for remedial work. Also, these methods are applicable for monitoring the effectiveness of existing bank protection structures (May (in preparation)).

Applications

General

50. During the early phases of this investigation, numerous bank erosion sites across the country were visited. Certain of the visited sites, as well as other sites, were also reviewed using imagery and topographic maps. On the bases of these visits and preliminary examinations, sites were selected for detailed studies. The criteria for selecting sites for detailed geomorphological studies included

severity of erosion, availability of existing information, and the typicality of erosion. Sites were also selected for the application of waterborne geophysical techniques using basically the same criteria. Although these studies were performed in different parts of the country, the observation and conclusions made are believed to be applicable nationwide.

Eel River, California

51. An example of the relative importance of nonsite specific factors influencing streambank erosion can be seen in the Eel River of northern California (Smith and Patrick 1979). Active streambank erosion is occurring in the alluvial valley of the lower Eel and its tributaries. At study sites on the Eel and a major tributary, the Van Duzen River, streambanks have receded an average of 67 and 71 ft per year, respectively, for the last 18 years. Figure C2 shows historic channels of the lower Eel River. The cause of streambank erosion appears to be related to the adjustment of the streams to decreased channel depth caused by increased sediment production in their basins (proportionalies 1 and 2 in paragraphs 13-15). In the analysis of factors influencing streambank erosion, both site and nonsite specific factors were found to be significant contributors.

52. Streambanks are composed of unconsolidated Holocene alluvium. The alluvial material varies in size from silt to cobbles and offers little resistance to lateral erosion. Additionally, both sites are located on the outside of meander bends and are subjected to maximum tractive forces during stream discharges up to bank-full capacity. Examination of historical topographic maps reveal considerable aggradation occurring at the Eel River test site between 1943 and 1972, accompanied by degradation in the middle and upper basin (Figure C3). An adjustment to decreased depth through increased width is evident in the growth of islands in the lower Eel River. Channel island area, measured on 1940, 1951, 1959, and 1972 topographic maps, increased 67 percent, while channel area increased 23 percent. Figure C4 shows the 1940 and 1972 channel configurations.

53. Factors influencing sediment transport and production to

the lower Eel and its tributaries are natural and human-induced. Natural characteristics of the basin that contribute to high erosion potential include basin topography, geology, soils, and climate.

54. A major contributor to high erosion potential is the topography. Much of the basin consists of mountain slopes. The slope inclinations vary tremendously but are commonly quite steep. Many slopes are delicately balanced and may fail at the slightest provocation. Unlike most drainage basins, the valley becomes more narrow in a downstream direction, causing restriction of flow with increased velocities and high erosion potential.

55. The nature of the geologic materials in the Eel River Basin also encourages high erosion rates. For the most part, the Franciscan formation (Jurassic and Cretaceous ages) underlying about 80 percent of the basin is highly unstable due to structural and compositional weaknesses. Large and small faults and shear zones are relatively numerous throughout the basin. The deeply weathered sandstones contain local amounts of shale and serpentinite. These characteristics and the rugged topography result in high natural erosion potential. The unstable nature of geologic materials throughout the basin is evident in the large number of debris slides, debris torrents, and earth flows. Figure C5 shows effects of geologic controls on the profile of and the mass wasting along the Van Duzen River.

56. Soil erosion hazard in the basin has been determined on the basis of land slope, soil texture and structure, type and density of vegetative cover, and amount of runoff. Classes of soil erosion hazard include low, moderate, high, and very hazardous. These classes make up 5.0, 14.0, 52.6, and 28.4 percent of the basin area, respectively (Dept. of Agriculture 1970). Most of the soils of the basin have at least a high soil erosion hazard or potential. The hazard is mainly related to removal of vegetative cover.

57. Climate characteristics of the Eel River Basin are highly conducive to the active modification of the landscape by running water. Precipitation amounts, although extremely variable in both temporal and spatial distribution, are relatively high for most of the

basin. Additionally, most of the precipitation and runoff occur during winter months when evaporation is insignificant and the erosive power of streams is at a maximum.

58. Although Wolman and Miller (1960) demonstrated that climatic events of moderate frequency are more significant than catastrophic floods in modifying certain landscapes, it has also been suggested that large, rare floods may profoundly alter basin and channel morphology in certain environments (Baker 1977). The effect of floods upon stream channels and sediment sources in the Eel River Basin has been well documented (Waanane, Harris, and Williams 1971). In December 1964, the Eel River experienced a flood with a return frequency of greater than 100 years. Precipitation in some locations exceeded 20 in. in a 48-hr period, sending river stages as much as 15 ft above previous record stages. Erosion from streambanks, landslides, and sheet flow caused tremendous sediment yields. For a 3-day period beginning 22 December 1964, suspended sediment discharge of the Eel River at Scotia, California, was computed at 116 million tons. This total exceeded the yield of 94 million tons for the previous 8 years. New water and sediment discharge records were established at all gaging stations within the basin.

59. This catastrophic flood resulted in substantial alteration of channel morphology in the Eel Basin. Hickey (1969) found that as a result of the flood sediment, deposition caused streambed elevations to rise 6 to 8 ft in the vicinity of the confluence of the Middle Fork of the Eel and Black Butte Rivers. He also noted that deposition continued during the next water year. Kelsey (1975) noted similar changes in streambed elevations of the Van Duzen River. An additional impact of the flood was to trigger extensive mass wasting events throughout the basin, which contributed greatly to sediment discharge.

60. Land utilization in the Eel River Basin is strongly related to vegetation type and distribution. The commercial timber industry is by far the most extensive and economically important land use activity in the basin. Large expanses of valuable timber species have attracted the logging industry for over 100 years. As a result,

much of the forest has been cut over and exists in some stage of second growth. Some cutover areas have been maintained in grass for grazing purposes.

61. Grazing of natural grasslands is the second most extensive land use practice in the Eel River Basin. Some areas have been grazed for over 100 years. As a result, natural perennial grasses have been removed and replaced by more exotic annuals. The annuals cover represents a decrease in protection from sheet, rill, and gully erosion. It has been determined that approximately one third of the grassland in the basin is deficient in protective vegetal cover (Dept. of Agriculture 1970). This problem is especially apparent on private lands that are grazed year round.

62. In estimating the relative contribution of natural and human-induced factors influencing accelerated sediment production in the Eel River Basin, it was determined that the flood of 1964 was largely responsible for the rapid influx of sediment. However, a detailed analysis of the source of sediments in the Eel River Basin revealed that at least 19 percent was caused by human activity. Thus, streambank erosion on the Lower Eel and Van Duzen Rivers must have been caused primarily by natural nonsite factors, which were significantly aggravated by human activity.

Tillatoba Creek, Mississippi

63. The basin of Tillatoba Creek is a 175-square-mile subunit of the Yazoo River Basin located in northwestern Mississippi directly east of the Mississippi Alluvial Plain. Human activities that have affected the fluvial conditions within Tillatoba Creek basin include overintensive agriculture and forestry and channelization within and downstream of the basin (Winkley 1977). These activities have resulted in pervasive streambank erosion, sediment accumulation, channel degradation, and overall channel instability. Field examination reveals nearly vertical, high banks and numerous exposed ledges of Pleistocene or Holocene materials forming waterfalls within the channels. The material in the exposed ledges is predominantly fine-grained soils; whereas, the channel material between waterfall areas

is predominantly sand with localized occurrences of gravel.

64. The studies conducted in the Tillatoba Creek basin consisted of historical analyses using topographic maps and conventional panchromatic aerial photography for the purpose of documenting and quantifying geomorphic changes and determining the cause of streambank erosion and channel instability (Whitten and Patrick (in preparation)).

65. Longitudinal profiles of the major tributaries were taken from 1:62,500-scale U. S. Geological Survey (USGS) topographic maps (1954 edition) and compared with 1976 Corps of Engineers Survey data (Figure C6). The 1954 profiles are seen to be irregular, and approximately six knickpoints can be identified on the profile of Tillatoba Creek. The 1976 survey data reveal fewer knickpoints and generally a smoother longitudinal profile. The longitudinal profiles indicate that approximately 15 ft of channel degradation has occurred between 1954 and 1976.

66. Conventional panchromatic aerial photographic coverage was obtained for selected reaches. Coverage was available for the years 1937, 1941, 1954, 1962, 1966, and 1976. Figure C7 illustrates geomorphic changes occurring between 1937 and 1976 on the lower reach of North Fork as evidenced from the photography. The 1937 view reflects more-or-less stable conditions, tree-lined banks, minor point bar accretion, and no apparent sediment accumulation. The 1941 view is similar; however, point bar enlargement is apparent. The 1954 and 1966 views show significantly increased point bar accretion and the upstream migration of apparent widening and instability. The examination of the photographs in stereo revealed that the point bars were developing at elevations lower than that of the 1937 floodplain and that the channel had degraded. The 1954 and 1966 views also showed that a thalweg was established at the lower elevation and that the former floodplain (1937-1941) was now a terrace.

67. Channel areas and lengths were measured for each period of historic coverage. The 1941 view was the basis for comparison for subsequent periods. Percent change before and since 1941 was

determined and plotted. Figure C8 shows such a plot for the Tillatoba Creek and the North Fork.

68. The apparent upstream migration of instability and the occurrence of head cutting is shown on the matched historical photography sequence for a reach of the South Fork. This sequence shown in Figure C9 includes the years 1954, 1962, and 1979. Locations "X" on the 1954 and 1962 photographs and locations "Y" on the 1962 and 1979 photographs are areas of overlapping coverage.

69. Figures C7 and C9 strongly indicate that instability has been triggered by downstream activities, most likely channelization. However, basin-wide land use must also be considered. This aspect was investigated by literature review and by the examination of historic aerial photographic coverages. The examination of the imagery resulted in the general conclusion that land use practices have improved since the early 1940's. This improvement has come about through return of much land, which had formerly been in cultivation, to pasture and woodland. The change in land use, as well as the construction of sediment retention structures, has apparently decreased sediment yields in the basin, and thereby decreased sediment loads in the basin's streams. These rather general surveys of historical land use support the contention that the accelerated erosion has been triggered by downstream conditions, namely channelization, or increased downstream flow conditions.

70. Streambank erosion has resulted from two interrelated processes which are initiated during channel degradation. One process is the development of overly high and overly steep banks, which may fail because of an increase in shear stress. The second process pertains to the occurrence of localized erosion resistant ledges in the channel and the influence of these ledges on degradation. The inability of the streams to easily cut through these ledges has resulted in extensive lateral erosion and meandering.

Missouri River, North Dakota

71. Studies of bank erosion occurring along the Missouri River have been conducted by the Missouri River Division (MRD), Corps of

Engineers (1977), as a part of a larger study of water resources development in the states of Nebraska, South Dakota, North Dakota, and Montana. These studies consisted of bank erosion surveys using conventional historic panchromatic aerial photographic coverage of reaches below six mainstem dams (Gavins Point, Fort Randall, Big Bend, Oahe, Garrison, and Fort Peck). These surveys only included erosion of high banks considered to be suitable for cultivation, recreation, or for building sites and did not include surveys of bank accretion. The historic aerial photography coverage included both predam and postdam coverages for most of the dams. These studies generally concluded that prior to the closing of the river by the dams, there had been no long-term net loss of high banks because of a balance between erosion and accretion. However, upon closing the river, the balance was disrupted by decreased peak flows and decreased sediment transport. The result of the changed flow and sediment condition was continued high bank loss, accompanied by a different form of accretion. Accretion occurs somewhat randomly along the channel rather than by point bar migration. Also, the study concluded that downstream of certain dams loss was less after closure than it was before (Garrison and Fort Randall reaches). Another more general account of the effects of dams on erosion processes is given by Rahn (1977).

72. Further geomorphic studies were conducted at the WES for the reach of river extending from Garrison Dam downstream to Bismarck, North Dakota (Patrick 1977). These studies were concerned with causes of bank erosion, the influence of geology and geomorphology, and effects of the dam on erosion processes. Conventional and special purpose aerial photography and topographic maps were used in the study and are given below:

Data Units*	Type of Coverage
1	USGS topographic maps (1:62,500), 1944-50, and USDA aerial photography, 1950
2	USGS topographic maps (1:24,000), 1958-1966, and USDA aerial photography, 1966
3	Special purpose (low altitude, panchromatic) aerial photography, 1974

* Data units represent periods of map or photographic coverage. For example, data unit 1 is the period of composite topographic map and aerial photograph coverage between 1944 and 1950. Note that both data units 1 and 2 reflect composite coverage.

73. The Missouri River is an incised stream whose meander pattern is partially controlled by hard points along the valley walls. A general examination of historic topographic maps and imagery indicated that the position of the river had remained the same at hard points although there had been changes between hard points. Comparisons were made between data units 1 and 2 and 2 and 3, with respect to island area, bank loss, and bank accretion. Figure C10 shows the bankline and island changes occurring between data unit 1 (1949) and data unit 2 (1969) for one reach of the river. The qualitative examination of maps such as the one shown in Figure C10 revealed that erosion and bank loss were not confined to the outside of meander bends and that the erosion locally occurred on straight reaches on both banks. Furthermore, bank accretion occurred randomly and did not seem to conform to the downstream development of point bars. Often the occurrence of erosion on both banks along a stretch is an indication of human-caused instability.

74. Quantitative comparisons of historical changes in morphology are shown in Figures C11 through C14. In these figures, morphological changes are presented in terms of areas of bank loss or accretion rather than volumes of loss or accretion. Although volume

is a more accurate measure of morphologic change, comparisons of areas are considered to show relationships similar to those evidenced by comparisons of volumes. However, some caution is necessary since a unit area of high bank loss may not be volumetrically equal to a unit area of point bar accretion. Figure C11 is a plot of areas of bank loss and accretion versus distance for the period of time between data units 1 and 2. The plot shows that reaches of predominant bank loss alternate with reaches of predominant bank accretion and that these reaches are controlled in a general manner by the locations of hard points. Figure C12 illustrates bank loss and accretion data for the period of time between data units 2 and 3. This plot shows an overall reduction in bank loss particularly in the 30-mile stretch downstream of the dam. The reduction in erosion is probably caused by the installation of bank protection structures prior to 1974 as well as to the development of a degree of equilibrium in the fluvial regime.

75. Bank loss and accretion may also be illustrated by cumulative curves. Figures C13 and C14 show plots of cumulative acres of bank loss and bank accretion, respectively, versus distance. The plots are useful for estimating the magnitude of erosion/accretion along the reach under study. Both plots generally show that both erosion and accretion have decreased with time. Using these plots, total accretion can be compared with total bank loss for a given period of time. Although they are not plotted separately, the cumulative bank loss curves superposed upon the cumulative accretion curves yield information on the cumulative net amount of loss and accretion for the period of interest. Examining the data in this way reveals that there has been no significant difference in the amount of land lost or gained from erosion or from accretion during the period between data units 1 and 2 within the 80-mile stretch. Between data units 2 and 3 for the same stretch, there has been more accretion than bank loss. The accreted material may be derived from degraded reaches upstream.

76. For each data unit the cumulative area of channel islands was calculated and plotted versus distance. The plots are shown in Figure C15. These data indicate that in the stretch between 15 and 65

miles below the dam, there has been a consistent and significant increase in apparent island area. With time, the magnitude of the increases in island area does not appear to correlate well with magnitudes of bank loss or accretion.

77. The longitudinal profiles compiled from data units 1 and 2 for the reach downstream from the dam are shown in Figure C16. The predam profile is relatively smooth, particularly considering that it represents 6 years of data. The postdam profile indicates that channel degradation has occurred and that it extends approximately 40 miles downstream of the dam. The degradation has probably been initiated by the clear water released from the dam. Note that there is no apparent aggradation downstream beyond the limit of scouring. Thus, the removal of sediment upstream and its movement downstream has apparently not resulted in downstream change in slope.

78. The determination of causes of erosion and relations between the causal process and the dam must include both qualitative and quantitative considerations. The most important consideration may, in fact, be a qualitative one, namely, the manner in which the erosion occurs. The observation that erosion/deposition processes were not related to point bar migration is significant and suggests instability, although the fact in itself does not indicate a cause. The correlation between erosion/accretion location and the location of hard points along the river suggests the importance of the hard points in controlling river behavior. The evidence that reaches of predominant erosion are separated by reaches of predominant accretion also suggests instability caused by the closure of the river. In order to develop meaningful relations, measurements of fluvial change must include deposition or accretion processes as well as erosion. Furthermore, all types of erosion and accretion should be surveyed; however, the categorization of the processes with respect to where they occur or with respect to land classification can be a useful management tool.

Waterborne geophysical
surveys for CE Districts

79. Whereas waterborne geophysical methods have been widely used for the past two decades in the offshore exploration for mineral resources, the application of these methods in fluvial environments has not been extensive. Therefore, a primary purpose of the geophysical surveys conducted under this task was to demonstrate the overall usefulness of these methods in the solution of engineering problems on navigable streams. Waterborne geophysical surveys were conducted on selected reaches of the Mississippi, Missouri, Ohio, and White Rivers and were described by May (in preparation). Generally, with the exception of the Mississippi River surveys, these surveys were conducted for and in conjunction with bank erosion studies conducted by CE Districts.

80. The identification of subaqueous slumps or slides is an important application of the side-scan sonar technique. Figure C17 is a side-scan sonar record taken in the vicinity of Ohio river mile 375 near Vanceburg, Kentucky. This record, as well as others, showed several subaqueous slump features (A) on the bottom of the channel. Generally, the location of the slump material indicated that the surface of slumping was significantly below normal low water level. Note that (B) and (E) are the toes of the right and left banks, respectively. The general surface configuration of the channel can be seen along the center of the record (C). Figure C18 is a side-scan sonar record from the Ohio River between river miles 337 and 338 near Greenup, Ohio. This record also shows the presence of numerous subaqueous slumps. Both records (Figures C17 and C18) demonstrate that bank erosion evidenced at the surface may be related to conditions or failure zones existing below water and on the channel sides and bottom; therefore, there is a need to consider lower bank protection methods.

81. The side-scan sonar survey can also provide information on channel bottom conditions which may impact either directly or indirectly on bank erosion or other aspects of channel stability and navigability. Figure C19 is a record at Old Lock and Dam 30 in the

vicinity of river mile 338 near Greenup, Ohio. The record shows the underwater remains of the lock and dam which were demolished in 1962. Although these structures apparently have not contributed to adverse fluvial conditions, the ability of the side-scan system to detect and resolve subaqueous features is apparent. Flow conditions and scour may be controlled or affected by wrecks submerged in the channel. Figure C20 is an example of such a wreck in the Mississippi River at river mile 109 near Chester, Illinois. The wreck is that of a steamboat which sank in the early 1900's; it is partially buried by sediment. Partially submerged wrecks or other objects within channels may pose navigation problems and also may cause currents directed toward banks to initiate bank erosion.

82. The continuous seismic reflection profiling (CSRP) system is a waterborne geophysical tool, which permits the identification of the thickness of alluvium beneath a channel and the location, extent, and possible influence of bedrock within or under the channel. The interrelations between channel alluvium and underlying bedrock are shown on the CSRP record (Figure C21) from a reach of the Ohio River near Vanceburg, Kentucky. The record shows the bedrock surface (A) on the left extending upwards to the right where it is exposed in scour channels (B) in the alluvium. The surface irregularities in the channel alluvium are apparent on this record. Figure C22 is a CSRP record of a reach of the Ohio River near Portsmouth, Ohio. The record shows the top of bedrock (B) on the left and sand waves (A) in the channel alluvium on the right.

83. The results of waterborne geophysical surveys generally demonstrated that these techniques were highly effective in fluvial environments in terms of the types of data obtained and with respect to the resolution and quality of the data. Furthermore, the data derived from such surveys are important for channel maintenance operations, the identification of navigational obstructions, the design of structures, and the monitoring of periodic changes in channel conditions. For streambank erosion studies, waterborne geophysical surveys can provide information on the nature and extent of bank instability, the

approximate depth at which failure occurs, the result of bedrock control, the effectiveness of bank stabilization structures, and the design for new structures.

Findings

84. Rivers are complex, dynamic systems, which exist in a state of quasi-equililibrium in terms of flow, sediment discharge, hydraulic geometry, climate, and geomorphic development. A state of dynamic, quasi-equilibrium also exists between a river and its upstream and downstream tributaries.

85. Streambank erosion may occur because of and may be manifested by three interrelated geomorphic processes: stream channel widening, channel deepening, and changing planform. These processes are caused by changing flow or sediment discharge and may be considered natural or accelerated erosion. Whereas natural erosion is generally initiated by periodic, meteorologic events, accelerated erosion is also initiated by such events and aggravated by human activities.

86. The occurrence of streambank erosion at many, if not most, sites can be related to both natural and accelerated causes. Generally, accelerated or human-induced erosion is extensive and poses the more serious problem.

87. Those human activities that appear to most often affect fluvial behavior and contribute to massive and extensive bank failures are: channelization, existence of dams on streams having large bed loads, agricultural and forestry practices, and urbanization. In some areas, streams have reacted to more than one of these activities. Channelization and overintensive land use are potentially the most adverse human activities.

88. The principles of river mechanics provide a valuable means of interpreting geomorphic data and determining explanations and possible causes of streambank erosion as well as other fluvial phenomena.

89. Geologic materials (soils and rock) in channels and banks are important factors controlling fluvial behavior. Soils control the

location and the rates of erosion on the basis of their relative erodibility and the stability of the soil mass. Sliding, slumping, and general slope instability are probably as common as soil erodibility. Bedrock occurrence in channels and along banks is of more importance in controlling the location of erosion than soils.

90. Conventional aerial photography provides relatively rapid and inexpensive means of studying and monitoring bank erosion sites. The examination of historic photography is particularly important in identifying trends and baselines. The principles of river mechanics provide a methodology for quantification of the information derived from the photography.

91. Waterborne geophysical techniques, including continuous seismic profiling and side-scan sonar, are effective methods for the collection of data on the materials underlying channels and on the nature of channel bottom. The data derived from these geophysical techniques are applicable to planning, design, and monitoring functons. The applications of these techniques to streambank erosion studies relate to the ability of these techniques to locate bedrock or other subbottom features and to identify subaqueous slumps and slides.

92. Streambank erosion, flooding, impaired navigation, and environmental degradation are mutually dependent adverse situations that cannot be viewed in isolation and cannot be evaluated or corrected without a strongly interdisciplinary approach. Generally, these situations must be considered in terms of fluvial geomorphology, geotechnical engineering, hydraulics, hydrology, and environmental science.

Recommendations

93. Proposed hydraulic structures and other hydraulic projects should include, as a part of their planning, an evaluation of the potential influence of the structure or project on the fluvial geomorphology. Those projects involving dams and channelization should receive careful study of potential influences.

94. To the extent practicable, comprehensive, interdisciplinary,

basin-wide studies should be conducted for the purposes of establishing detailed data bases and determining the relations between water resource requirements and the impact of these requirements on fluvial geomorphology as well as on environmental quality. Geomorphological studies should include the use of aerial imagery.

95. The operation and maintenance of existing projects should include a periodic review of upstream and downstream fluvial conditions for the purpose of identifying potentially adverse effects and for planning remedial actions, if necessary. On large, navigable streams, periodic, waterborne geophysical surveys should be made.

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Table C1

Influences of Site and Nonsite Factors

Eel River, California

Independent & Influencing Variables \ Dependent Variables	Soils	Landslides	Vegetation	Topography	Sediment Yield	Runoff	Channel Widening	Channel Deepening	Sinuosity Changes	[Flow]	[Channel Width]	[Channel Depth]	[Channel Slope]	[Bank Materials]	[Sediment discharge]	Flows (Basin)	Bank Erosion
[Flow]							X	X	X		[X]	[X]	[X]	[X]	[X]		
Topography	X	X	X			X										X	
[Sediment Discharge]							X	X	X		[X]	[X]	[X]	[X]			
Soils		X	X		X	X											
Climate*	X		X	X		X											
[Bank Materials]							X	X	X	[X]							
Lithology*	X	X		X													
Flows (Basin)		X			X					(X)							
Landslides	X			X	X												
Vegetation	X				X	X											
Runoff		X			X											X	
Forestry*	X		X														
Roads*			X	X													
Structure/Tectonics*		X		X													
Grazing*			X														
[Channel Width]										[X]							
[Channel Depth]										[X]							
[Channel Slope]										[X]							
Channel Widening																	X
Channel Deepening																	X
Sinuosity Changes																	X
Sediment Yields															(X)		

* Independent variable.

[Flow] Site factor.

X Link between variables.

(X) Links between site and nonsite factors.

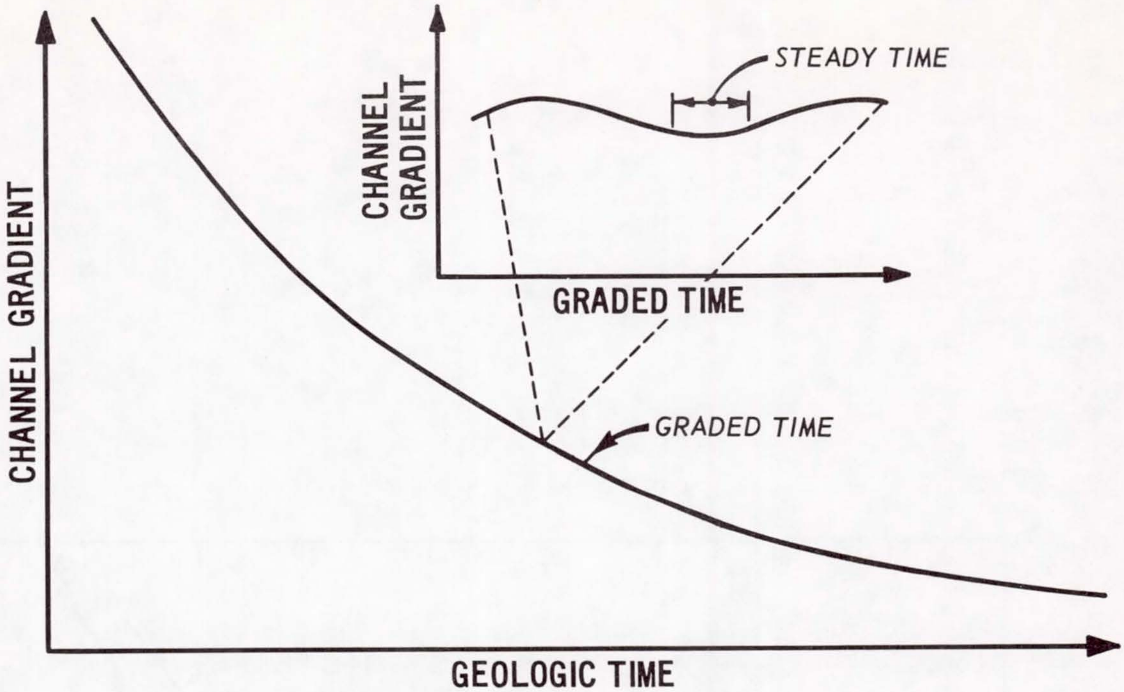


Figure C1. The influence of time on channel morphology (after Schumm 1971)

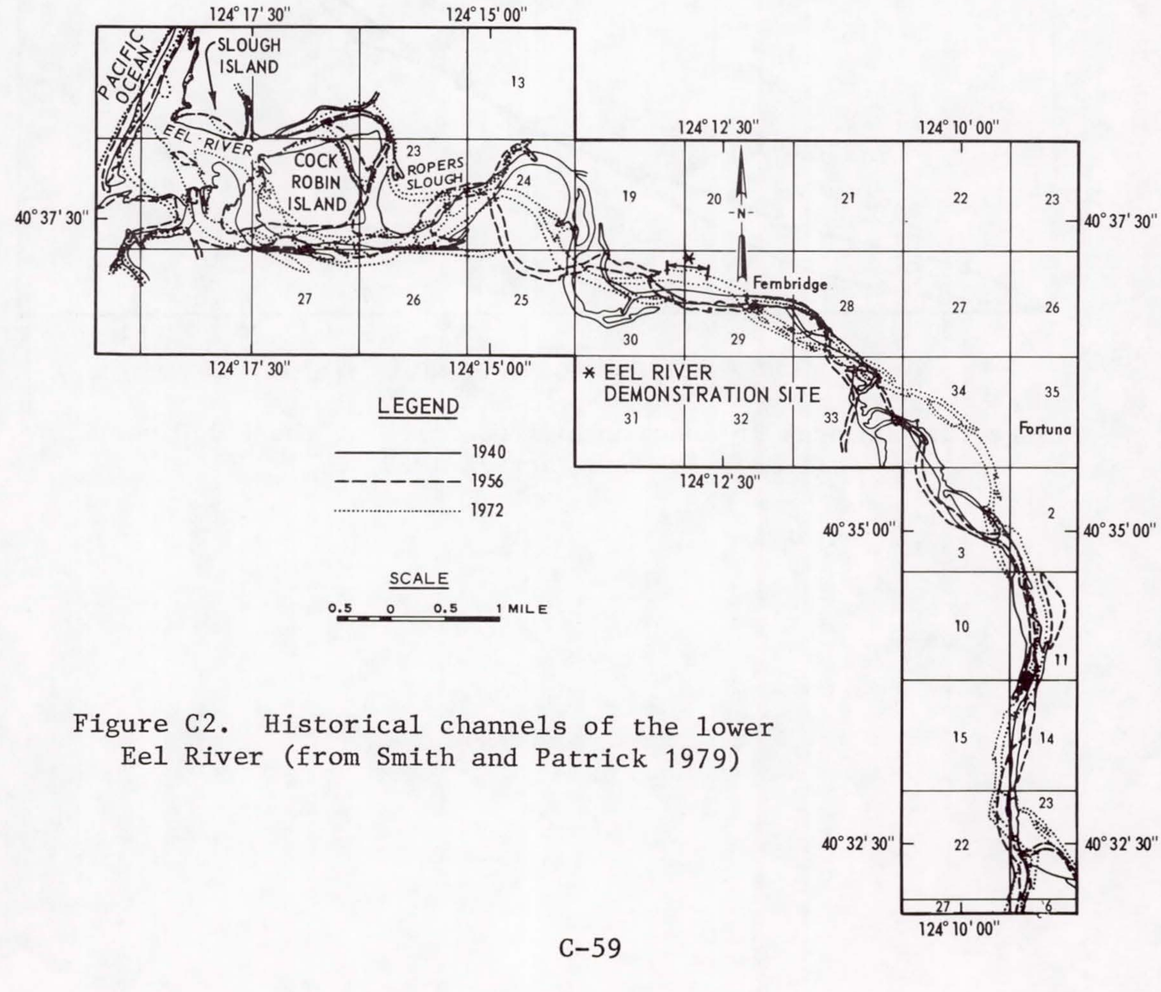


Figure C2. Historical channels of the lower Eel River (from Smith and Patrick 1979)

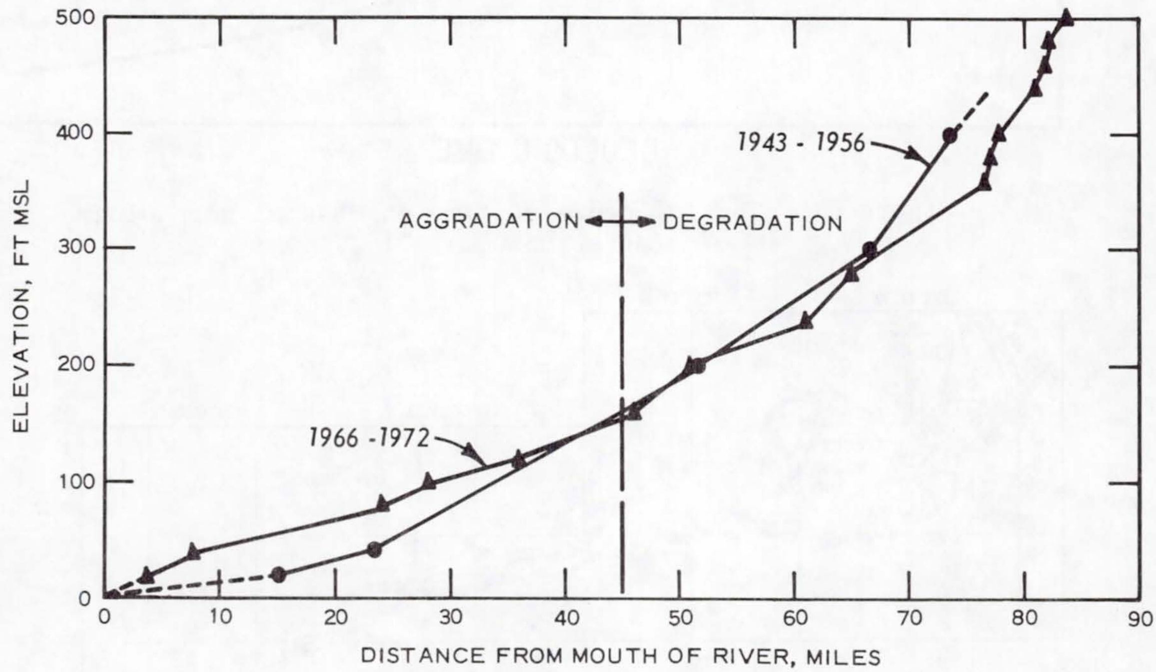
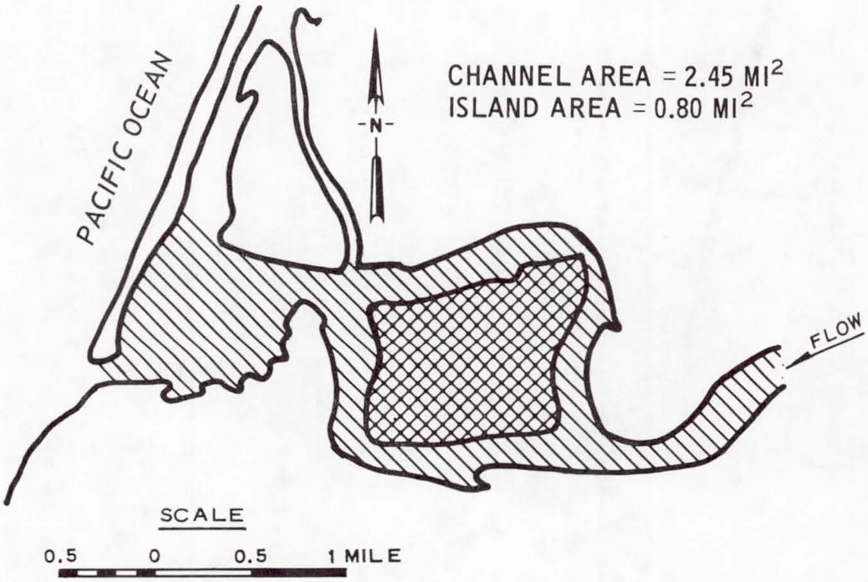
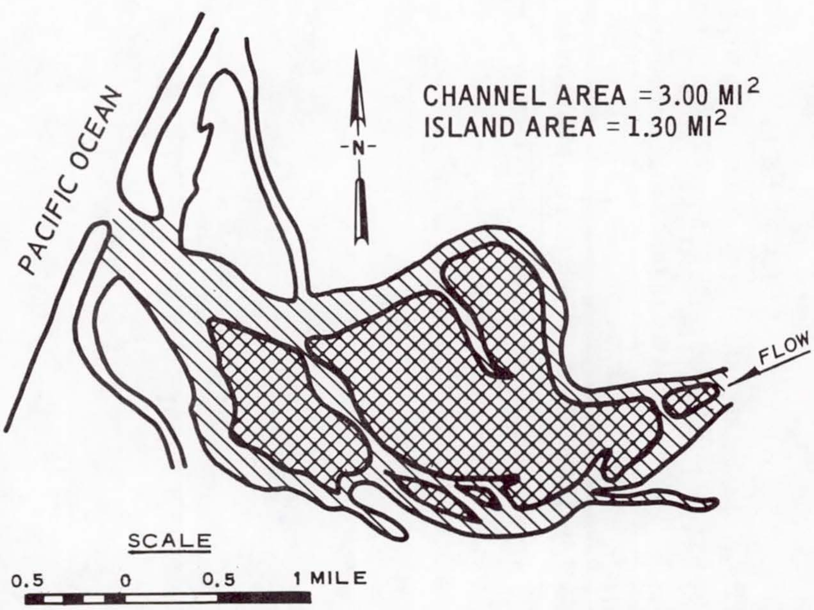


Figure C3. Changes in longitudinal profiles of the Eel River (from Smith and Patrick 1979)



(Ferndale Quad (1:62,500), 1940)



(Ferndale And Cannibal Island Quads (1:24,000), 1972)

Figure C4. Changes in channel configuration in the Eel River Delta (from Smith and Patrick 1979)

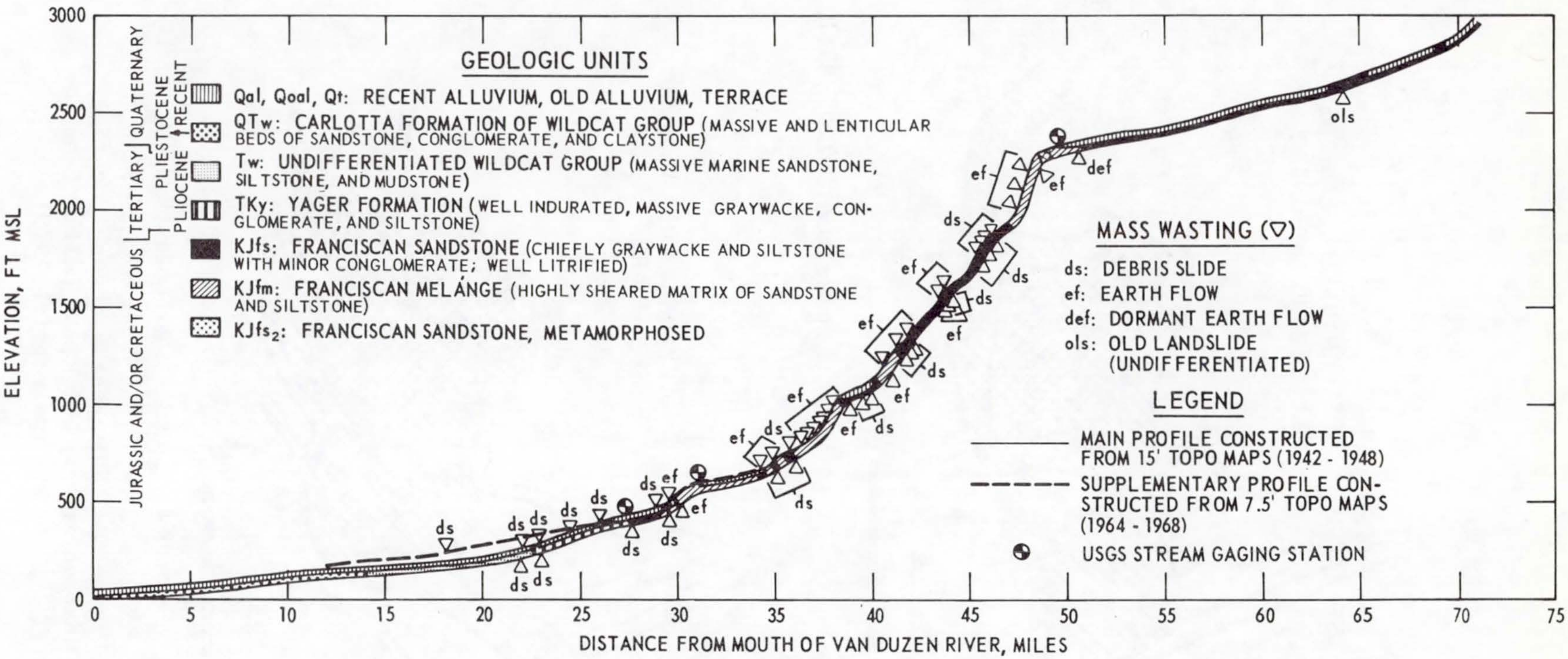


Figure C5. The effects of geological controls along the Van Duzen River (from Smith and Patrick 1979)

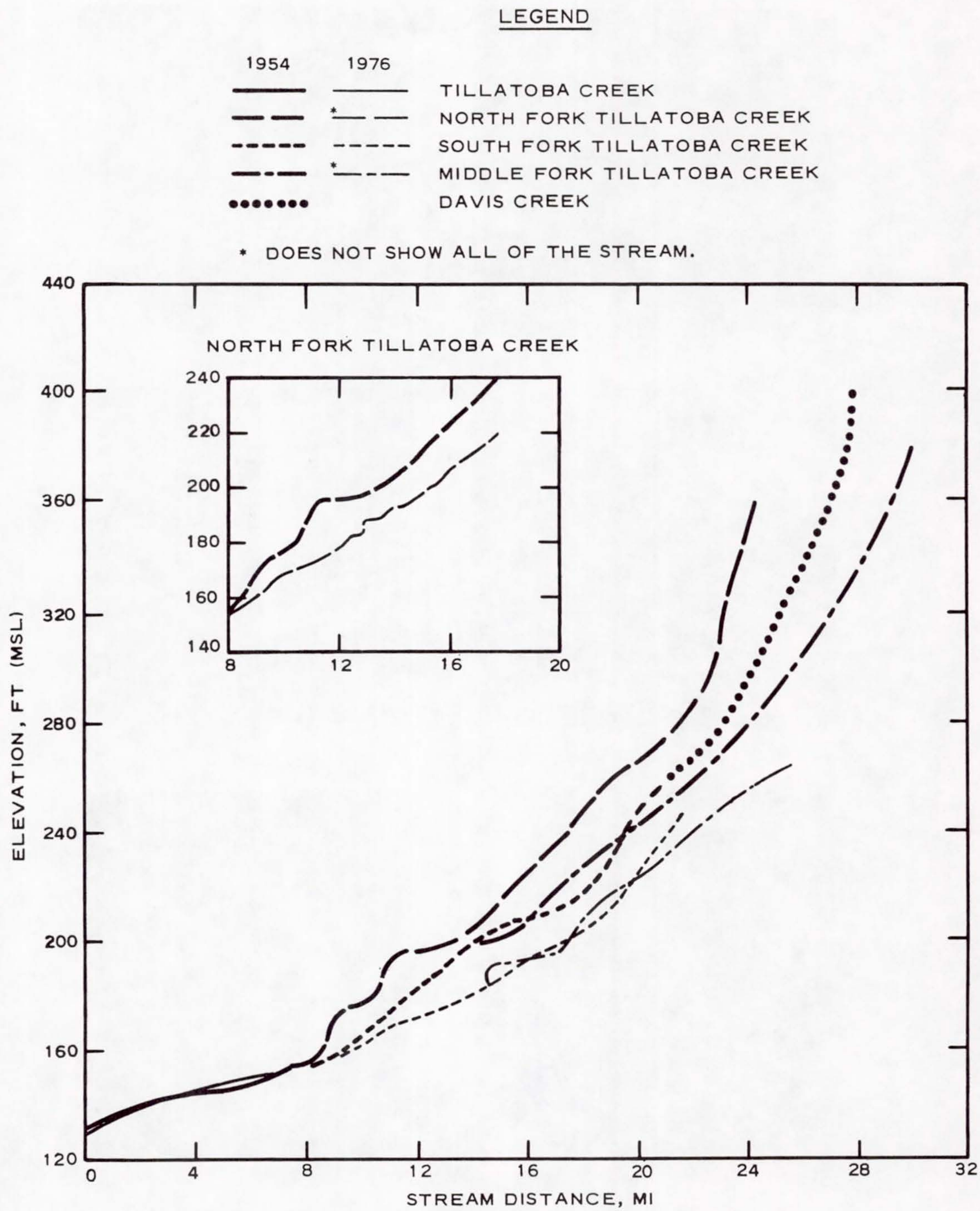


Figure C6. Changes in longitudinal profiles of Tillatoba Creek and principal tributaries (from Whitten and Patrick 1981)

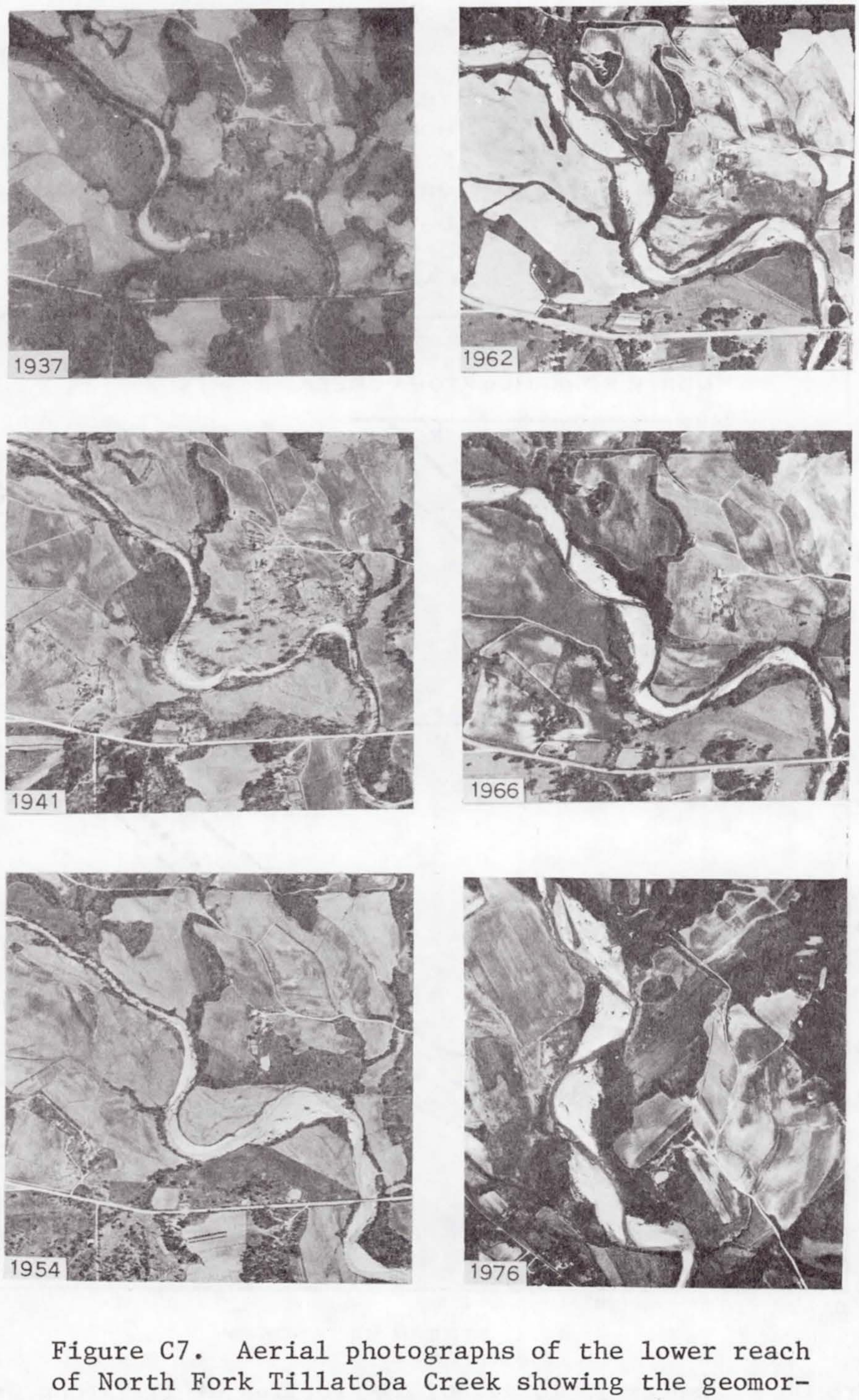


Figure C7. Aerial photographs of the lower reach of North Fork Tillatoba Creek showing the geomorphic changes between 1937 and 1976 (from Whitten and Patrick 1981)

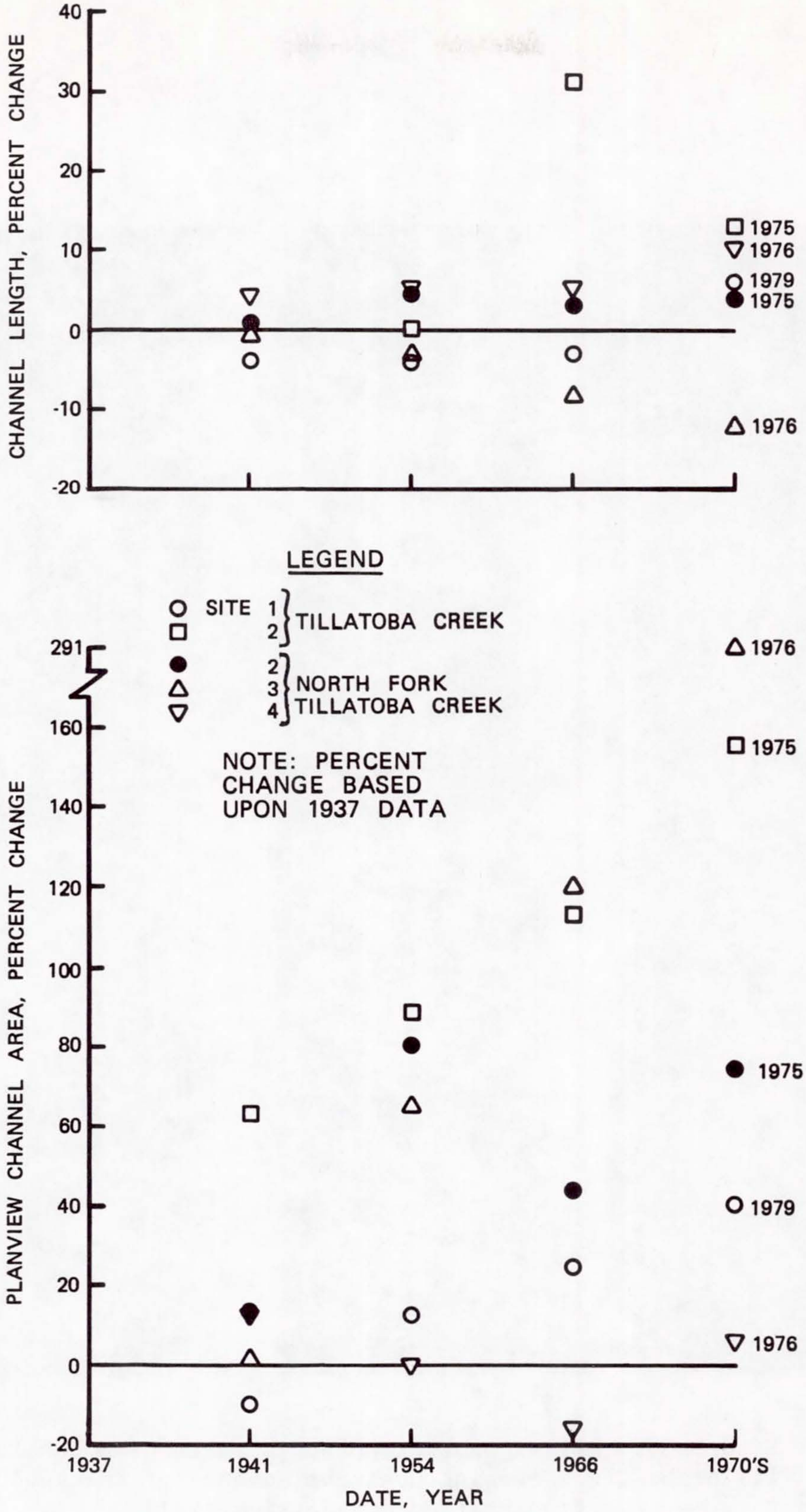


Figure C8. Changes in channel area and length of Tillatoba Creek and North Fork (from Whitten and Patrick 1981)

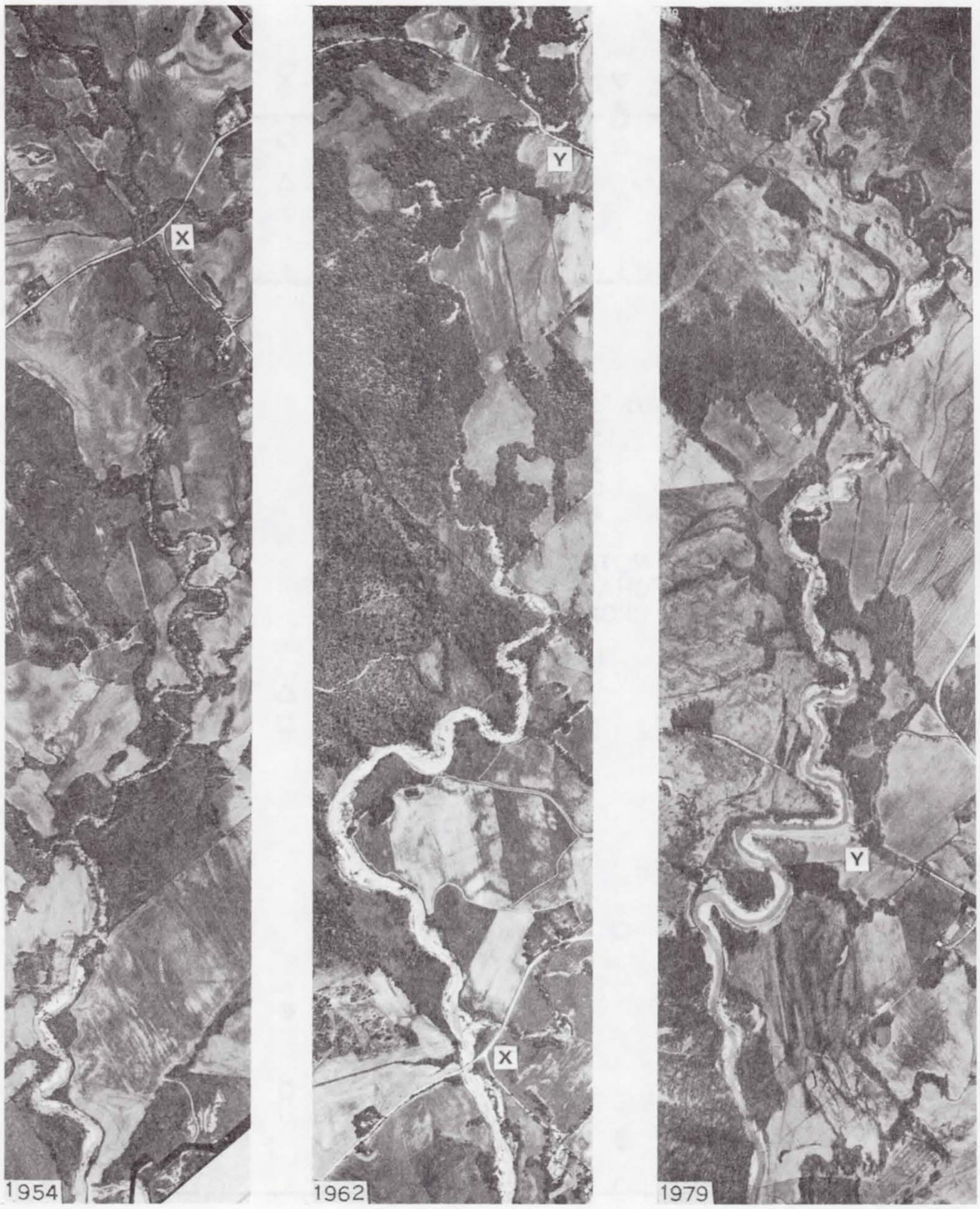


Figure C9. Aerial photographs of a reach of South Fork Tillatoba Creek showing upstream advance of knickpoint (from Whitten and Patrick 1981)

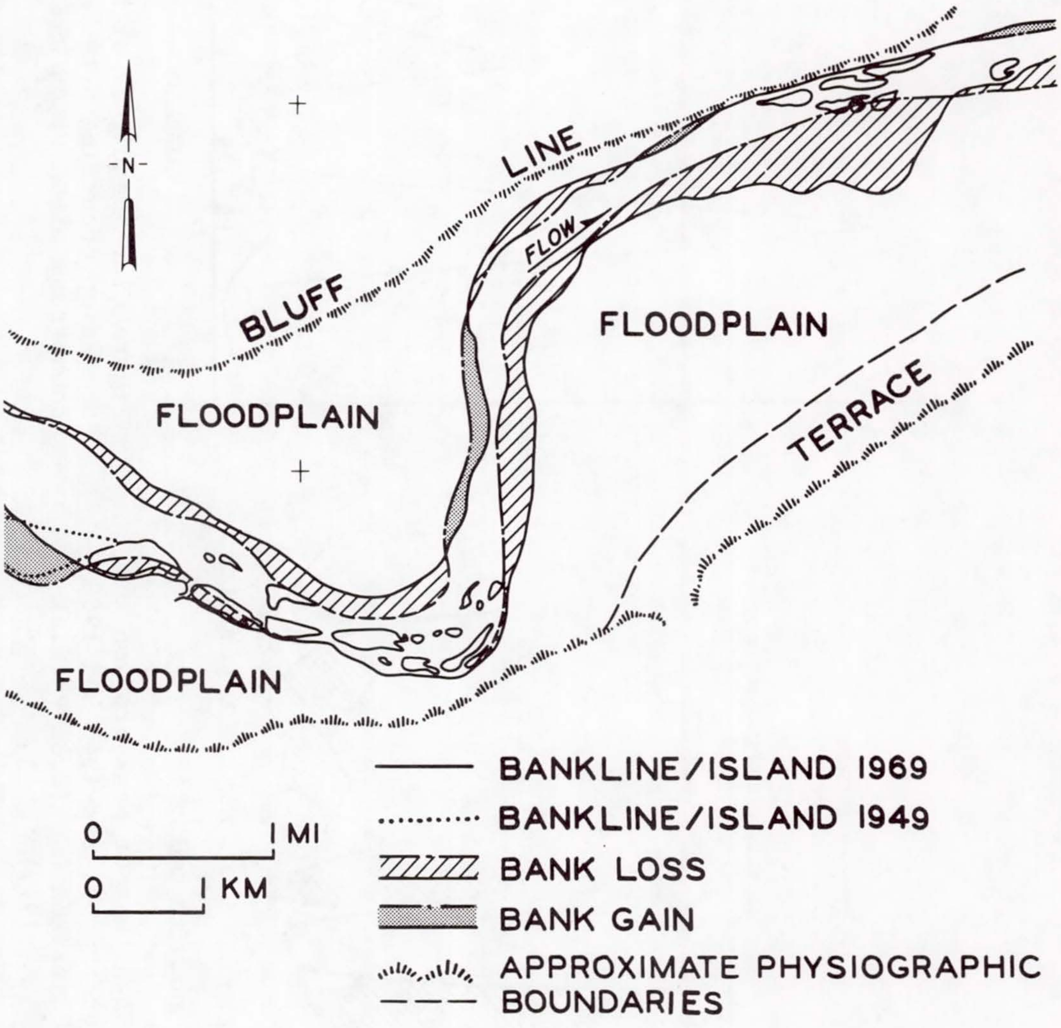


Figure C10. Changes in bankline occurring between 1949 and 1969 for a reach of the Missouri River below Garrison Dam (from Patrick 1977)

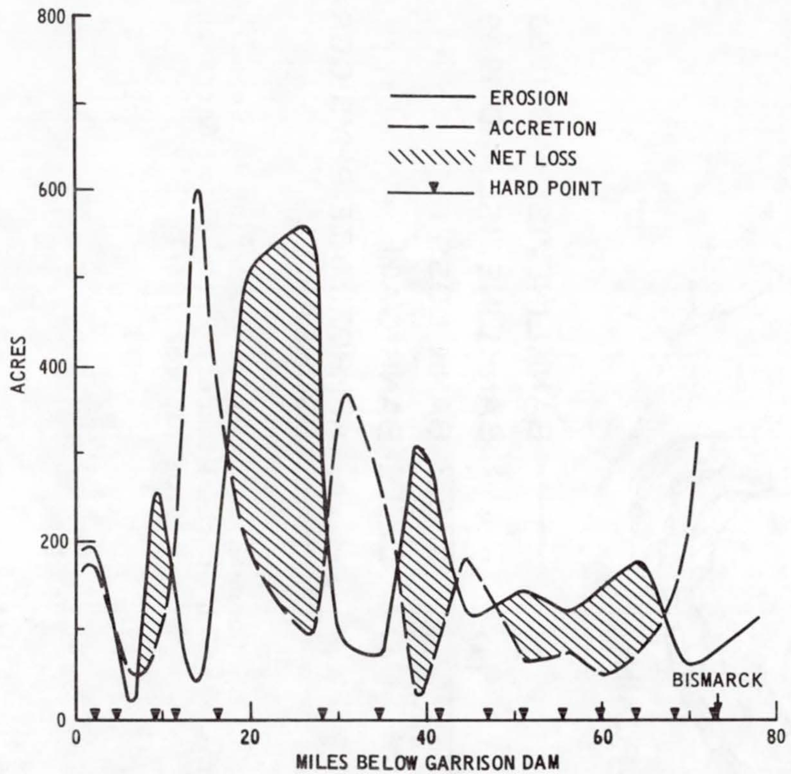


Figure C11. Magnitude of bank erosion and accretion occurring between 1940 and 1960 downstream of Garrison Dam (from Patrick 1977)

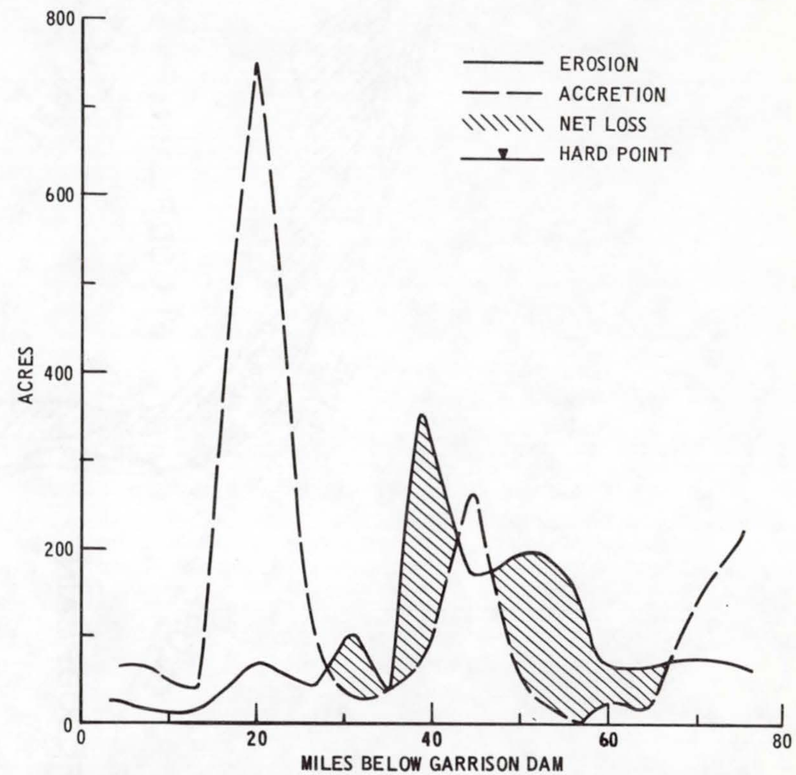


Figure C12. Magnitude of bank erosion and accretion occurring between 1960 and 1974 downstream of Garrison Dam (from Patrick 1977)

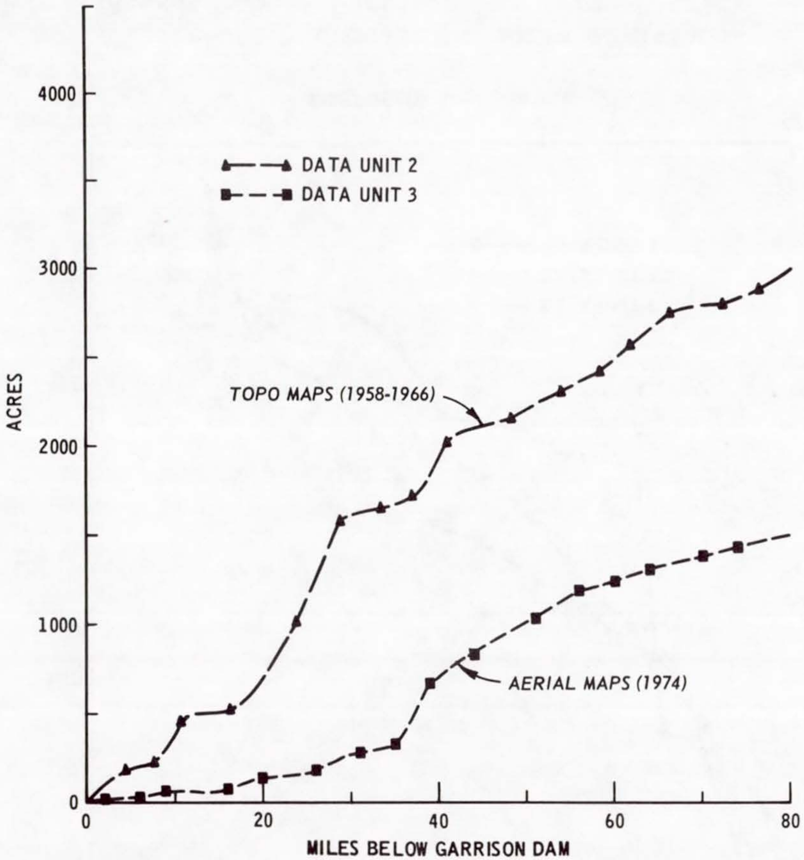


Figure C13. Cumulative acres of bank loss downstream of Garrison Dam (from Patrick 1977)

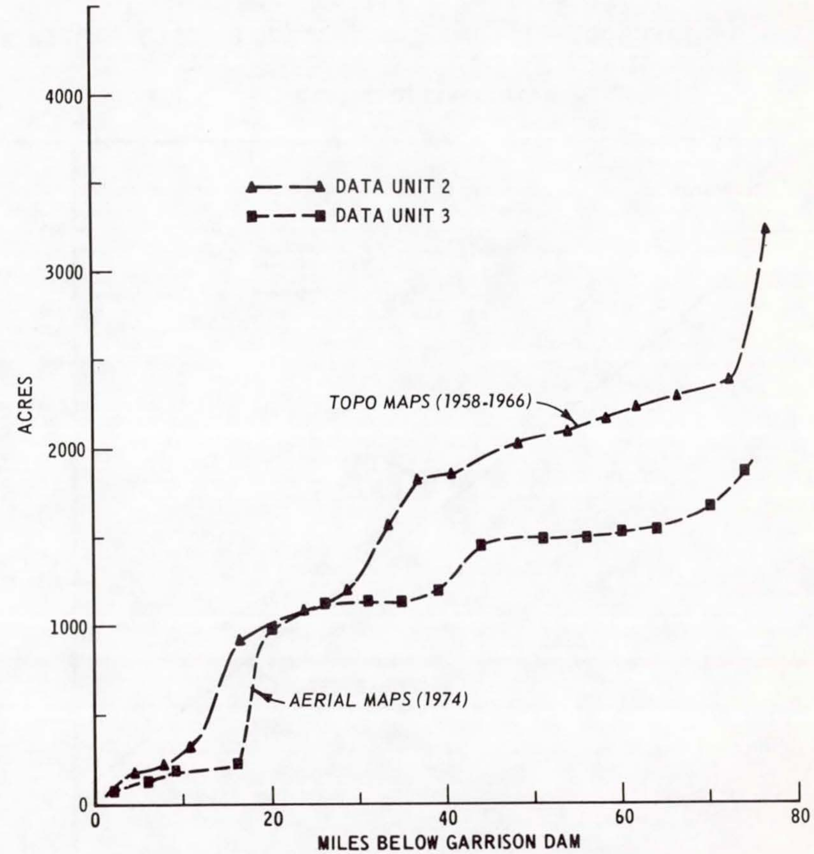


Figure C14. Cumulative acres of bank accretion downstream of Garrison Dam (from Patrick 1977)

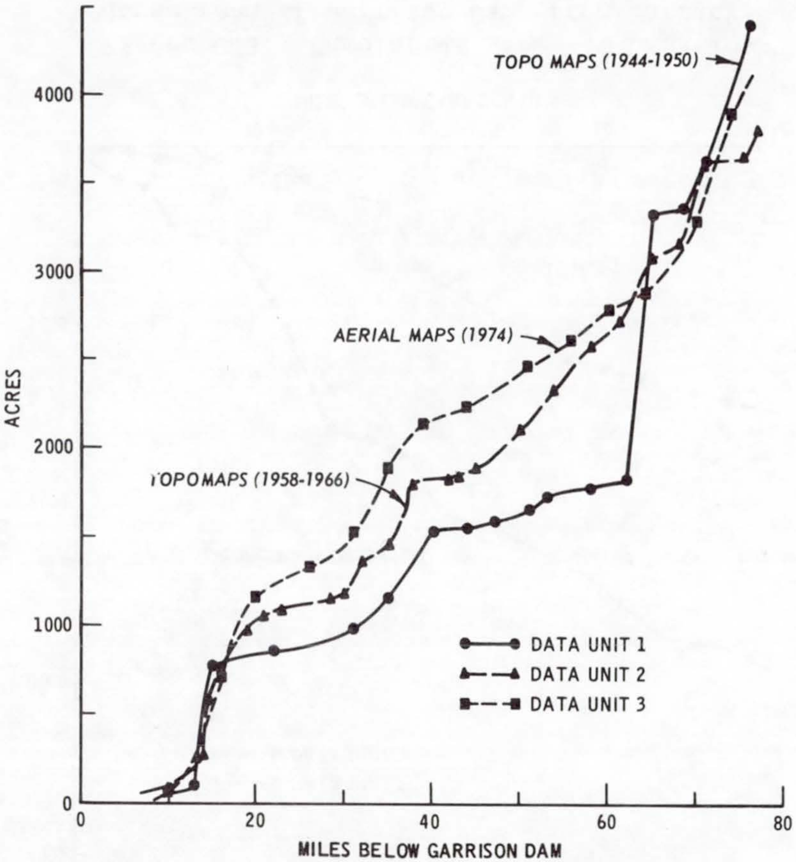


Figure C15. Cumulative acres of islands downstream of Garrison Dam (from Patrick 1977)

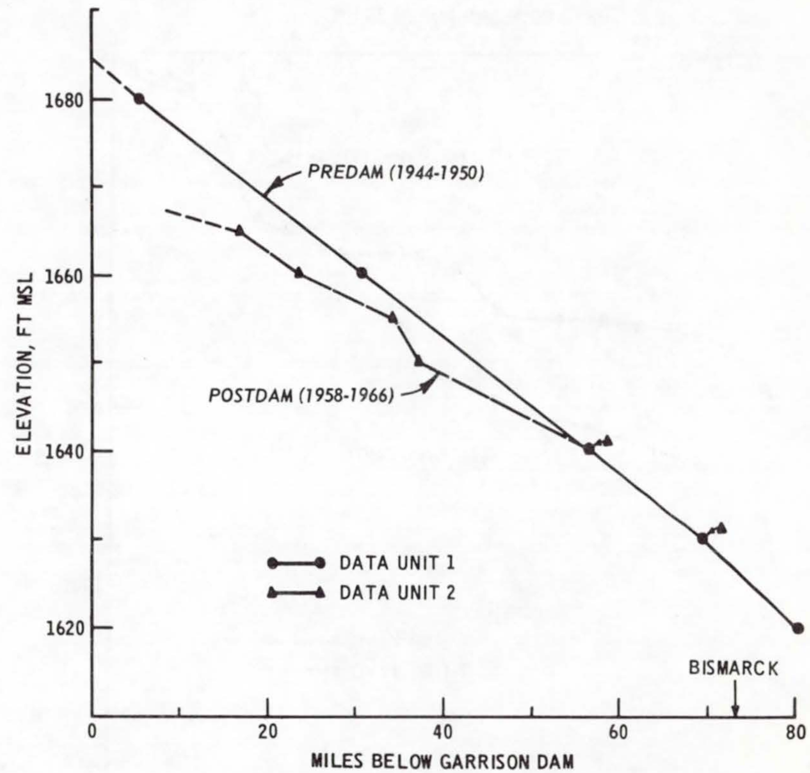


Figure C16. Longitudinal profiles downstream of Garrison Dam (from Patrick 1977)

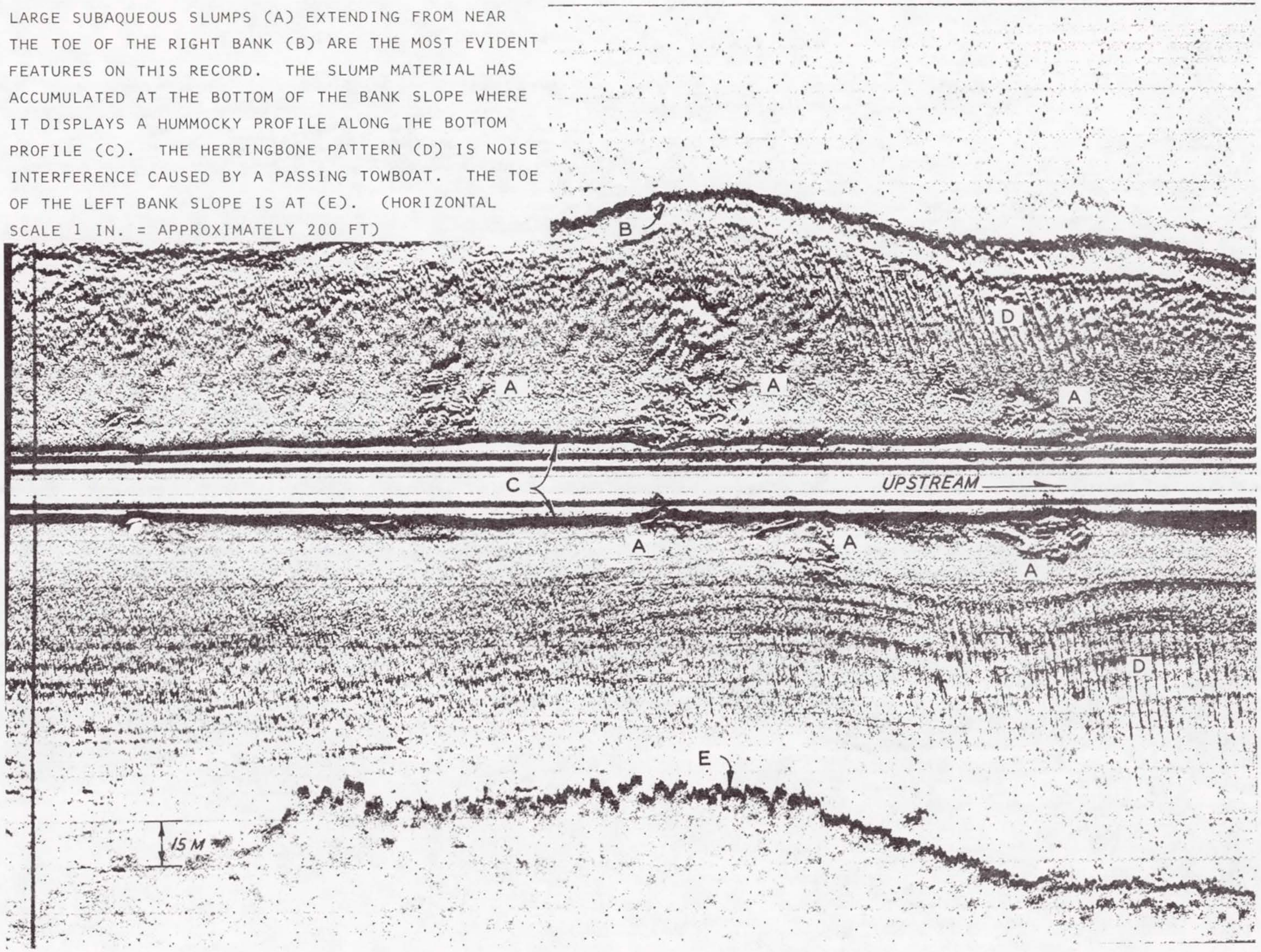


Figure C17. Side-scan sonar record of the Ohio River in vicinity of river mile 375 near Vanceburg, Kentucky

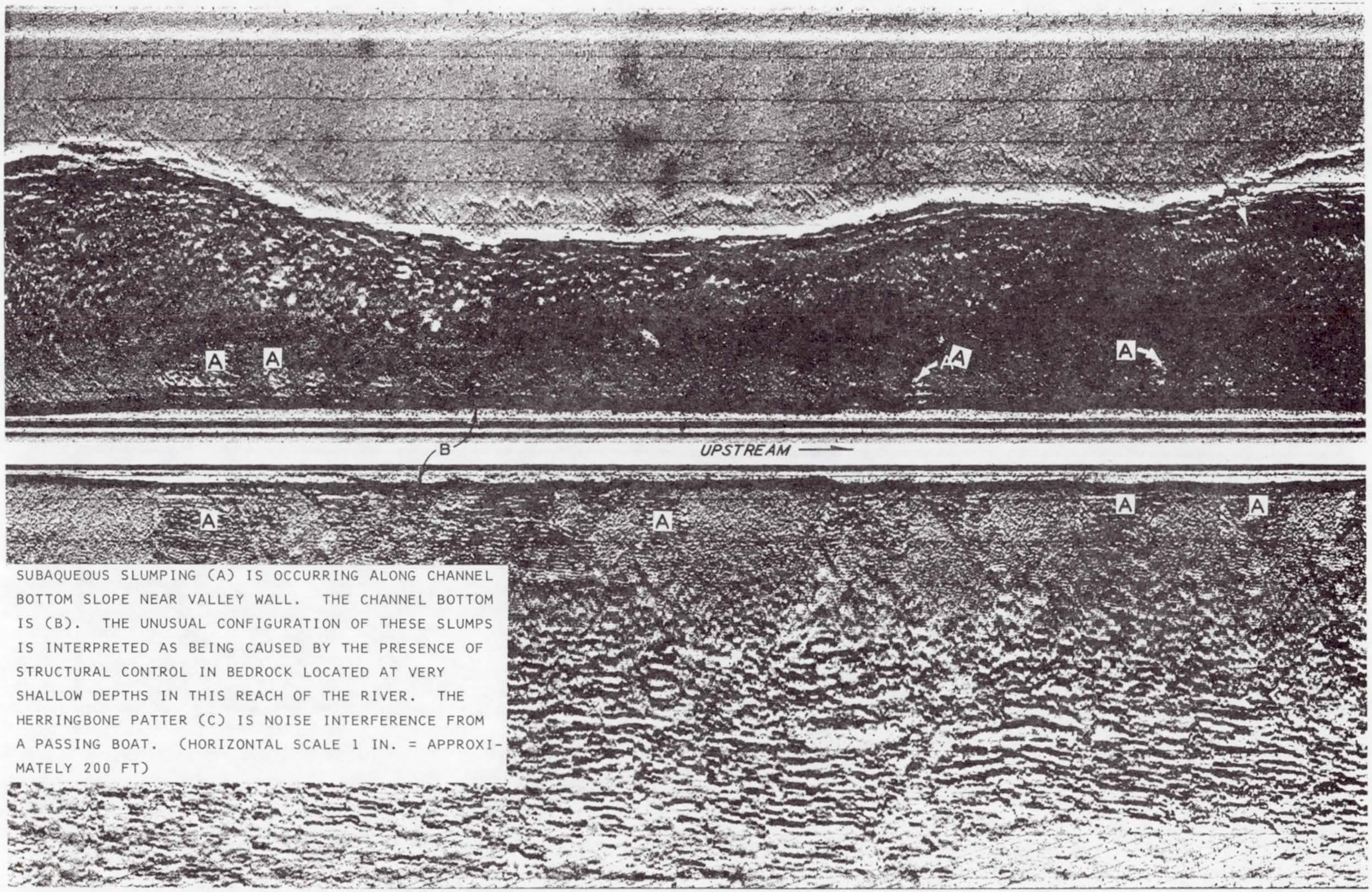
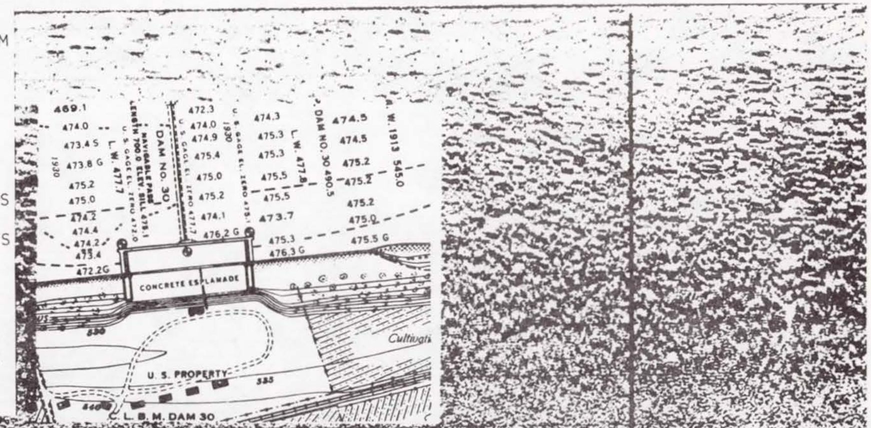


Figure C18. Ohio River between river miles 337 and 338, near Greenup, Ohio

LOCK AND DAM 30 WAS DEMOLISHED IN ABOUT 1962 AFTER A NEW LOCK AND DAM HAD BEEN CONSTRUCTED DOWNSTREAM. AN INSET, TAKEN FROM AN EARLY NAVIGATION CHART OF THE OHIO RIVER SHOWING THE CONFIGURATION OF LOCK AND DAM 30, IS INCLUDED TO PROVIDE A COMPARISON BETWEEN THE SIDE-SCAN RECORD AND THE CHART. THE REMAINS OF LOCK AND DAM 30 CAN BE SEEN CLEARLY ON THE SIDE-SCAN RECORD. MOORING CELLS (A) CHARACTERISTICALLY PROVIDE INTENSE HYPERBOLA SIGNATURES. THE REMAINS OF THE INNER (B) AND OUTER (C) LOCK WALLS PROVIDE STRONG SIGNAL REFLECTIONS. THESE STRUCTURES APPEAR CURVY DUE TO DISTORTION CAUSED BY DEVIATIONS IN THE SURVEY BOAT'S COURSE. THE OLD EMBANKMENT CAN BE SEEN AT (D) WHERE THE BOTTOM PROFILE INTERSECTS IT. CONCRETE STEPS (E) LEADING UP FROM THE CONCRETE ESPLANADE (G) ARE PARTIALLY SILTED OVER AT THE LOWER LEVEL (F). THE LIGHT TONE AND FINE TEXTURE EXHIBITED BY THE AREA OCCUPIED BY THE ESPLANADE AND STEPS MAY BE DUE TO ELEVATION DIFFERENCES RESULTING IN DEPOSITION OF THE COARSEST MATERIALS IN THE AREAS OF LOWER ELEVATIONS AND FINER SEDIMENTS IN AREAS OF HIGHER ELEVATIONS. THE CHANNEL BOTTOM PROFILE IS (H). (HORIZONTAL SCALE 1 IN. = APPROXIMATELY 200 FT)



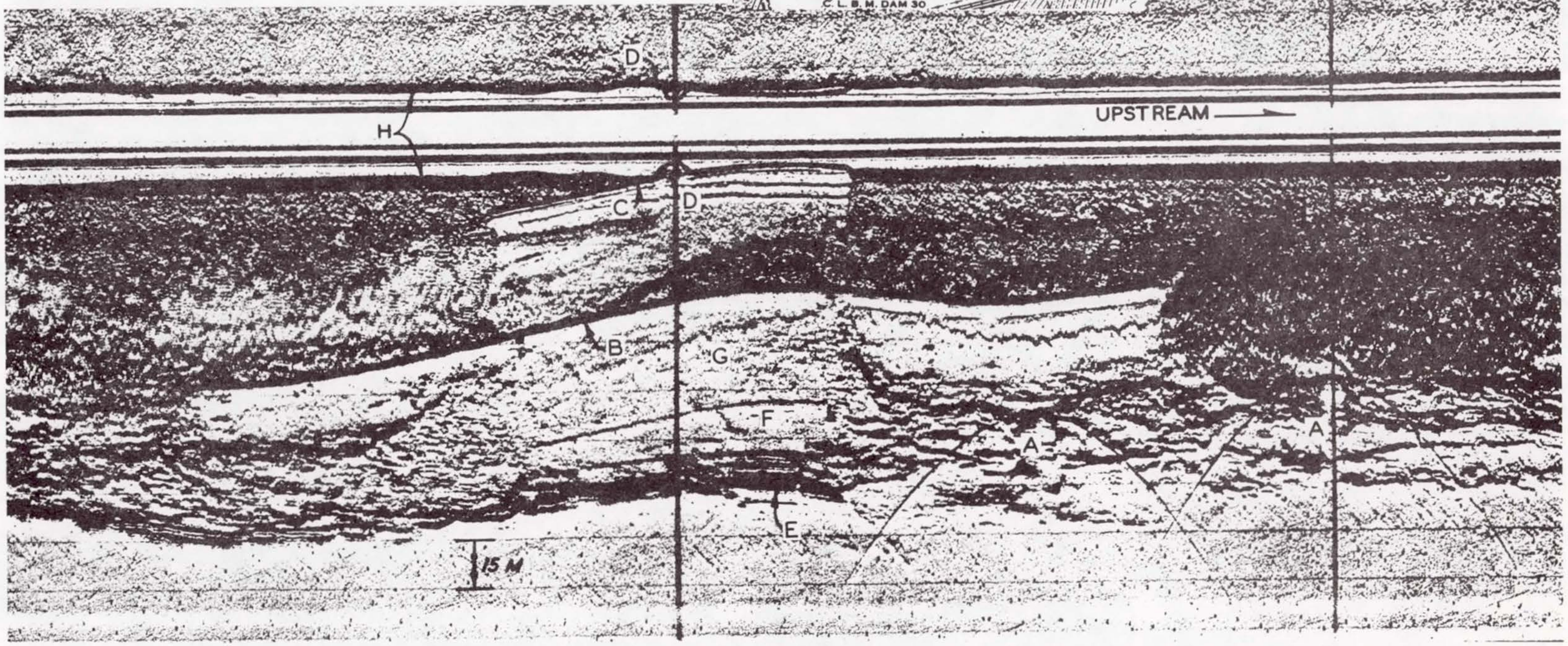


Figure C19. Side-scan record of Ohio River at old Lock and Dam 30 in vicinity of river mile 338 near Greenup, Ohio

THE REMAINS OF A STEAMBOAT THAT SANK IN THE MISSISSIPPI RIVER IN THE EARLY 1900'S LIES IN ABOUT 30 FT OF WATER AND IS ORIENTED PERPENDICULAR TO THE CHANNEL FLOW. THE BOW OF THE BOAT IS AT (A), THE STERN AT (B), AND THE CHANNEL BOTTOM AT (C). THE BOAT IS A POINT FOR DEPOSITION AND HAS BEEN PARTIALLY BURIED BY SEDIMENT (D). (HORIZONTAL SCALE 1 IN. = APPROXIMATELY 200 FT)

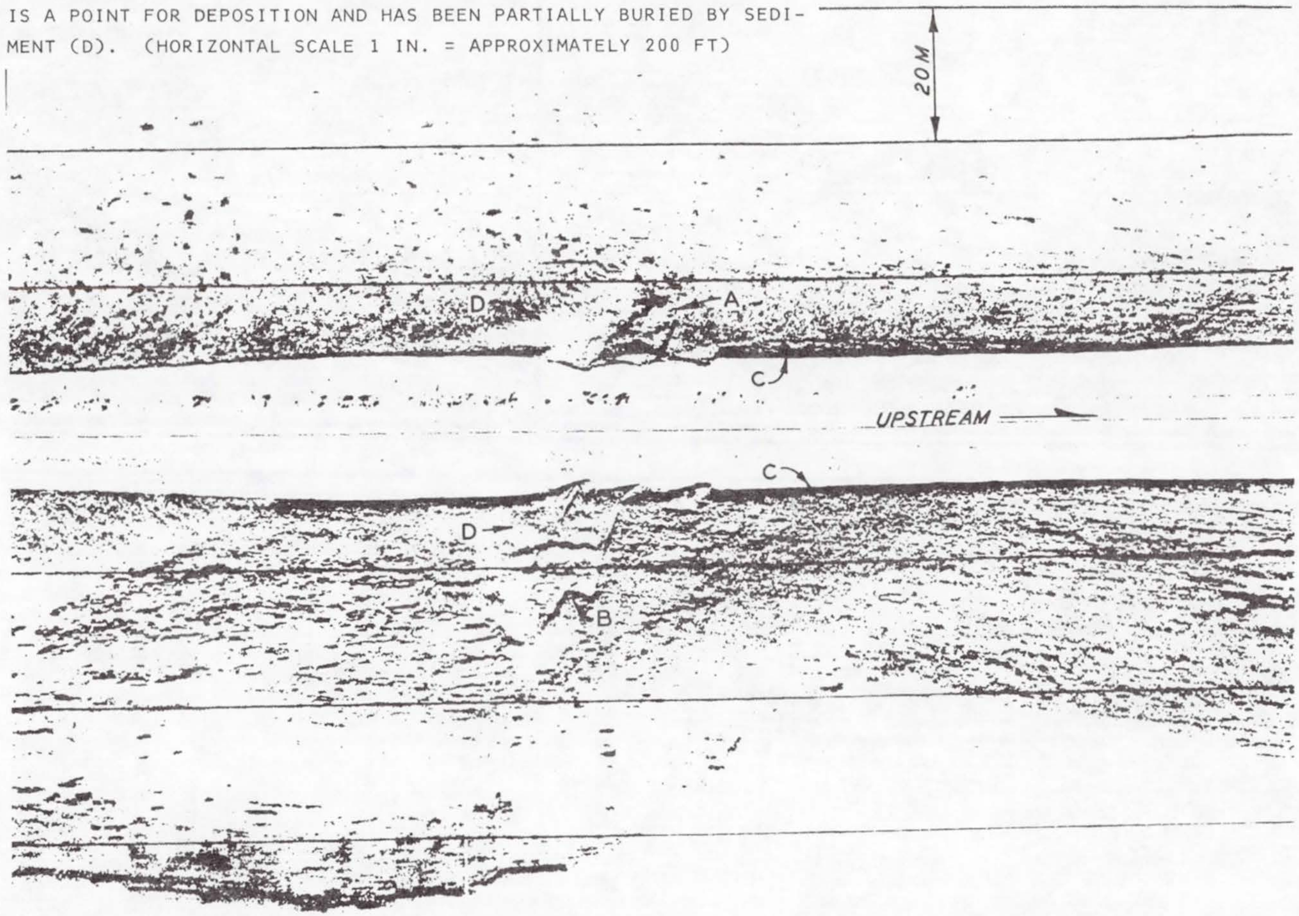


Figure C20. Side-scan sonar record in the vicinity of river mile 109 at Chester, Illinois

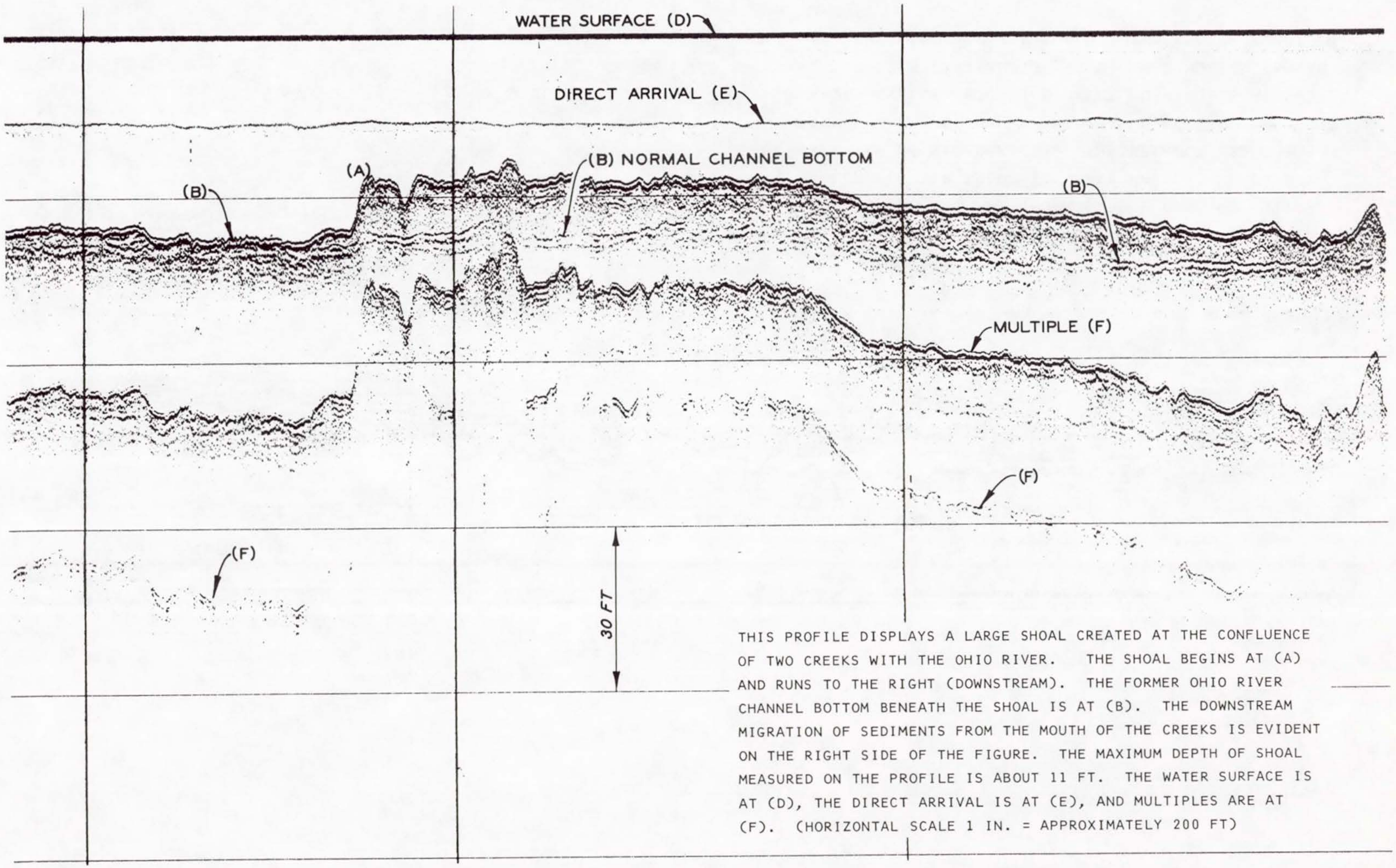


Figure C21. Subbottom profile, Ohio River, above Vanceburg, Kentucky

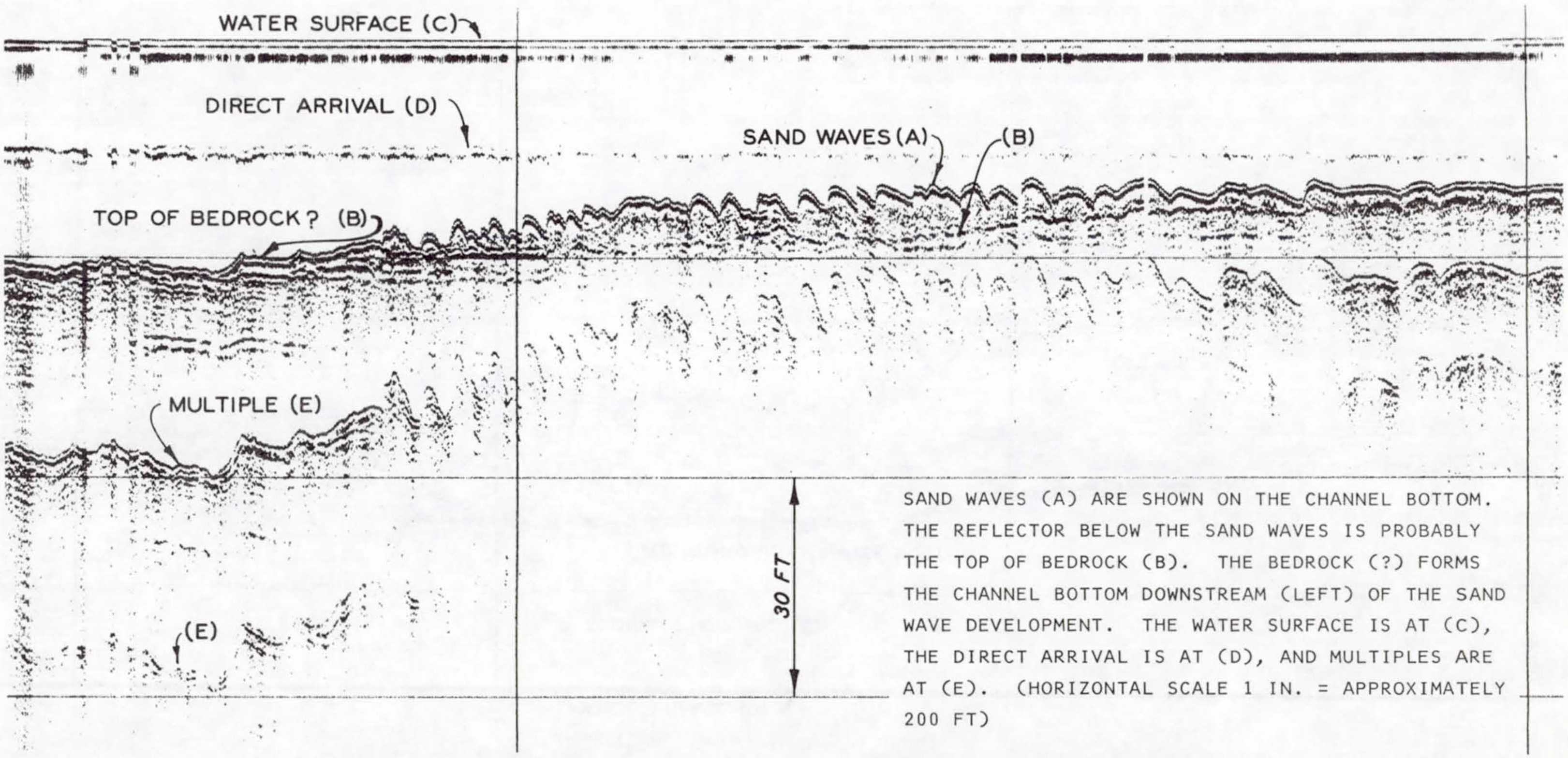


Figure C22. Subbottom profile, Ohio River, Portsmouth, Ohio

PART II: RESEARCH ON SOIL PROPERTIES AFFECTING BANK STABILITY

Research Plan

96. The objectives of this research were to (a) develop equipment and test procedures for measuring rate of erosion versus hydraulic or tractive stress (shear stress exerted on the soil by flowing water) for samples of natural soils having sufficient cohesiveness to allow undisturbed samples to be taken; (b) conduct laboratory tests on representative samples of natural soils and river water furnished by Corps of Engineers (CE) Districts to develop a method to predict the tractive shear stress at which erosion is initiated (critical tractive shear stress) and the rate of erosion; (c) develop a procedure for evaluating streambank stability using erosion and shear strength properties determined from laboratory tests conducted on undisturbed samples of natural soil; and (d) estimate bank recession, resulting from erosion and slope failure, for flows at normal water level and for rapid drawdown at selected time intervals.

Laboratory Equipment and Procedures to Measure Soil Erosion

Tractive shear stress in nature and in the laboratory

97. In order to establish the characteristics of the laboratory device to measure soil erosion, knowledge of tractive shear stresses occurring in nature needs to be determined. For steady uniform open channel flow there are no accelerations, streamlines are straight and parallel, and the pressure distribution is hydrostatic. The slope of the water surface, channel bed, and energy gradeline are parallel. Steady uniform flow is an idealized concept for alluvial channels and, even under controlled laboratory conditions, is difficult to obtain. However for some field and laboratory applications, the flow is steady and changes in channel width, depth, or flow direction (which would result in nonuniform flow) are so small that the flow can be considered

uniform. Steady, gradually varied flow is nonuniform since changes in depth and velocity take place slowly over large distances. In gradually varied flow, the actual flow depth is either larger than or smaller than the normal depth and either larger than or smaller than the critical depth. Normal depth is that depth of flow (depth is included in the hydraulic radius) that would exist for uniform flow determined from the Manning's n equation

$$V = \frac{1.486}{n} R^{2/3} S_f^{1/2} \tag{C1}$$

where

V = average velocity

n = Manning's roughness coefficient

R = hydraulic radius (cross-sectional area divided by wetted perimeter)

S_f = slope of the energy gradeline

The critical depth is the depth of flow when the Froude number equals unity where the the Froude number is defined as

$$F = \frac{V}{gd} \tag{C2}$$

where

F = Froude number

g = acceleration of gravity

d = actual flow depth (equals critical depth when F = 1)

The actual flow depth can be different from the normal depth because of changes in slope of the channel bed, changes in cross section, and flow around bends.

98. The average tractive shear stress acting on the bed of a straight alluvial channel for steady uniform flow is

$$\tau = \gamma_w R S_o \quad \text{(C3)}$$

where

τ = average tractive shear stress

γ_w = unit weight of water

S_o = channel bed slope (equal to water surface slope as well as energy gradeline)

For gradually varied flow, Simons et al. (1975) express the average tractive shear stress acting on the bed of a straight alluvial channel as

$$\tau = \gamma_w R S_f \quad \text{(C4)}$$

For relatively wide (channel width to depth of flow equal to or greater than 10) trapezoidal or rectangular channels, the hydraulic radius may be replaced by the depth of flow with little loss in accuracy (Figure C23). For a relatively wide straight alluvial channel for steady uniform flow, the average tractive shear stress acting on the bed is

$$\tau = \gamma_w d S_o \quad \text{(C5)}$$

For a relatively wide straight alluvial channel with gradually varied flow, the average tractive shear stress acting on the bed is

$$\tau = \gamma_w d S_f \quad \text{(C6)}$$

For relatively wide trapezoidal or rectangular channels of finite width, the maximum tractive shear stress acting on the channel sides is about 75 percent of the value acting on the bed for channels of infinite width as shown in Figure C24 (Lane 1952).

99. In a curved alluvial channel, the velocity of flow may be higher on the outside of the bend (concave bank) during normal flow and higher on the inside of the bend (convex bank) during flood flow as indicated in Figure C25 (Russell 1967). The distinction between

normal and flood flow is significant because field observations have shown that 90 percent of all significant bank erosion occurs during major flood events (Simons et al. 1979). The changes in velocity cause even larger changes in the tractive shear stresses acting on the bed and sides of the channel as shown in Figure C26 (Soil Conservation Service 1977).

100. The tractive shear stresses acting on the bed of a relatively wide straight alluvial channel for steady uniform flow for various values of depths of flow and channel bed slopes calculated using Equation C5 are listed in Table C2. For the range of interest of typical values of depths of flow and channel bed slopes which occur in nature, the average tractive shear stress on the bed varies from 0 to 2.5 lb/ft^2 (Table C2). The average tractive shear stress on the sides of a relatively wide straight alluvial channel for steady uniform flow is about 75 percent of the value acting on the bed or 0 to 1.9 lb/ft^2. The average tractive shear stress on the sides of a relatively wide curved alluvial channel for steady uniform flow may be as much as twice the value for a straight channel (Figure C26) or 0 to 3.8 lb/ft^2.

101. When an undisturbed sample of soil is taken in the field and brought into the laboratory to measure the erodibility of the soil, the scaling relationships (length, time, and force) are all equal to unity. Therefore, the tractive shear stress to be applied to the soil sample in the laboratory is the same as that in the field.

Laboratory recirculating tilting flume

102. Laboratory flumes are devices that have been used to measure soil erosion (Perry 1975), and it was decided in this research program to construct a flume for this purpose. On 7 August 1979, Contract No. DACW39-79-C-0069 was awarded to Engineering Laboratory Design, Inc., of Lake City, Minnesota, to construct a laboratory recirculating tilting flume to measure soil erosion. A self-contained flume with integral pump and reservoir was delivered to the U. S. Army Engineer Waterways Experiment Station (WES) on 29 October 1979. The flume (Figure C27) has a working channel length of 12 ft, width of 12 in., and depth of

18 in. The water is recirculated using a Jacuzzi low-pressure, high-volume centrifugal pump, Model L 15FH8, rated to deliver 2250 gal/min at 10 ft of head. The pump is powered by a close-coupled 15-hp, 230 v, 3-phase motor, and the quantity of flow is regulated with an 8-in.-diam butterfly valve installed in the supply line (Figure C28). A sealed fiberglass steel-reinforced headbox, fitted with a motorized aluminum headgate and turning vanes to direct the flow of the water (Figure C29), is mounted on the upstream end of the channel. The side-walls and floor of the channel section were fabricated of abrasion-resistant 0.5-in.-thick Plexiglas. An aluminum motorized tailgate to control the tailwater elevation and turning vanes to direct the flow of water to the reservoir are located at the downstream end of the channel (Figure C30). The channel section has power tilt from 0 to 16 percent through electrically operated synchronized jack screws (Figure C31). Figure C32 shows the control box for the headgate, tailgate, and slope. A soil sample, either 3 or 5 in. in diameter, corresponding to usual field soil sample sizes, is mounted flush with the floor of the flume 3 ft from the tailgate (Figure C33). No provision is made for maintaining the constant temperature of the eroding water. The temperature of the eroding water increases at the rate of 0.7°F/min when the butterfly valve is 1/4 open. This factor could be important for long duration ($\geq$15 min) tests on erosion resistant materials because for saturated remolded illitic soil it has been shown that the susceptibility to erosion increases as the temperature of the eroding fluid increases as indicated in Figure C34 (Ariathurai and Arulanandan 1978).

Calibration of the flume

103. The tractive force acting on the soil sample mounted flush with the floor of the flume is given by Equation C4. Prior to construction of the flume, in order to size the pump required it was necessary to make some theoretical calculations of the tractive shear stress. For these calculations, uniform flow conditions were assumed and the tractive shear stress was calculated using Equation C3.

According to Albertson, Barton, and Simons (1960), the water horsepower of the pump was calculated from

$$hp = \frac{\gamma_w QH}{550} \qquad (C7)$$

where

hp = water horsepower of pump

Q = discharge

H = head

For an assumed head of 16 ft, Figure C35 shows the theoretical relationship between tractive shear stress, discharge, and water horsepower as a function of flow depth and bed slope for uniform flow conditons.

104. The flume was calibrated using a variable-reluctance differential pressure transducer in conjunction with an 0.125-in.-outside-diameter (OD) Pitot tube. The Pitot tube was used in sensing the piezometric pressure and stagnation pressure (Figures C33 and C36). The flow, total head, and static pressures were transmitted by 0.125-in. plastic tubes from the Pitot tube to a variable reluctance differential pressure transducer (Figure C37), Model P90D, Pace Engineering Company. The electrical signal from the transducer was fed into a transducer indicator (Figure C37), Model CD25, Pace Engineering Company, which measures the transducer signal by means of a digital indicator and a pointer deflection on a meter scale (Brown and Chu 1968).

105. An empirical relationship developed by Preston (1954) indicates that the velocity distribution near a smooth surface is

$$\frac{v}{v_s} = 8.74 \left(\frac{v_s y}{\nu} \right)^{1/7} \qquad (C8)$$

where

v = flow velocity at a distance y from the boundary

v_s = shear velocity

y = distance from the boundary

ν = kinematic viscosity of the fluid

Simons and Senturk (1976) expressed the shear velocity as

$$v_s = \sqrt{\tau/\rho} \tag{C9}$$

where ρ represents the mass density of the fluid. Thus by measurement of the flow velocity near the bed, the tractive shear stress acting on the bed can be determined.

106. Through the use of the Pitot tube, a pressure head can be measured at any point in the flow. The flow velocity can be calculated by the relationship

$$\frac{v^2}{2g} = \frac{p - p_o}{\rho g} \tag{C10}$$

where

p = dynamic pressure measured at the tip of the Pitot tube

p_o = static pressure measured near the tip of the Pitot tube

If the Pitot tube is placed on the bed of the flume, the distance from the boundary at which the flow velocity is measured is

$$y = \frac{d_t}{2} \tag{C11}$$

where d_t is the OD of the Pitot tube.

107. Substituting Equations C9-C11 into Equation C8 gives

$$\frac{p - p_o}{\tau} = 38.2 \left(\frac{\sqrt{\tau/\rho}\ d_t}{2\nu} \right)^{2/7} \tag{C12}$$

which can be rearranged to

$$\tau = (p - p_o)^{7/8} \left[\frac{\rho^{1/7}}{38.2} \left(\frac{2\nu}{d_t} \right)^{2/7} \right]^{7/8} \tag{C13}$$

Equation C13 enables a relatively simple calculation for tractive shear stress on acting on the bed of the flume based on a Pitot tube reading at the boundary and properties of the fluid. For an 0.125-in.-OD Pitot tube and water at 70°F

$$\tau = 9.62 \times 10^{-3}(p - p_o)^{7/8} \qquad (C14)$$

where τ is in lb/ft^2. Figure C38 shows the calibration curve for the flume relating tractive shear stress and bed slope, as a function of headgate opening and water level in headtank for water at 70°F. The range of tractive shear stresses in the laboratory flume varies from 0 to 0.6 lb/ft^2, which is somewhat lower than the range of tractive shear stresses that occurs in nature on channel beds and that varies from 0 to 2.5 lb/ft^2 (Table C2). However, this limitation is not severe because the relationship between erosion rate and tractive shear stress is usually linear and can be extrapolated upward to 2.5 lb/ft^2. From pressure differences measured for various bed slopes (0 to 10 percent), headgate openings (0 to 4 in.), and water levels in the headtank, velocity profiles were determined using Equation C10 and plotted in Figures C39 through C41. The approximate average velocity shown in Figure C38 ranges from 8 to 15 ft/sec. From pressure differences measured for zero bed slope, headgate opening of 3 in., and a half headtank of water, the velocity profile was determined at various cross sections along the flume using Equation C10 as illustrated in Figure C42.

Test procedure

108. The laboratory flume is designed to accommodate soil samples 3 in. in diameter by 0.75 to 1.5 in. high or 5 in. in diameter by 0.75 to 1.5 in. high. If the undisturbed soil sample to be tested was taken from a location below the groundwater table and therefore was saturated in the field, the trimmed undisturbed soil sample is soaked in a solution of the soils pore fluid until the weight of the soil sample becomes constant (Arulanandan, Gillogley, and Tully 1980). The soil sample is then weighed, inserted into the flume, and positioned so that the soil surface is flush with the channel bed as shown in Figure C33. Normally, cohesive soil samples are strong enough to permit

them to be handled and inserted in the flume without support. Soils that will not remain intact without support may be contained within a retainer ring that fits into the sample holder in the flume.

109. Due to the relatively large (360 gal) quantity of water recirculated in the flume, tap water (see Table C3 for properties) is used for erosion testing whenever the total amount of cations (calcium, magnesium, potassium, and sodium) in the river water is equal to or less than 5 milliequivalents/liter. If the river water concentration is greater than 5 milliequivalents/liter, special provisions should be made to use actual river water in the erosion testing. The influence of the river (eroding) water on the erodibility of cohesive soils is discussed in the following section.

110. If the undisturbed soil sample to be tested was taken from a location above the groundwater table and therefore was partially saturated in the field, it is necessary to determine the water uptake rate of the undisturbed soil sample during the erosion test. Duplicate undisturbed soil samples are trimmed, and one soil sample is weighed, inserted into the flume, and positioned so that the soil surface is flush with the channel bed. Following completion of the erosion test, the duplicate undisturbed soil specimen is inserted into the flume and a soaking test is conducted, using the same test duration and depth of water as the eroding test, to determine the water uptake rate of the undisturbed soil sample. The water uptake rate determined from the soaking test is the baseline used in differentiating between soil weight gain due to water uptake and soil weight loss due to erosion when interpreting the results of the erosion test.

111. After positioning the undisturbed soil sample for the erosion test, the headgate opening, channel bed slope, and butterfly valve are adjusted to give a relatively low tractive shear stress, the pump motor is turned on, and flow through the flume commences. Each erosion test is continued for 5 min. Immediately after beginning the erosion test, the temperature of the eroding water is recorded and the tip of the Pitot tube is positioned just above the surface of the soil in the center of the soil sample; after allowing time for the static and

dynamic pressures to come to equilibrium (about 2 min), the reading of pressure differential is taken. At the end of the test, the test duration is recorded and the temperature of the eroding water is measured. The soil sample is removed from the flume, blotted with paper tissues in a consistent manner to remove excess water, and weighed as promptly as possible. The top of the soil sample is trimmed to a distance below the depth of erosion, and the sample is weighed again. Erosion tests are repeated using a different headgate opening, channel bed slope, or butterfly valve position to give an increased tractive shear stress until sufficient data are obtained to obtain a plot of tractive shear stress versus erosion rate. The erosion rate is calculated from

$$\dot{e} = \frac{\Delta W}{A \times \Delta T} \qquad \text{(C15)}$$

where

$\dot{e}$ = erosion rate

ΔW = soil dry weight loss due to erosion

A = area of soil sample exposed to erosion

ΔT = test duration

and plotted versus the tractive shear stress in Figure C43. The time between erosion tests should be brief to avoid air-drying the soil sample. Following the last erosion test, a water content determination is made of the top 1/4 in. of the soil sample.

Prediction of Erodibility of Soils

Introduction

112. This section of the report describes methods for prediction of critical tractive shear stresses for both cohesionless and cohesive soils. These values are then used as a basis, together with other parameters, for predicting the erodibility of undisturbed saturated soils in the field.

Erodibility of cohesionless soils

113. The erosion characteristics of cohesionless soils are

controlled by gravitational forces. The basic parameters affecting the erosion of cohesionless soils are the particle size, particle shape, gradation, relative density, and type and amount of sediment present in the eroding fluid. The critical tractive shear stress is defined in Figure C43 as the shear stress at zero erosion rate. Figure C44 shows the relationship between critical tractive shear stress and mean particle diameter for sand and gravel (Lane 1952). The critical tractive shear stress for cohesionless material on the channel sides is reduced from that on the channel bed to allow for the gravitational component of the forces acting on the soil particle using the following expression developed by Simons et al. (1975):

$$K = \cos \Theta \sqrt{1 - \frac{\tan^2 \Theta}{\tan^2 \phi_R}} \qquad \text{(C16)}$$

where

K = reduction factor

Θ = slope angle

ϕ_R = angle of repose of soil

The angle of repose of the soil for use in Equation C16 may be estimated using Figure C45 (Lane 1952). The critical tractive shear stress on the channel side τ_{sc} then is

$$\tau_{sc} = K\tau_{bc} \qquad \text{(C17)}$$

where τ_{bc} is the critical tractive shear stress on the channel bed.

Erodibility of cohesive soil

114. The erosion characteristics of cohesive soils are controlled by surface (physico-chemical) forces. The basic parameters affecting the erosion of cohesive soils, as listed in Table C4, are the type and amount of cations (calcium, magnesium, potassium, and sodium) in the soil pore water, composition of the soil including the type and amount of clay minerals present, and type and amount of cations in the eroding fluid (Perry 1975).

115. During the period September 1977 to January 1980, under Contract No. DACW39-77-C-0080, a study was conducted by Arulanandan, Gillogley, and Tully (1980) at the University of California, Davis, in an attempt to develop a method to predict the hydraulic shear stress at which erosion is initiated (critical shear stress) and the rate of erosion of natural cohesive soil along the streambank. In order to obtain a wide range of properties with sufficient geographical distribution, soil and river water samples were requested from CE Districts in the continental United States.

River (eroding) water properties

116. The total amount of cations (calcium, magnesium, potassium, and sodium) in the river (eroding) water significantly influences the erosion of cohesive soils. Usually as the total amount of cations in the river (eroding) water decreases, the critical tractive shear stress of the soil decreases and the rate of change of erosion rate increases (Figure C46 by Arulanandan, Gillogley, and Tully (1980)). The numerical values given in Figure C46 represent average values calculated in the University of California, Davis, contract study from soils obtained from 14 locations in the United States. The total amount of cations in river water depends upon the local geography, climate, and cultural effects resulting from the activities of man (Hem 1970, Hynes 1970, Livingstone 1963, and Wetzel 1975). The total amount of cations in most United States river waters ranges from 0 to 10 milliequivalents/liter with some river waters in the southwest as high as 50 milliequivalents/liter (Table C5 by Arulanandan, Gillogley, and Tully (1980)).

Prediction of critical tractive shear stress

117. The results of the University of California, Davis, contract study did not give a method to predict the critical tractive shear stress for undisturbed natural soils. However, it was shown that a relationship between critical tractive shear stress, sodium

adsorption ratio (SAR*), dielectric dispersion,** and soil pore fluid concentration for saturated remolded soil with distilled water as the eroding fluid (Figures C49-C52 by Alizadeh 1974 and Heinzen 1976) gave a predicted value of critical tractive shear stress that was generally less than the measured value (Figure C53). Since the critical tractive shear stress usually increases as the total amount of cations in the eroding fluid increases (Figure C46) and is greater for undisturbed soil than for remolded soil (Figure C54†), Figures C49 through C52, which are based upon remolded soil using distilled water as eroding fluid, should give a lower bound to the critical tractive shear stress for a natural saturated undisturbed soil subjected to tractive shear stress from river (eroding) water.

Prediction of erosion rate

118. A relationship was developed between the critical tractive shear stress and the rate of change of erosion rate (defined in Figure C43) for saturated remolded soils with distilled water as the eroding fluid as shown in Figure C55 (Arulanandan, Gillogley, and Tully 1980).

$$S = \left(30.093898 - 17.089563\tau_c + 4.024129\tau_c^2 - 0.427815\tau_c^3 + 0.016856\tau_c^4\right)10^{-4} \quad \text{(C18)}$$

---

* $SAR = \dfrac{Na}{\sqrt{0.5(Ca + Mg)}}$

** The dielectric dispersion is the response of a soil to an electric current in the radio frequency range, which is related to the soil composition, type and amount of clay mineral (Figure C47), moisture content, and structure of the soil (Arulanandan 1966, Kandiah 1974, Sargunam 1973, and Smith 1971). The dielectric dispersion may be predicted from the cation exchange capacity (cations required to balance the charge deficiency) of a natural soil as shown in Figure C48 (Fernando, Burau, and Arulanandan 1977).

† The numerical values given in this figure represent average values calculated in the University of California, Davis, contract study from soils obtained from 23 locations in the United States.

where

S = rate of change of erosion rate $\left(\frac{gm}{dyne \times min}\right)$

τ_c = critical tractive shear stress $\left(\frac{dynes}{cm^2}\right)$

Using the relationship (Figure C43)

$$\dot{e} = S(\tau - \tau_c) \qquad \tau > \tau_c \tag{C19}$$

where

$\dot{e}$ = erosion rate $\left(\frac{gm}{cm^2 \times min}\right)$

τ = applied tractive shear stress $\left(\frac{dynes}{cm^2}\right)$

for natural saturated undisturbed soil subjected to hydraulic shear stress from river (eroding) water

$$\dot{e}_{\substack{UN\\RW}} = C_1 C_2 S_{\substack{RM\\DW}} \left(\tau - C_3 C_4 \tau_{c_{\substack{RM\\DW}}}\right) \qquad \tau > C_3 C_4 \tau_{c_{\substack{RM\\DW}}} \tag{C20}$$

where

$\dot{e}_{\substack{UN\\RW}}$ = erosion rate for saturated undisturbed soil with river water as eroding fluid

C_1 = constant giving average influence of remolding on rate of change of erosion rate (equal to 13.0 from Figure C54)

C_2 = constant giving average influence of eroding fluid concentration on rate of change of erosion rate (equal to 0.13 from Figure C46)

$S_{\substack{RM\\DW}}$ = rate of change of erosion rate for saturated remolded soil with distilled water as eroding fluid (from Equation C18 or Figure C55)

C_3 = constant giving average influence of remolding on critical shear stress (equal to 7.1 from Figure C54)

C_4 = constant giving average influence of eroding fluid concentration on critical shear stress (equal to 12.5 from Figure C46b)

$\tau_{c_{RM\,DW}}$ = critical tractive shear stress for saturated remolded soil with distilled water as eroding fluid (Figures C48 through C52)

Substituting for C_1 , C_2 , C_3 , and C_4

$$\dot{e}_{UN\,RW} = 1.7S_{RM\,DW}\left(\tau - 88.8\tau_{c_{RM\,DW}}\right) \qquad \tau > 88.8\tau_{c_{RM\,DW}} \qquad \text{(C21)}$$

Equation C21 should give a reasonable estimate of the erosion rate for saturated undisturbed soil with river water as eroding fluid. Additional laboratory erosion tests need to be conducted to better define the correction factors for remolding and eroding fluid concentration on critical tractive shear stress and rate of change of erosion.

Procedure for Evaluating Streambank Stability of Cohesive Soils

Overview of the procedure

119. The concept for evaluating streambank stability, presented in Figure C56, can be used to determine the bank recession with time for a selected river cross section. This information could then be used in planning and designing streambank protection for the river.

Determination of tractive shear stress

120. The tractive shear stress acting on the banks and bed of the channel shown in Figure C56a is calculated using Equation C3, C4, C5, or C6 and Figures C24 and C26. This method is applicable to steady uniform or gradually varied flow and does not take into account variations in tractive shear stress due to spiral (or helicoidal) flow, secondary currents, or flow separation in curved reaches (Bathurst, Thorne, and Hey 1979; Leeder and Bridges 1975; and Leopold 1966).

Determination of erosion rate

121. The erosion rate for each soil layer shown in Figure C56a may be predicted based upon Equation C21 or measured in the laboratory flume as described in paragraph 108.

Changes in geometry due to erosion

122. The bank recession or bed degradation due to erosion of each soil layer shown in Figure C56b is

$$\delta_{\substack{UN\\RW}} = \frac{\dot{e}_{\substack{UN\\RW}} \times \Delta T}{\gamma_m} \qquad \text{(C22)}$$

where

$\delta_{\substack{UN\\RW}}$ = bank recession or bed degradation due to erosion for saturated undisturbed soil with river water as eroding fluid

ΔT = interval of time

γ_m = wet unit weight of soil

Equation C22 is an upper bound solution because it does not take into account accretion along the banks or bed aggradation as eroded soil from upstream is deposited at the cross section shown in Figure C56b. A sediment transport analysis that involves hydraulic sorting and armoring would be necessary to include the effects of deposition (Graf 1971, Hydrologic Engineering Center 1977, Linder 1976, and Simons and Senturk 1976).

Changes in geometry due to slope failure

123. In addition to changes in geometry due to erosion, slope failure may cause changes in geometry as noted in Figure C56c. In order to analyze the stability of a streambank, information is needed on geometry, soil properties (wet unit weight, cohesion, angle of internal friction), pore water pressures, and external loads present (surcharge). The factor of safety is defined as

$$\text{F.S.} = \frac{\text{shear strength of the soil}}{\text{shear stress required for equilibrium}} \qquad \text{(C23)}$$

where F.S. is the factor of safety. Slope failure results when F.S. < 1 or shear stress $>$ shear strength. Increases in shear stress may result from changes in geometry (increase in height or steepness) due to erosion, increase in external loads (surcharge), or release of water load against the lower slope due to rapid drawdown of the river water level or bed degradation or toe removal by erosion. Decrease in shear strength of the soil may result from increase in pore pressure, soil expansion, or shear displacement.

124. When the cross section of a streambank is changed because of soil being eroded away as shown in Figure C56b, this process is analogous to the excavation of a natural slope in conventional slope stability analysis. If the soil is eroded away rapidly, such as during the passing of a storm hydrograph of a few days duration, and the soil comprising the streambank is relatively impervious (permeability less than 10^{-3} cm/sec), the slope stability analysis should be conducted using total stress analysis (Chowdhury 1978, Duncan and Buchignani 1975, Edil and Vallejo 1977, Hey 1979, U. S. Army Corps of Engineers (in preparation), and Vallejo 1977). The soil shear strength is determined from unconsolidated-undrained triaxial compression tests on undisturbed soil specimens or field vane shear tests corrected for anisotropy and strain rate (Duncan and Buchignani 1975). The total stress analysis is also used when rapid drawdown of the river water level occurs and the soil comprising the streambank does not have sufficient time for drainage. For this condition, the soil shear strength is based upon the minimum of the combined strength envelopes from consolidated-undrained triaxial compression and consolidated-drained direct shear tests on undisturbed soil specimens.

125. If the soil comprising the streambank is free-draining (permeability greater than 10^{-3} cm/sec), the slope stability analysis shown in Figure C56c should be conducted using effective stress analysis. The soil shear strength is determined from consolidated-drained triaxial or direct shear tests on remolded soil specimens or is estimated from correlations with the standard penetration test. Pore pressures are determined from a flow net or field measurements.

Reiteration through erosion
and slope stability analyses

126. In order to determine the bank recession with time, it is necessary to reiterate through the analyses for bank erosion and slope failure given in Figure C56. Changes in geometry due to erosion, such as toe recession or bed degradation, may precipitate slope failure with resulting retreat of the top of the streambank. The bank recession with time is equal to the cumulative bank recession due to erosion and retreat of top bank due to slope failure. The procedure for evaluating streambank stability is illustrated by the enclosed example problem.

Summary

127. The erosion characteristics of cohesionless soils, which are controlled by gravitational forces, are fairly well understood. However, the development of a procedure for streambank stability analysis has been stymied, in part, by a lack of understanding of the erosive characteristics of cohesive soils, which are controlled by physical and electrical phenomena. Analyses of laboratory test results obtained using a flume and rotating cylinder apparatus at the University of California, Davis, revealed relationships among critical tractive shear stress, electrical properties of the soils, and rates of erosion for saturated remolded soils using distilled water as the eroding fluid. Correction factors were obtained for the effects of remolding and salt concentrations of the eroding fluid. The laboratory relationships can be adjusted by the correction factors to estimate erodibility of saturated undisturbed soil subjected to current induced tractive shear stress by river water for use in bank stability analyses. Capability in laboratory measurements of soil erosion characteristics under hydraulic flows was expanded by an experimental self-contained laboratory recirculating tilting flume for applying hydraulic shear stresses to a soil sample.

128. The analysis of streambank changes caused by soil erosion is analogous to conventional stability analysis of an excavated slope.

Bank recession with time can be estimated by using a conceptual procedure that combines erosion characteristics and conventional soil parameters used in limit equilibrium slope stability analyses. Erosional changes in geometry, such as toe recession or bed degradation, can precipitate slope failure with resulting top retreat of the streambank. The bank recession with time is equal to the cumulative bank recession caused by erosion and slope failures. The analysis of a generalized streambank section evaluated for bank and bed erosion and slope stability under normal flow conditions and during the passage of flood is illustrated by an example problem.

129. To evaluate streambank stability, it is necessary to estimate changes in geometry due to erosion and slope movements. Bank recession or bed degradation estimated from the laboratory relationships developed for tractive (current) erosion is an approximation because it does not take into account such things as accretion along the banks, secondary currents, freeze-thaw, and bed aggradation as eroded soil from upstream is deposited at the reach of the river under consideration. A sediment transport analysis that includes hydraulic sorting and armoring would be necessary to include the effects of deposition. In addition to changes in geometry due to current erosion, bank failure causes changes in geometry. Bank failure results when the induced shear stresses exceed the shear strength of the bank soils. Increases in shear stress can result from increase in slope height or steepness, increase in external loads (surcharge), and rapid drawdown of the river. Decreases in shear strength of the soil can result from an increase in pore water pressure, soil expansion, or shear movements.

130. Simple homogeneous banks are most easily handled by the suggested procedure for evaluating streambank stability. Simplifying procedures common in conventional soil mechanics practice permits complex heterogeneous banks to be evaluated. The suggested procedures are slightly more complex and unique only in that the erodibility of the bank soils is incorporated into the assessment of equilibrium and potential bank failure.

131. The research developed theoretical approaches and the use

of experimental laboratory equipment and procedures. Field validation is highly desirable and, in fact, required to establish the credibility of the laboratory results and the conceptual approaches.

Recommendations

132. The laboratory equipment and relationships developed in this research for predicting the critical tractive shear stress and erosion rate for saturated undisturbed cohesive soils subjected to tractive shear stresses from river water should be field validated to establish the credibility of the conceptual approaches.

133. Analytical procedures should be expanded to include variable hydraulic regimes and geomorphic processes.

134. Additional laboratory and field research should be conducted to better simulate the whole erosion processes which influence bank stability.

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Table C2

Tractive Shear Stress Acting on the

Bed of a Relatively Wide Straight Alluvial Channel for Steady Uniform Flow*

Depth ft	Tractive Force, lb/ft^2**				
	Drop = 1 ft/mile; Slope = 0.00015	Drop = 5 ft/mile; Slope = 0.00095	Drop = 10 ft/mile; Slope = 0.00188	Drop = 15 ft/mile; Slope = 0.00284	Drop = 20 ft/mile; Slope = 0.00379
1	0.01	0.06	0.11	0.18	0.24
5	0.06	0.29	0.58	0.88	1.18
10	0.11	0.60	1.17	1.74	2.36
20	0.24	1.19	2.35	3.50	4.73
40	0.47	2.37	4.69	6.99	9.46
100	1.19	5.93	11.73	17.47	23.66

Range of interest for typical values of depths of flow and channel bed slopes which occur in nature lies above this line.

* $\tau = \gamma_w d S_o$ (Equation C5 in text).

** $1\ lb/ft^2 = 478.82\ dynes/cm^2$.

Table C3

Chemical Analysis of WES Tap Water, 20 February 1981

	meq/ℓ				meq/ℓ	Na	
pH	Na*	K*	Mg*	Ca*	Na + K + Mg + Ca	%	SAR**
8.0	0.41	0.13	0.35	0.99	1.88	21.8	0.50

* Na = sodium, K = potassium, Mg = magnesium, Ca = calcium.

$$** \ SAR = \frac{Na}{\sqrt{0.5(CA + Mg)}}$$

Table C4

Variables Affecting Erosion of Cohesive Soils

Soil Pore Water	Soil	Eroding Fluid
1. Type and amount of cations (calcium, magnesium, potassium, and sodium)	1. Composition (percentages of sand, silt, clay, organic matter, and gypsum)	1. Type and amount of cations (calcium, magnesium, potassium, and sodium)
	2. Type and amount of clay mineral (kaolinite, illite, and montmorillonite)	2. Temperature
	3. Moisture content	3. pH
	4. Dry unit weight	4. Type and amount of sediment present
	5. pH	

Table C5

Properties of River Water Tested in University of California, Davis, Study

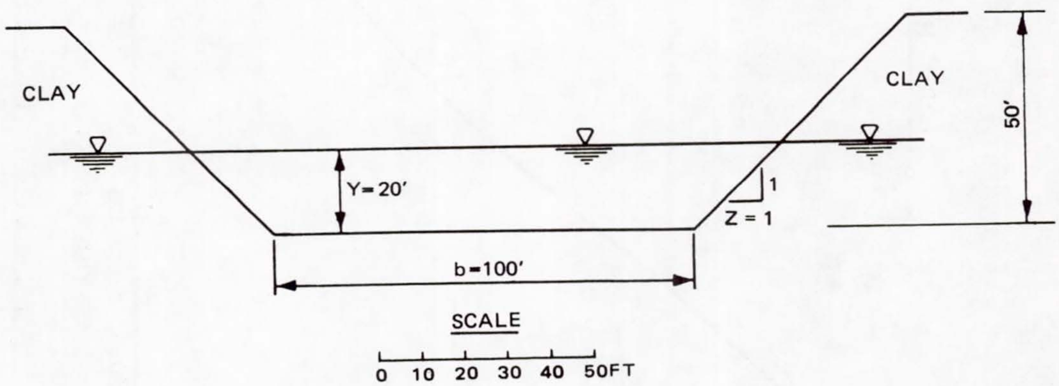
CE District	River	pH	meq/ℓ				meq/ℓ	Na	SAR**
			Na*	K*	Mg*	Ca*	Na + K + Mg + Ca	%	
Albuquerque	Rio Grande	7.8	1.60	0.12	1.05	1.05	3.82	41.9	1.6
	Arkansas	8.2	12.30	0.27	5.75	5.75	24.07	51.1	5.1
Fort Worth	Trinity	6.9	4.10	0.33	1.15	1.15	6.70	61.2	3.8
Galveston	Nueces	7.9	35.70	0.65	6.00	6.00	48.40	73.8	14.6
Kansas City	Delaware	7.6	0.30	0.14	1.35	1.35	3.10	9.6	0.3
	Wakarusa	7.9	0.60	0.07	2.60	2.60	5.90	10.2	0.4
Little Rock	Arkansas	7.6	0.75	0.06	0.60	0.60	2.00	37.5	1.0
	Black	7.5	0.05	0.05	0.55	0.55	1.20	4.2	0.1
Memphis	White	7.5	0.10	0.08	0.70	0.70	1.60	6.2	0.1
Mobile	Tombigbee	7.0	0.20	0.07	0.20	0.20	0.67	29.9	0.5
New Orleans	Mississippi	8.1	0.78	0.08	1.00	1.00	2.68	29.1	0.8
Omaha	James	7.6	2.20	0.38	4.75	4.75	12.10	46.3	1.0
Philadelphia	White Clay	6.7	0.33	0.14	0.47	0.47	1.41	23.4	0.5
Sacramento	Sacramento	7.4	0.40	0.06	0.46	0.46	1.40	28.6	0.6
St. Louis	Mississippi	7.6	0.70	0.14	1.35	1.35	3.50	20.0	0.6
San Francisco	Dry Creek	7.5	0.40	0.04	1.05	1.05	2.50	16.0	0.4
	Eel	7.8	0.40	0.05	1.15	1.15	2.80	14.3	0.4
Savannah	Savannah	6.9	0.22	0.05	0.07	0.07	0.41	53.7	0.9
Tulsa	Caney	7.1	1.60	0.11	2.00	2.00	5.71	28.0	1.1
	Verdigris	6.8	0.74	0.18	1.15	1.15	3.20	23.1	0.7

* Na = sodium, K = potassium, Mg = magnesium, Ca = calcium.

** $SAR = \frac{Na}{\sqrt{0.5\ (CA + Mg)}}$

Example Problem: Procedure for Evaluating Streambank Stability

Given:



Normal flow conditions

Storm hydrograph (next page)

n = 0.040

River water: Na + K + CA + Mg = 2.5 meq/ℓ

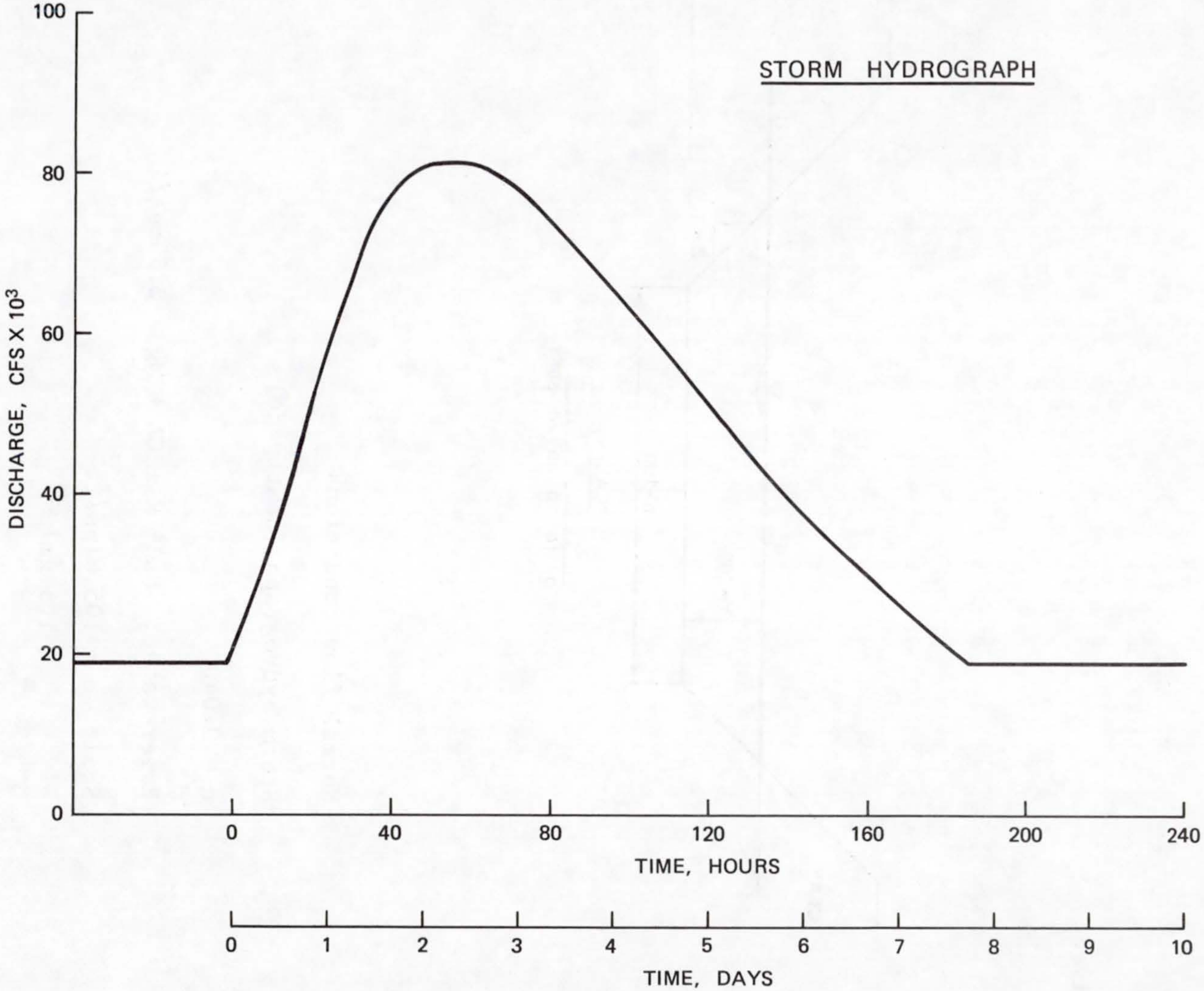
Soil: c = 105 kips/ft^2

γ_m = 1.5 gm/cm^3

Dielectric Dispersion = 20

SAR = 10

Na + K + Ca + Mg = 50 meq/ℓ


STORM HYDROGRAPH
DISCHARGE, CFS X 10^3
100
80
60
40
20
0
0
40
80
120
160
200
240
TIME, HOURS
0
1
2
3
4
5
6
7
8
9
10
TIME, DAYS

Required:

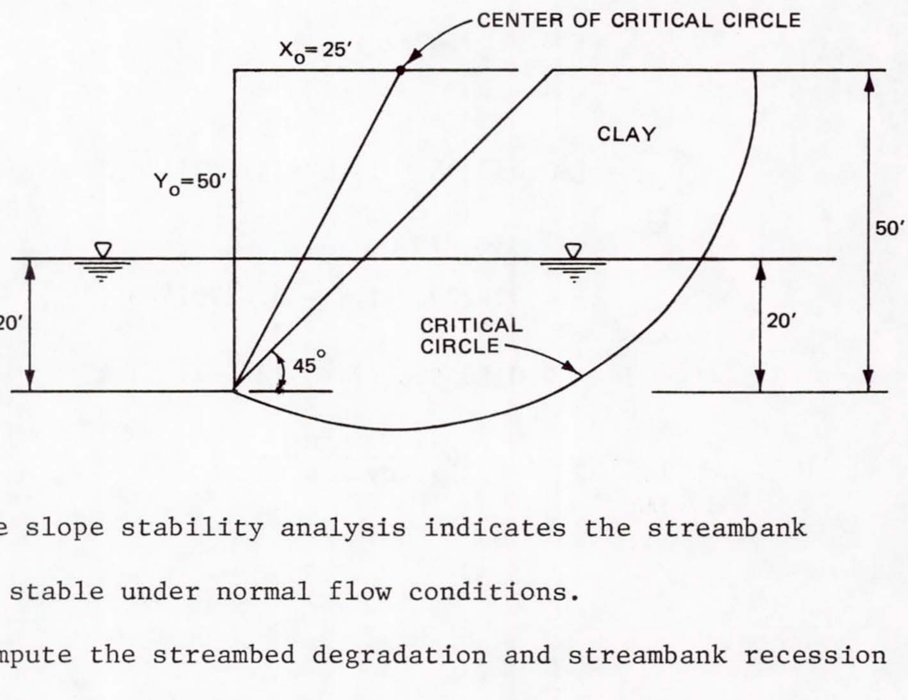
Determine the streambed degradation and streambank recession due to erosion and slope failure for the initial conditions (normal flow) and for the storm hydrograph.

Solution:

(1) Compute the slope stability under normal flow conditions at T = 0 hours, Q = 19200 cfs. Using Waterways Experiment Station Library (WESLIB) computer program I0009 Simplified Bishop's Method

$$F.S. = 1.57$$

with the center of the critical circle located as shown below



The slope stability analysis indicates the streambank is stable under normal flow conditions.

(2) Compute the streambed degradation and streambank recession due to erosion under normal flow conditions at T = 0 hr, Q = 19200 cfs. Determine the critical tractive stress for saturated remolded soil with distilled water as eroding

fluid. From Figure C50, for dielectric dispersion = 20, SAR = 10, and soil pore fluid concentration = 50 meq/ℓ

$$\tau_{c_{RM\atop DW}} = 7 \text{ dynes/cm}^2$$

Determine the rate of change of erosion rate for saturated remolded soil with distilled water as eroding fluid. From Equation C18 (Figure C55)

$$S_{RM\atop DW} = (30.093898 - 17.089563\ \tau_{c_{RM\atop DW}}$$

$$+ 4.0241293\ \tau^2_{c_{RM\atop DW}} - 0.42781446\ \tau^3_{c_{RM\atop DW}}$$

$$+ 0.016856061\ \tau^4_{c_{RM\atop DW}})\ 10^{-4}$$

$$S_{RM\atop DW} = [30.093898 - 17.089563\ (7)$$

$$+ 4.0241293\ (7)^2 - 0.42781446\ (7)^3$$

$$+ 0.01685606\ (7)^4]\ 10^{-4}$$

$$S_{RM\atop DW} = 1.37 \times 10^{-4}\ \frac{\text{gm}}{\text{dyne x min}}$$

Determine the erosion rate for saturated undisturbed soil with river water as eroding fluid. From Equation C21

$$\dot{e}_{\substack{UN\\RW}} = 1.7\ S_{\substack{RM\\DW}}\ (\tau - 88.8\ \tau_{c_{\substack{RM\\DW}}})$$

$$\dot{e}_{\substack{UN\\RW}} = 1.7\ (1.37 \times 10^{-4})\ [\tau - 88.8\ (7)]$$

$$\dot{e}_{\substack{UN\\DW}} = 2.329 \times 10^{-4}\ \frac{gm}{dyne \times min} \left(\tau - 621.6\ \frac{dynes}{cm^2}\right)$$

The bed degradation or bank recession with time for saturated undisturbed soil with river water as eroding fluid is given by Equation C22

$$\delta_{\substack{UN\\RW}} = \frac{\dot{e}_{\substack{UN\\RW}} \times \Delta T}{\gamma_m}$$

$$\delta_{\substack{UN\\RW}} = \frac{2.329 \times 10^{-4}\ \frac{gm}{dyne \times min} \left(\tau - 621.6\ \frac{dynes}{cm^2}\right) \times \Delta T}{1.5\ \frac{gm}{cm^3}}$$

where τ is in dynes/cm^2, ΔT minutes, and $\delta_{\substack{UN\\RW}}$ centimetres.

For a trapezoidal channel the area is (Chow 1959)

$$A = (b + zy)\ y$$

$$A = [100 + (1)(20)]\ 20$$

$$A = 2400\ ft^2$$

The hydraulic radius is

$$R = \frac{A}{b + 2y\sqrt{1 + z^2}}$$

$$R = \frac{2400}{100 + 2(20)\sqrt{1 + (1)^2}}$$

$$R = 15.329 \text{ ft}$$

The velocity is

$$V = \frac{Q}{A}$$

$$V = \frac{19200}{2400}$$

$$V = 8.00 \text{ ft/sec}$$

The slope of the energy gradeline can be determined from Manning's equation

$$Q = \frac{1.49}{n} A R^{2/3} S_o^{1/2}$$

$$S_o = \left[\frac{Q}{\frac{1.49}{n} A R^{2/3}}\right]^2$$

$$S_o = \left[\frac{19200}{\frac{1.49}{0.040}(2300)(15.329)^{2/3}}\right]^2$$

$$S_o = 0.0012$$

The tractive shear stress acting on the bed of the channel is found from Equation C5

$$\tau_{bed} = \gamma_w R S_o$$

$$\tau_{bed} = (62.4)(15.329)(0.0012)$$

$$\tau_{bed} = 1.1586 \text{ psf}$$

$$\tau_{bed} = 554.8 \text{ dynes/cm}^2$$

Since

$$\tau_{bed} < 88.8\ \tau_c$$

$$554.8 < 621.6$$

there is no erosion of the channel bed under the initial conditions at T = 0 hr, Q = 19200 cfs. Therefore

$$\dot{e}_{\substack{UN \\ RW_{bed}}} = \delta_{\substack{UN \\ RW_{bed}}} = 0$$

The ratio of channel width to depth of flow is

$$\frac{b}{y} = \frac{100}{20} = 5$$

From Figure C24,

$$\frac{\tau_{side}}{\tau_{bed}} = 0.75$$

$$\tau_{side} = 0.75\ \tau_{bed}$$

$$\tau_{side} = 0.75\ (554.8)$$

$$\tau_{side} = 416.1 \text{ dynes/cm}^2$$

Since

$$\tau_{side} < 88.8\ \tau_c$$

$$416.1 < 621.6$$

there is no erosion of the channel sides under the initial conditions at T = 0 hr, Q = 19200 cfs.

Therefore

$$\dot{e}_{UN_{RW_{side}}} = \delta_{UN_{RW_{side}}} = 0$$

Under normal flow conditions at T = 0 hr, Q = 19200 cfs, there is no erosion of the channel bed or sides and the streambank is stable against slope failure. Therefore, there is no bed degradation or streambank recession. These conditions may change as the storm hydrograph passes the cross section under consideration.

(3) Compute the streambed degradation and streambank recession due to erosion for the storm hydrograph at T = 6 hr, Q = 28000 cfs. The width of the channel bed is

$$b = 100 + 2\ \Sigma\ \delta_{UN_{RW_{side}}}$$

$$b = 100 \text{ ft}$$

The slope of the streambank is

$$z = \frac{y - \Sigma\ \delta_{UN_{RW_{side}}}}{y}$$

$$z = \frac{20}{20} = 1$$

The depth of flow is solved by trial-and-error procedure.

Assume $y = 24$ ft

$$A = (b + zy)\ y$$

$$A = [100 + (1)(24)]\ 24$$

$$A = 2976 \text{ ft}^2$$

$$R = \frac{A}{b + 2y\sqrt{1 + z^2}}$$

$$R = \frac{2976}{100 + 2\ (24)\sqrt{1 + 1^2}}$$

$R = 17.727$ ft

$$Q = \frac{1.49}{n} A\ R^{2/3}\ S_o^{1/2}$$

$$Q = \frac{1.49}{0.040} (2976)(17.727)^{2/3}\ (0.0012)^{1/2}$$

$Q = 26108$ cfs $<$ 28000 cfs

Assume $y = 26$ ft

$A = (b + zy)\ y$

$A = [100 + (1)\ (26)]\ 26$

$A = 3276\ ft^2$

$$R = \frac{A}{b + 2y\sqrt{1 + z^2}}$$

$$R = \frac{3276}{100 + 2(26)\sqrt{1 + 1^2}}$$

$R = 18.878$ ft

$$Q = \frac{1.49}{n} A\ R^{2/3}\ S^{1/2}$$

$$Q = \frac{1.49}{0.040} (3276)(18.878)^{2/3}\ (0.0012)^{1/2}$$

$Q = 29.970$ cfs $>$ 28000 cfs

Assume $y = 25$ ft

$A = (b + zy)\ y$

$A = [100 + (1)(25)]\ 25$

$A = 3124\ ft^2$

$$R = \frac{A}{b + 2y\sqrt{1 + z^2}}$$

$$R = \frac{3124}{100 + 2(25)\sqrt{1 + 1^2}}$$

$$R = 18.303 \text{ ft}$$

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

$$Q = \frac{1.49}{0.040} (3124)(18.303)^{2/3} (0.0012)^{1/2}$$

$$Q = 27997 \text{ cfs} \approx 28000 \text{ cfs} \quad \text{O.K.}$$

Thus, the depth is $y \approx 25$ ft.

$$V = \frac{Q}{A}$$

$$V = \frac{27997}{3124}$$

$$V = 8.96 \text{ fps}$$

$$\tau_{bed} = \gamma_w R S_o$$

$$\tau_{bed} = (62.4)(18.303)(0.0012)$$

$$\tau_{bed} = 1.3705 \text{ lb/ft}^2$$

$$\tau_{bed} = 656.2 \text{ dynes/cm}^2$$

$$\dot{e}_{\substack{UN\\RW_{bed}}} = 1.7\, S_{\substack{RM\\RW}} (\tau_{bed} - 88.8\, \tau_{c_{\substack{RM\\DW}}})$$

$$\dot{e}_{\substack{UN\\RW_{bed}}} = 1.7\, (1.37 \times 10^{-4})\, [\tau_{bed} - 88.8\,(7)]$$

$$\dot{e}_{\substack{UN\\RW_{bed}}} = 2.329 \times 10^{-4}\, (\tau_{bed} - 621.6)$$

$$\dot{e}_{UN_{RW_{bed}}} = 2.329 \times 10^{-4} (656.2 - 621.6)$$

$$\dot{e}_{UN_{RW_{bed}}} = 0.00807 \frac{gm}{cm^2 \times min}$$

$$\delta_{UN_{RW_{bed}}} = \frac{\dot{e}_{UN_{RW_{bed}}} \times \Delta T}{\gamma_m}$$

$$\Delta T = 4 - 0 = 4 \text{ hr}$$

$$\Delta T = 360 \text{ min}$$

$$\delta_{UN_{RW_{bed}}} = \frac{0.00807 \times 360}{1.5}$$

$$\delta_{UN_{RW_{bed}}} = 1.942 \text{ cm}$$

$$\delta_{UN_{RW_{bed}}} = 0.064 \text{ ft}$$

$$\frac{b}{y} = \frac{100}{25} = 4$$

From Figure C24

$$\frac{\tau_{side}}{\tau_{bed}} = 0.74$$

$$\tau_{side} = 0.74 (\tau_{bed})$$

$$\tau_{side} = 0.74 (656.3)$$

$$\tau_{side} = 485.7 \text{ dynes/cm}^2$$

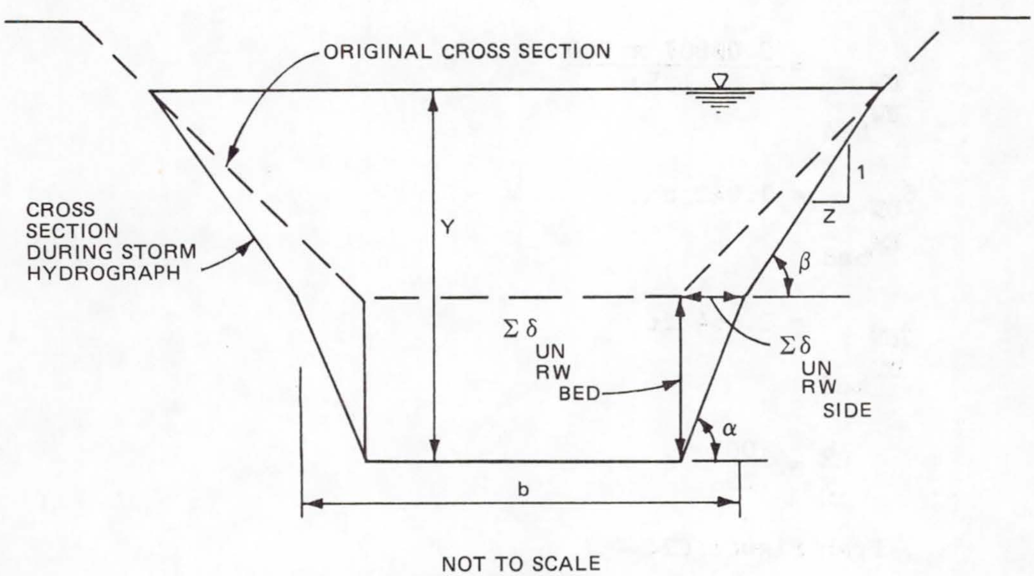
$$\tau_{side} < 88.8 \tau_c$$

$$485.7 < 621.6$$

Therefore, there is no erosion of the channel sides at T = 4 hr, Q = 28000 cfs.

$$\dot{e}_{\substack{UN\\RW_{side}}} = \delta_{\substack{UN\\RW_{side}}} = 0$$

(4) The streambed degradation and streambank recession due to erosion for the entire storm hydrograph was solved in 6-hr increments on the WES computer and is given in the inclosed tabulation where the parameters are defined below.



The results of the erosion analysis indicated that a bed degradation of 20.1 ft and lower bank recession of 5.2 ft would occur as the storm hydrograph passed the cross section of the stream. This method of analysis is an upper bound solution because it does not take into account accretion along the banks or bed aggradation as eroded soil from

Streambed Degradation and Streambank Recession Due to Erosion During Storm Hydrograph

T hr	Q cfs	A ft^2	R ft	Y ft	V fps	τ_{bed} dynes/cm^2	$\dot{e}_{UN}$ RW_{bed} $\frac{gm}{cm^2 \times min}$	$\Sigma\delta_{UN}$ RW_{bed} ft	τ_{side} dynes/cm^2	$\dot{e}_{UN}$ RW_{side} $\frac{gm}{cm^2 \times min}$	$\Sigma\delta_{UN}$ RW_{side} ft	b ft	Z	α deg	β deg
0	19,200	2400.0	15.329	20.0	8.00	554.8	0	0	416.1	0	0	100.00	1.000	90.0	45.0
6	28,000	3124.3	18.303	25.0	8.96	656.2	0.00807	0.06	485.7	0	0	100.00	1.000	90.0	45.0
12	33,000	3504.3	19.715	27.5	9.42	706.9	0.01986	0.22	530.2	0	0	100.00	1.000	90.0	45.0
18	38,500	3905.4	21.116	30.0	9.86	757.1	0.03156	0.47	567.8	0	0	100.00	1.000	90.0	45.0
24	44,600	4333.6	22.524	32.7	10.29	807.6	0.04332	0.81	605.7	0	0	100.00	1.000	90.0	45.0
30	51,800	4820.4	24.033	35.6	10.75	861.7	0.05591	1.25	646.2	0.00571	0.05	100.09	0.999	87.9	45.0
36	58,700	5271.2	25.353	38.1	11.14	909.0	0.06693	1.78	681.7	0.01401	0.15	100.31	0.996	85.0	45.1
42	64,800	5658.8	26.436	40.3	11.45	947.8	0.07598	2.38	710.9	0.02080	0.32	100.64	0.992	82.3	45.2
48	70,000	5982.0	27.309	42.0	11.70	979.1	0.08327	3.03	734.3	0.02626	0.53	101.05	0.988	80.2	45.3
54	74,000	6226.5	27.951	43.3	11.88	1002.2	0.08863	3.72	751.6	0.03028	0.76	101.53	0.983	78.4	45.5
60	77,600	6443.7	28.511	44.4	12.04	1022.2	0.09331	4.46	766.7	0.03379	1.03	102.06	0.977	77.0	45.7
66	80,000	6587.1	28.875	45.1	12.15	1035.3	0.09347	5.22	776.5	0.03607	1.31	102.63	0.971	75.9	45.8
72	81,000	6646.3	29.026	45.3	12.19	1040.7	0.09761	5.99	780.5	0.03701	1.61	103.21	0.965	75.0	46.0
78	81,200	6657.9	29.057	45.3	12.20	1041.8	0.09787	6.76	781.4	0.03721	1.90	103.80	0.958	74.3	46.2
84	81,100	6651.8	29.043	45.2	12.19	1041.3	0.09775	7.53	781.0	0.03712	2.19	103.80	0.951	73.8	46.4
90	80,900	6639.7	29.015	45.1	12.18	1040.3	0.09752	8.30	780.2	0.03694	2.48	104.96	0.945	73.3	46.6
96	80,300	6603.9	28.926	44.8	12.16	1037.1	0.09678	9.06	777.8	0.03639	2.77	105.54	0.938	73.0	46.8
102	79,500	6556.2	28.807	44.5	12.13	1032.8	0.09578	9.81	774.6	0.03564	3.05	106.10	0.931	72.7	47.1
108	78,000	6466.5	28.580	44.0	12.06	1024.7	0.09388	10.55	768.5	0.03422	3.32	106.64	0.923	72.5	47.3
114	76,000	6346.4	28.272	43.3	11.98	1013.7	0.09131	11.27	760.2	0.03229	3.57	107.15	0.916	72.4	47.5
120	73,800	6213.4	27.926	42.5	11.88	1001.3	0.08843	11.97	750.1	0.03013	3.81	107.62	0.910	72.3	47.7
126	72,000	6103.9	27.638	41.9	11.80	990.9	0.08602	12.65	743.2	0.02832	4.03	108.06	0.902	72.3	47.9
132	70,000	5981.5	27.312	41.2	11.70	979.2	0.08329	13.30	734.4	0.02628	4.24	108.48	0.895	72.3	48.2
138	67,300	5815.0	26.861	40.2	11.57	963.1	0.07953	13.93	722.3	0.02345	4.42	108.85	0.888	72.4	48.4
144	65,000	5671.8	26.467	39.4	11.46	949.0	0.07624	14.53	711.7	0.02099	4.59	109.18	0.881	72.5	48.6

(Continued)

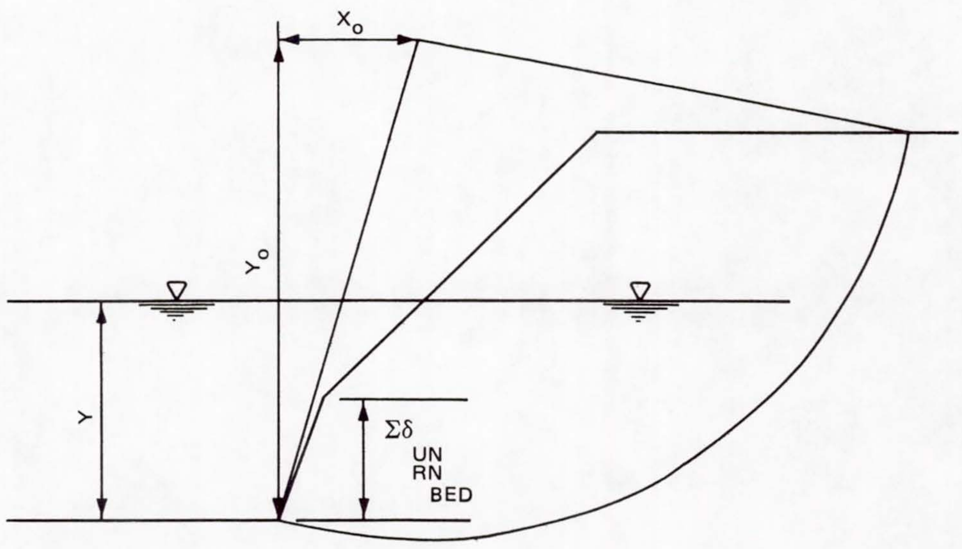
Streambed Degradation and Streambank Recession Due to Erosion During Storm Hydrograph (Concluded)

T hr	Q cfs	A ft^2	R ft	Y ft	V fps	τ_{bed} $dynes/cm^2$	$\dot{e}_{UN}$ RW_{bed} $\frac{gm}{cm^2 \times min}$	$\Sigma\delta_{UN}$ RW_{bed} ft	τ_{side} $dynes/cm^2$	$\dot{e}_{UN}$ RW_{side} $\frac{gm}{cm^2 \times min}$	$\Sigma\delta_{UN}$ RW_{side} ft	b ft	Z	α deg	β deg
150	62,800	5533.8	26.081	38.6	11.35	935.1	0.07302	15.10	701.3	0.01857	4.74	109.47	0.874	72.6	48.8
156	60,000	5356.3	25.577	37.6	11.20	917.0	0.06881	15.65	687.8	0.01541	4.86	109.72	0.868	72.8	49.0
162	58,000	5228.4	25.207	36.9	11.09	903.8	0.06572	16.16	677.8	0.01310	4.96	109.92	0.862	72.9	49.2
168	55,800	5086.3	24.790	36.1	10.97	888.9	0.06224	16.65	666.7	0.01048	5.04	110.09	0.856	73.2	49.4
174	53,200	4916.5	24.283	35.1	10.82	870.6	0.05800	17.11	653.0	0.00731	5.10	110.20	0.851	73.4	49.6
180	51,100	4777.9	23.862	34.3	10.69	855.6	0.05448	17.54	641.7	0.00467	5.14	110.28	0.846	73.7	49.8
186	48,600	4610.9	23.345	33.3	10.54	837.0	0.05017	17.93	627.8	0.00143	5.15	110.30	0.841	74.0	49.9
192	46,300	4455.4	22.854	32.4	10.39	819.4	0.04607	18.30	614.6	0	5.15	110.30	0.837	74.3	50.1
198	44,200	4311.7	22.392	31.6	10.25	802.8	0.04221	18.63	602.1	0	5.15	110.30	0.832	74.8	50.2
204	42,000	4159.2	21.892	30.6	10.10	784.9	0.03803	18.93	588.7	0	5.15	110.30	0.827	74.8	50.4
210	40,000	4018.8	21.422	29.8	9.95	768.1	0.03411	19.20	576.1	0	5.15	110.30	0.820	75.2	50.6
216	37,400	3833.6	20.788	28.7	9.76	745.3	0.02882	19.42	559.0	0	5.15	110.30	0.815	75.2	50.8
222	35,400	3688.9	20.281	27.8	9.60	727.1	0.02458	19.62	545.3	0	5.15	110.30	0.810	75.3	51.0
228	34,000	3586.3	19.914	27.1	9.48	714.0	0.02152	19.79	535.5	0	5.15	110.30	0.803	75.4	51.2
234	32,000	3437.9	19.373	26.2	9.31	694.6	0.01701	19.92	521.0	0	5.15	110.30	0.796	75.5	51.5
240	30,000	3287.1	18.810	25.2	9.13	674.4	0.01230	20.02	505.8	0	5.15	110.30	0.790	75.6	51.7
246	28,700	3187.6	18.431	24.6	9.00	660.8	0.00914	20.09	495.6	0	5.15	110.30	0.782	75.6	51.9
252	27,000	3055.7	17.919	23.7	8.84	642.5	0.00486	20.13	481.9	0	5.15	110.30	0.777	75.7	52.2
258	25,700	2953.3	17.513	23.0	8.70	627.9	0.00147	20.14	470.9	0	5.15	110.30	0.771	75.7	52.4
264	24,600	2865.6	17.159	22.5	8.58	615.2	0	20.14	461.4	0	5.15	110.30	0.771	75.7	52.4

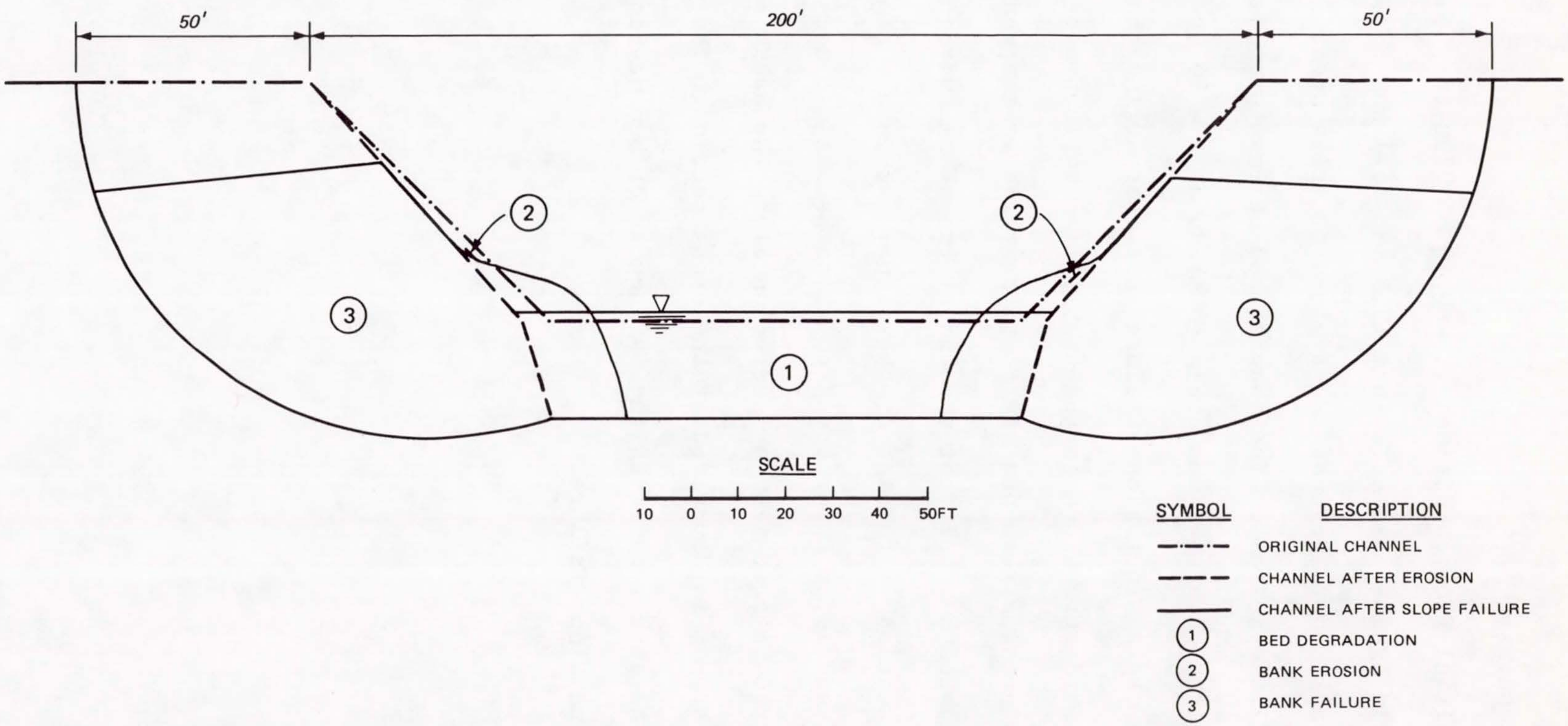
upstream is deposited at the cross section. A sediment transport analysis such as HEC-6 would be required to include the effects of deposition (Hydrologic Engineering Center 1977).

(5) The slope stability was evaluated for several points in time along the storm hydrograph using WESLIB computer program Simplified Bishop's Method as given below:

T hours	Q cfs	Y ft	$\Sigma\delta_{UN\,RW\,bed}$ ft	F.S.	Center Coordinates of Critical Circle X_o ft	Y_o ft
0	19200	20.1	0	1.57	25	50
36	58700	38.1	1.8	2.15	25	75
78	81200	45.3	6.8	2.14	0	110
126	72000	41.9	12.6	1.41	-75	60
192	46300	32.4	18.3	1.09	0	200
264	24600	22.5	20.1	0.96	25	50



The results of the slope stability analysis indicate the slope would be stable throughout most of the storm hydrograph due to the stabilizing influence of the high water level in the stream. However, as the water level in the stream drops and the bed degradation at the toe of the slope increases, the factor of safety approaches unity indicating impending slope failure at the end of the storm hydrograph. Assuming that slope failure takes place at $T = 264$ hr, the final cross section will be similar to that shown on the following page.


50'
200'
50'
2
2
3
3
1
SCALE
10 0 10 20 30 40 50FT
SYMBOL
DESCRIPTION
ORIGINAL CHANNEL
CHANNEL AFTER EROSION
CHANNEL AFTER SLOPE FAILURE
1 BED DEGRADATION
2 BANK EROSION
3 BANK FAILURE

Summary of Results:

For initial flow conditions (T = 0, Q = 19200 cfs) the streambank is stable against slope failure (F.S. = 1.57) and no erosion of the bed or bank occurs because the applied tractive shear stress is less than 621.6 dynes/cm^2. The channel bed begins to erode at T = 6 hr and the channel sides begin to erode at T = 30 hr. The factor of safety against slope failure increases during the passing of the storm hydrograph due to the stabilizing influence of the high water level in the stream but starts to decrease as the peak flow passes and approaches unity at the end of the storm hydrograph when the bed degradation at the toe of the slope reaches a maximum. The erosion analysis is an upper bound solution because it does not take into account bed aggradation or accretion along the banks as eroded soil from upstream is deposited at the cross section. The final cross section of the stream reflects the influences of bed degradation, bank recession, and slope failure.

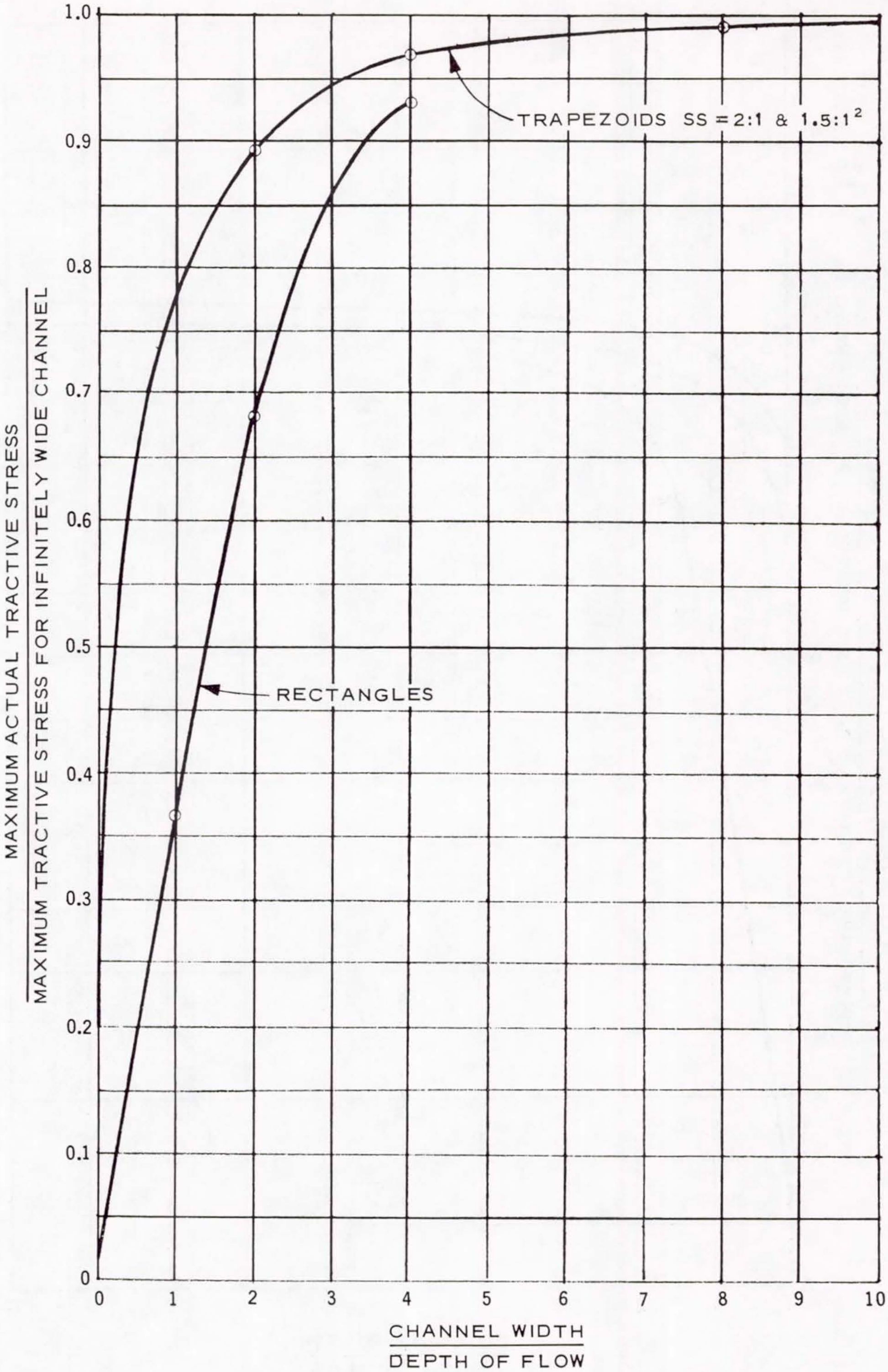


Figure C23. Ratio of actual maximum tractive shear stress on bed of channel of finite width to maximum tractive shear stress on bed of infinitely wide channel (from Lane 1952)

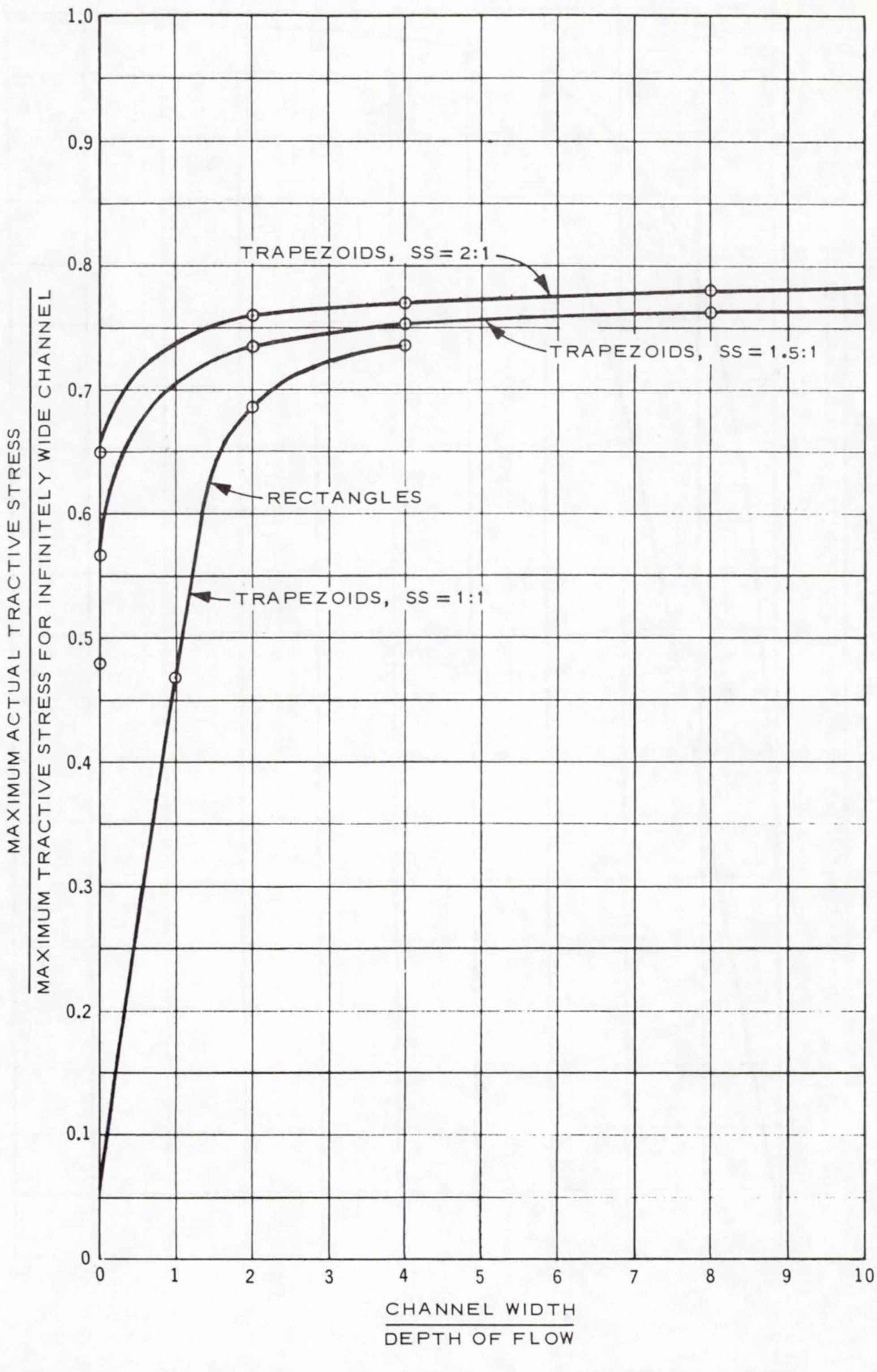
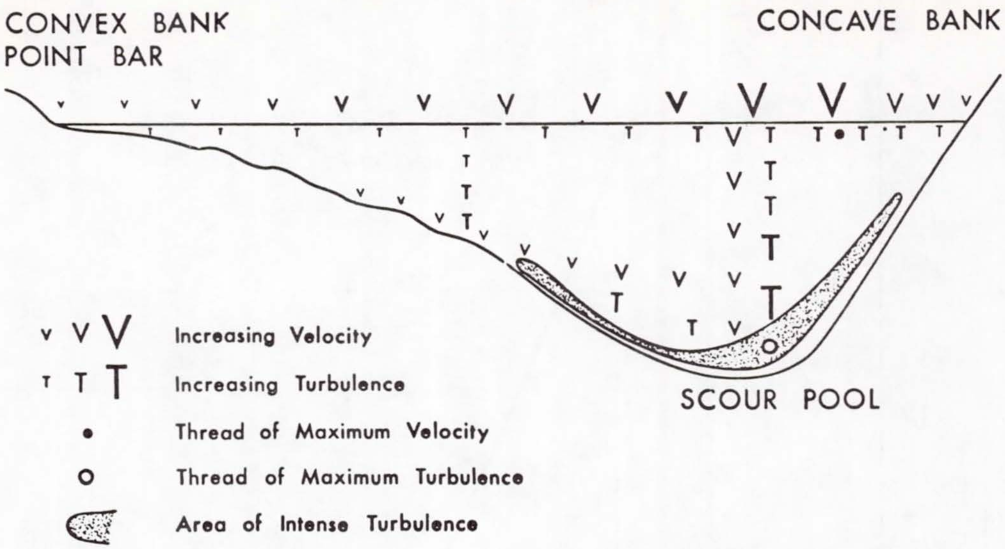
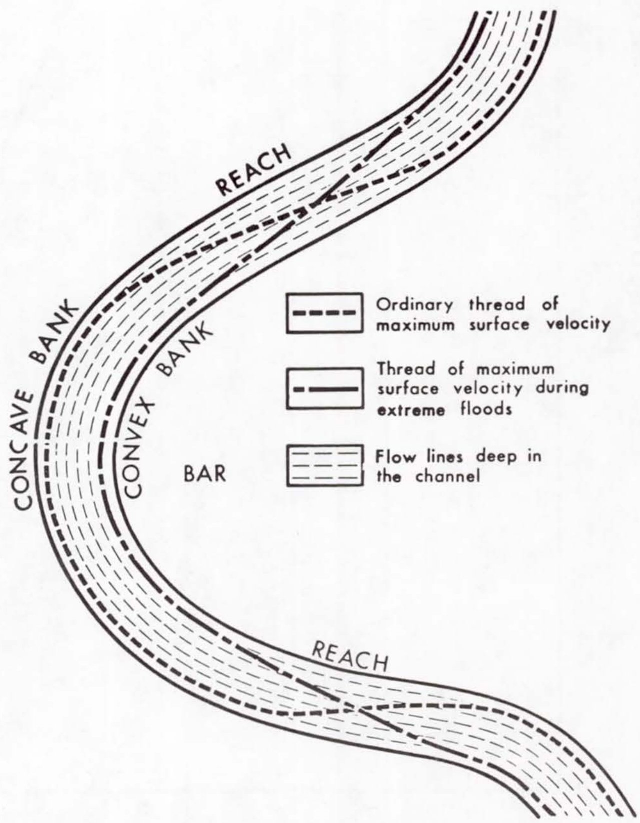


Figure C24. Ratio of actual maximum tractive shear stress on side of channel of finite width to maximum tractive shear stress on bed of infinitely wide channel (from Lane 1952)



A. VELOCITY AND TURBULENCE IN A RIVER BEND



B. LOCATION OF MAXIMUM VELOCITY DURING NORMAL AND FLOOD FLOWS

Figure C25. Velocity in a river bend during normal and flood flows (from Russell 1979)

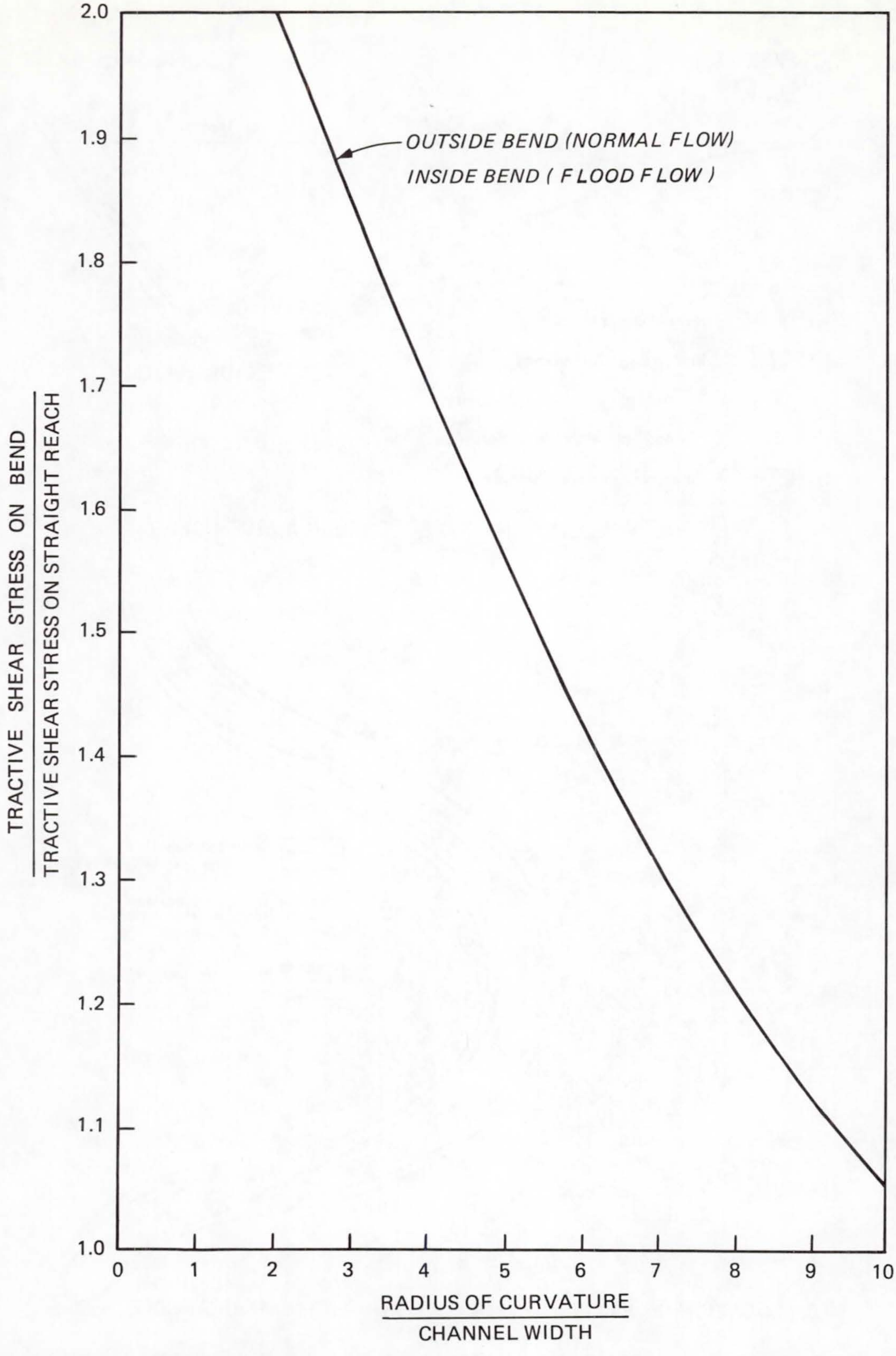


Figure C26. Ratio of tractive shear stress on bend to tractive shear stress on straight reach (from Soil Conservation Service 1977)

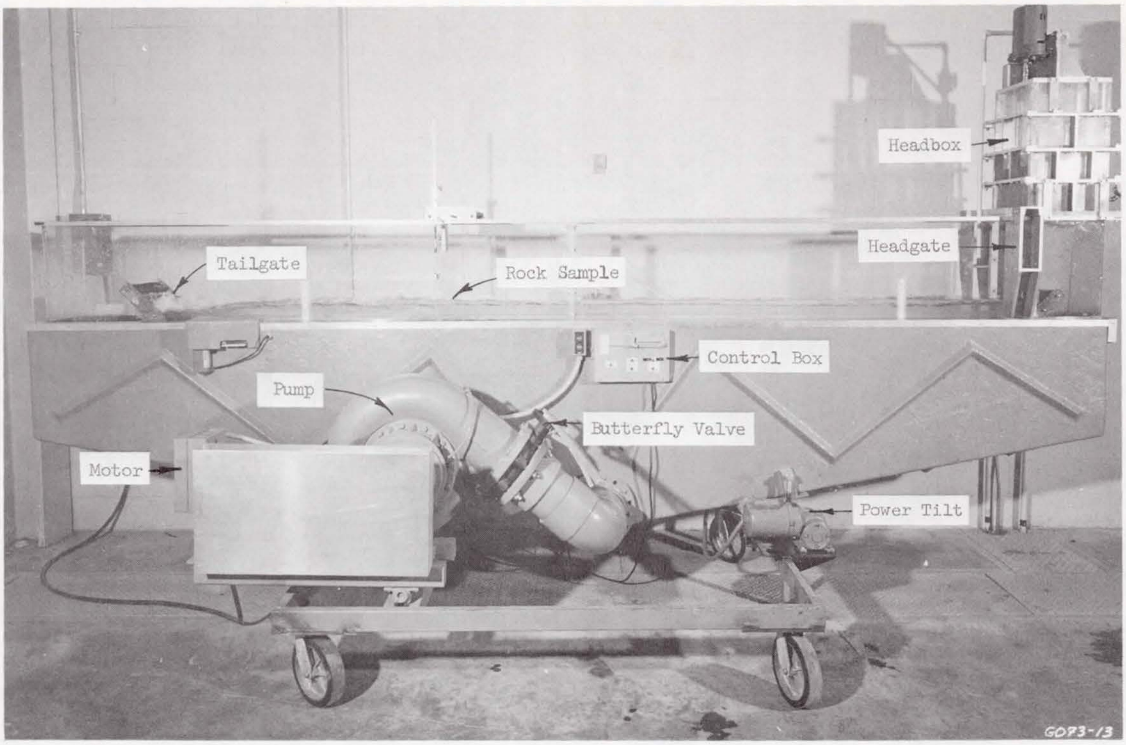


Figure C27. Overall view of laboratory recirculating tilting flume to measure soil erosion

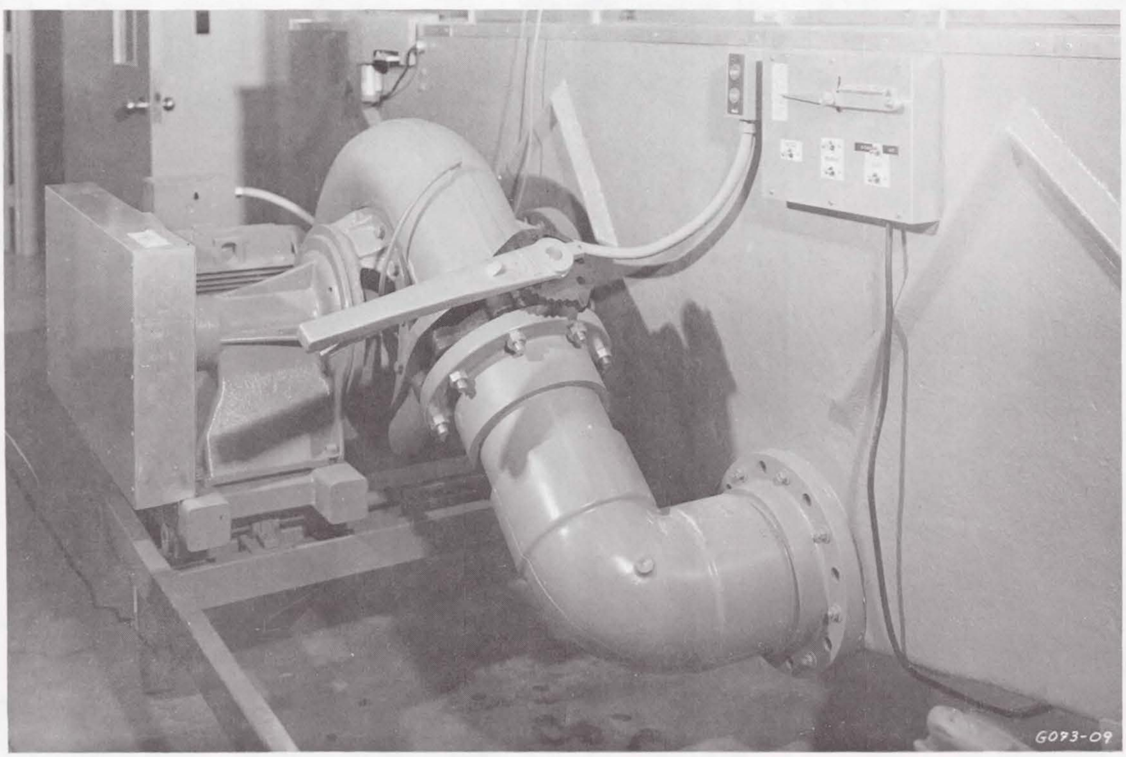


Figure C28. Pump, motor, and butterfly valve for recirculating water in flume

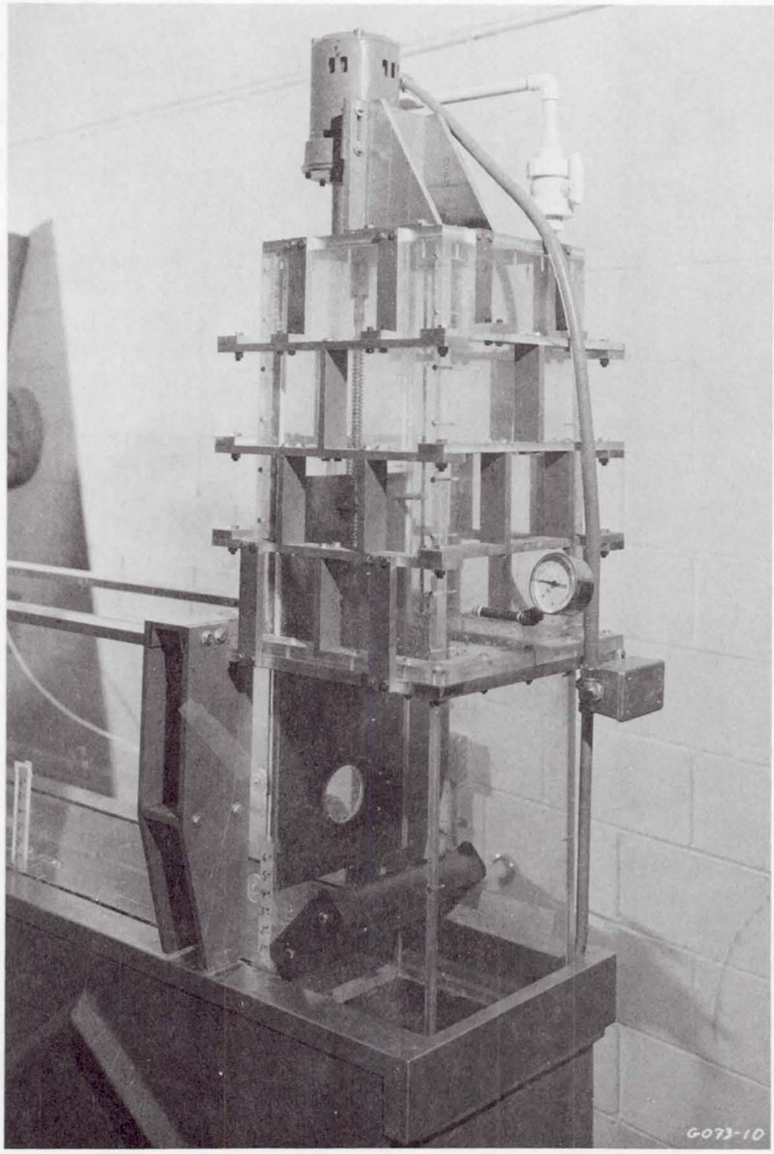


Figure C29. Reinforced headbox with motorized aluminum headgate and turning vanes

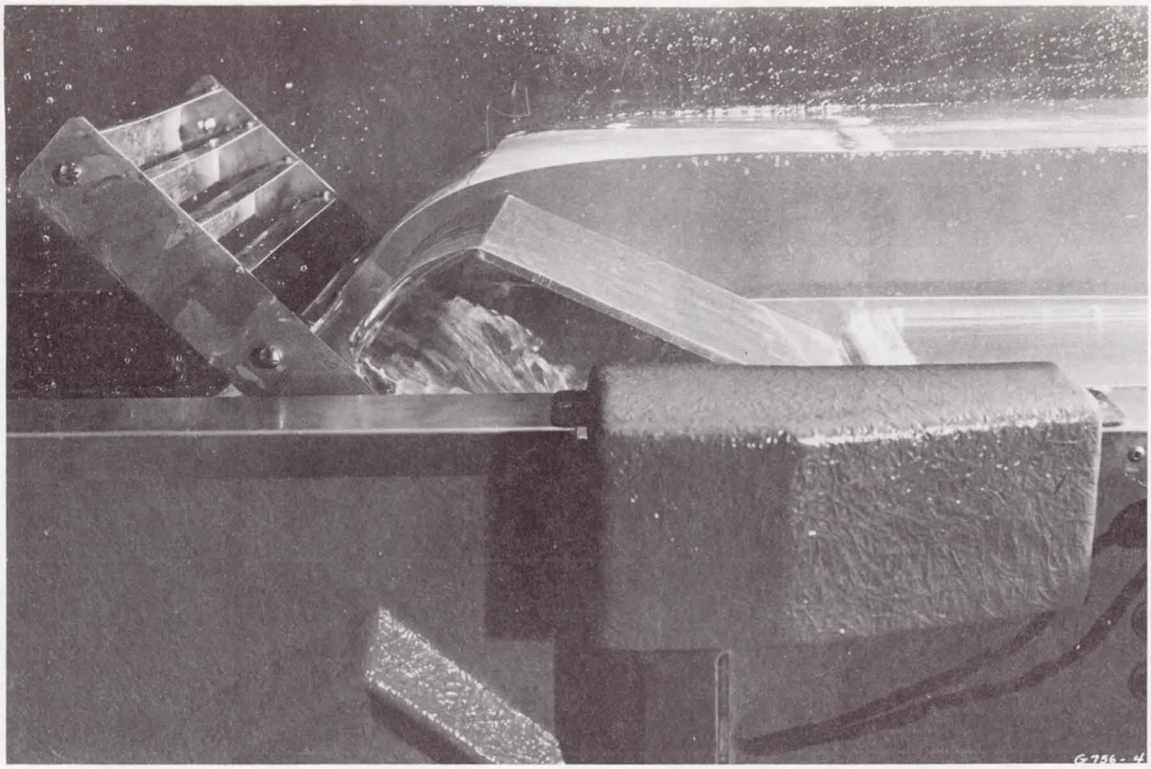


Figure C30. Motorized aluminum tailgate and turning vanes

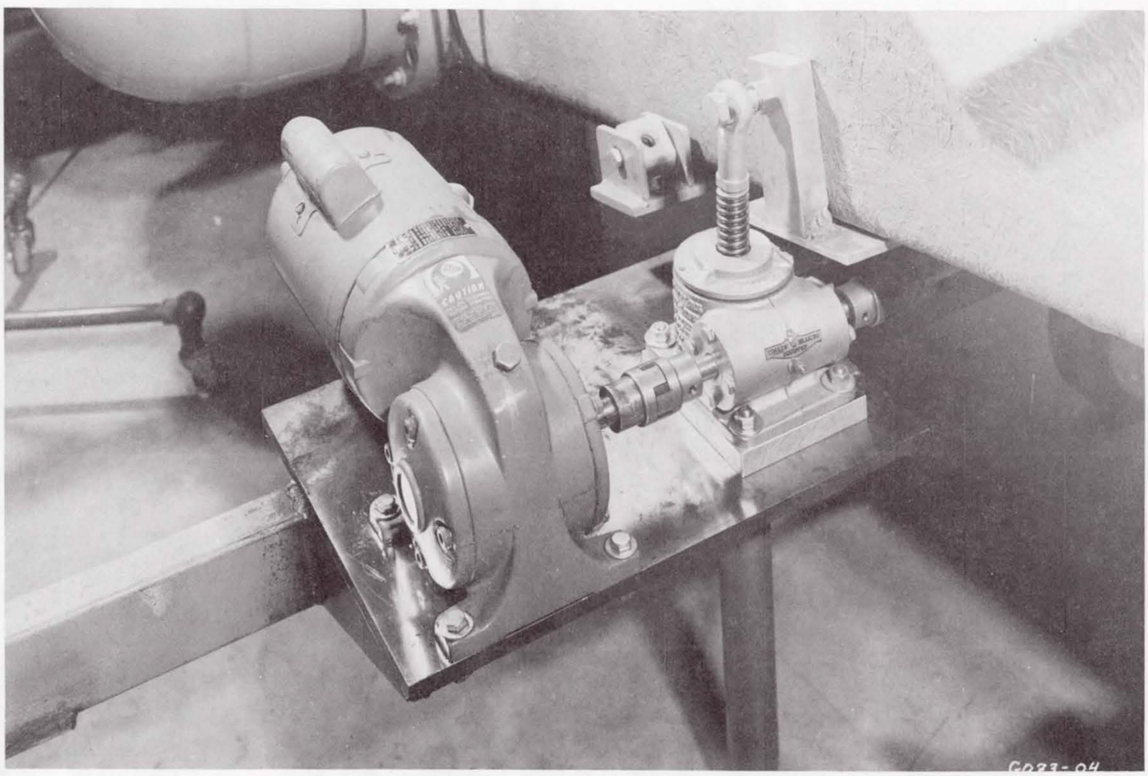


Figure C31. Electrically operated synchronized jack screws to tilt the flume

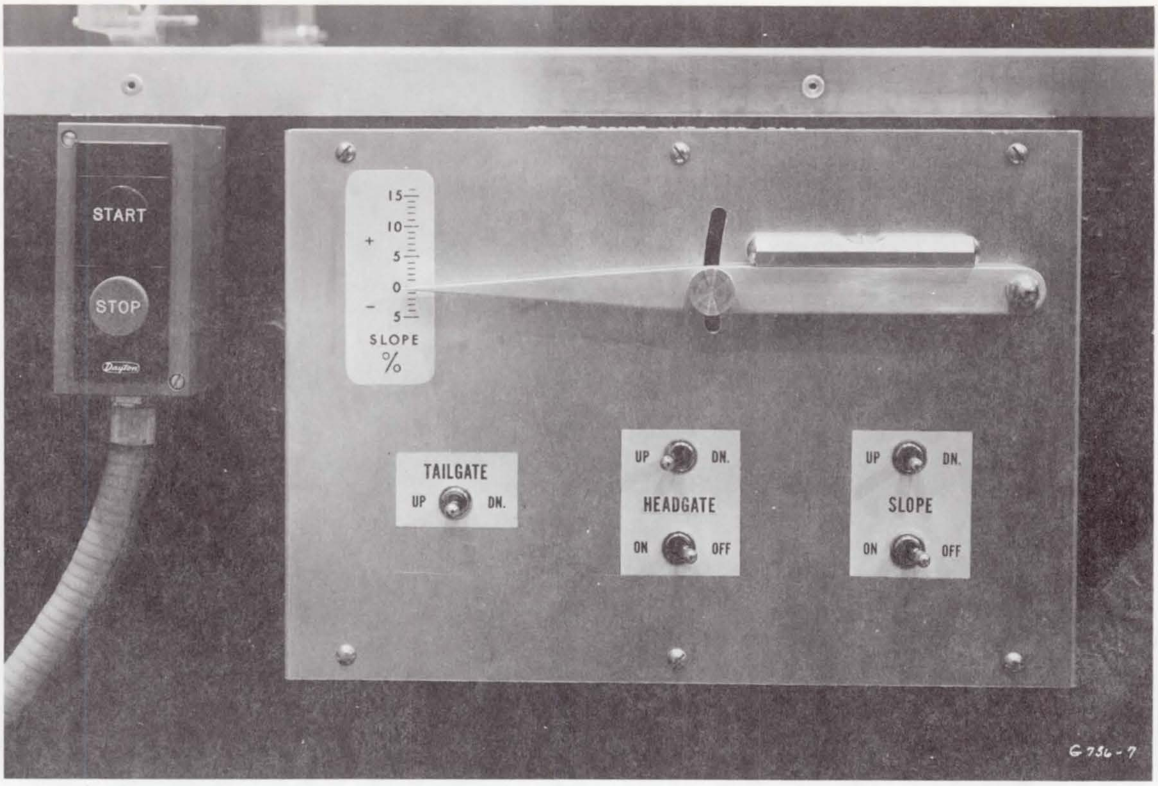


Figure C32. Control box for headgate, tailgate, and slope

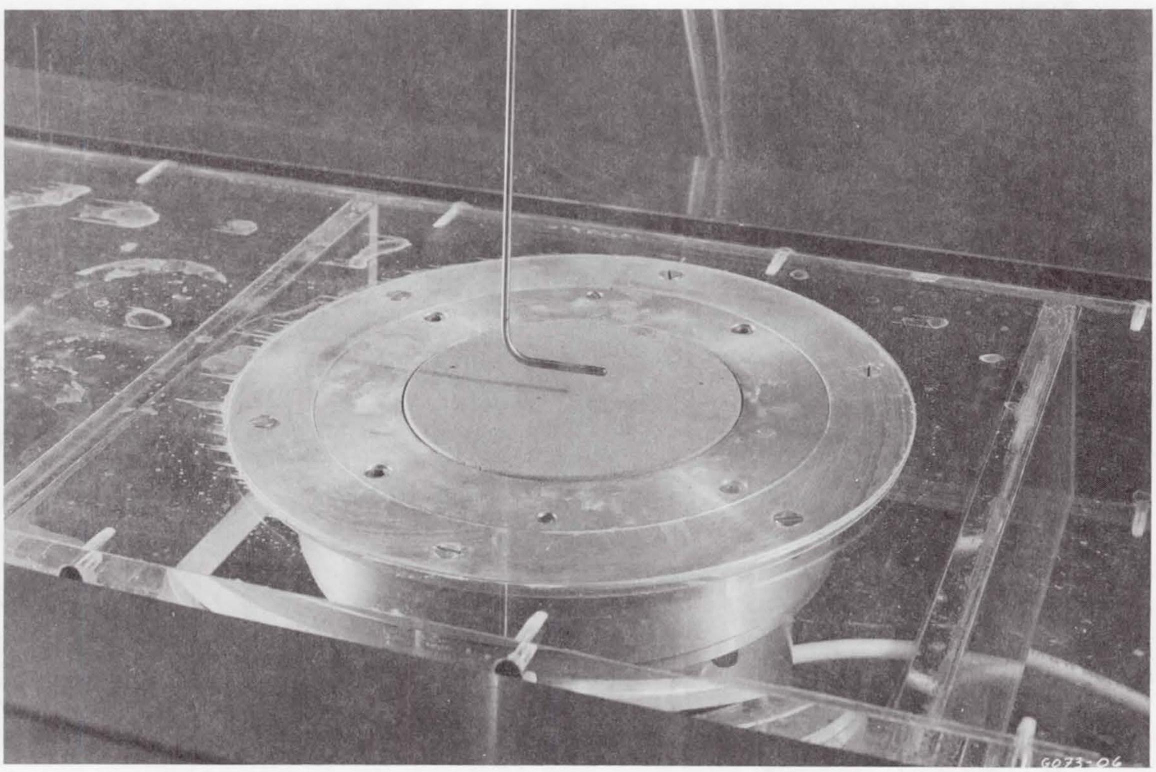


Figure C33. Soil sample mounted flush with bottom of flume and Pitot tube

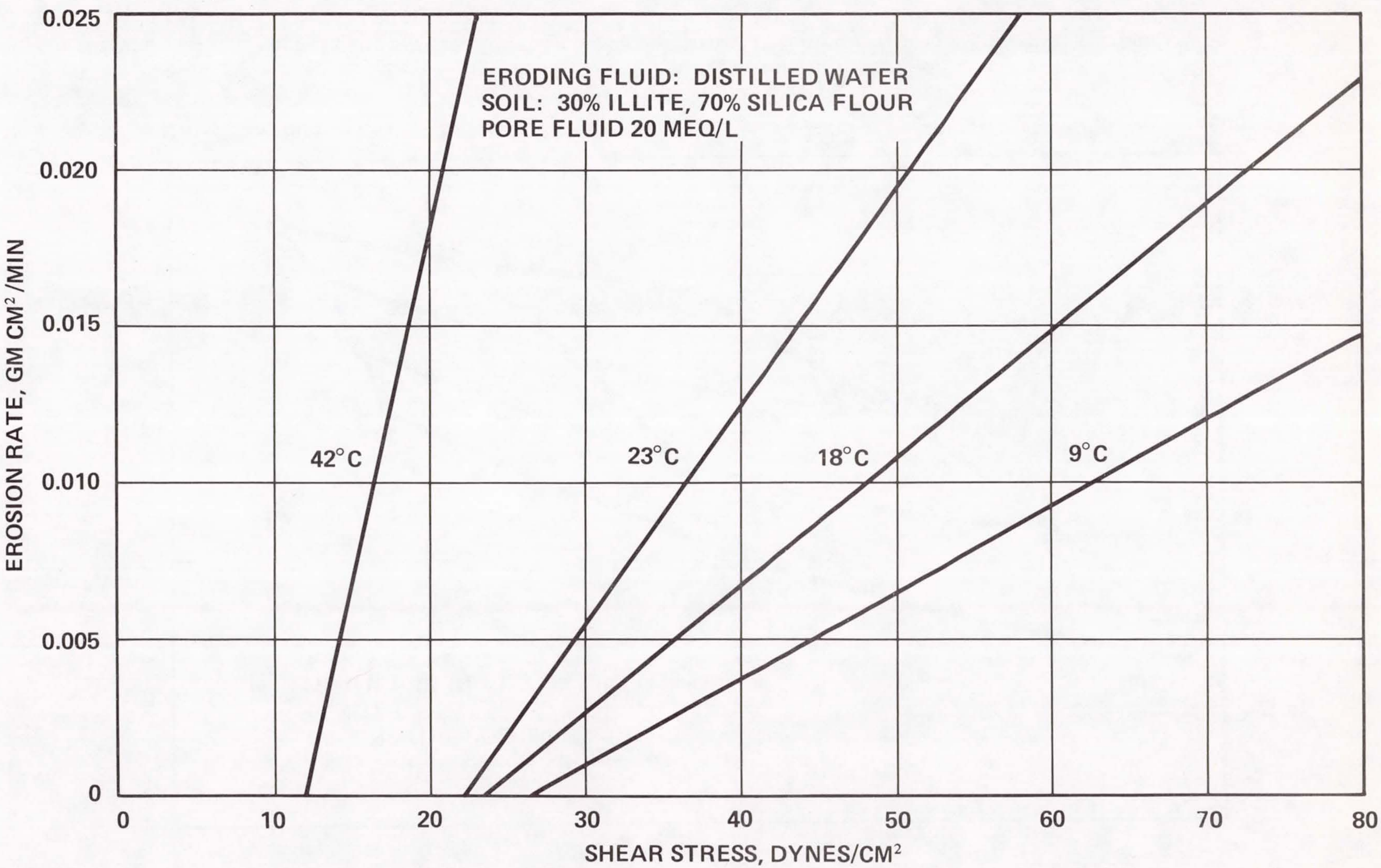


Figure C34. Influence of temperature on erodibility of saturated remolded illitic soil (from Ariathurai and Arulanandan 1978)

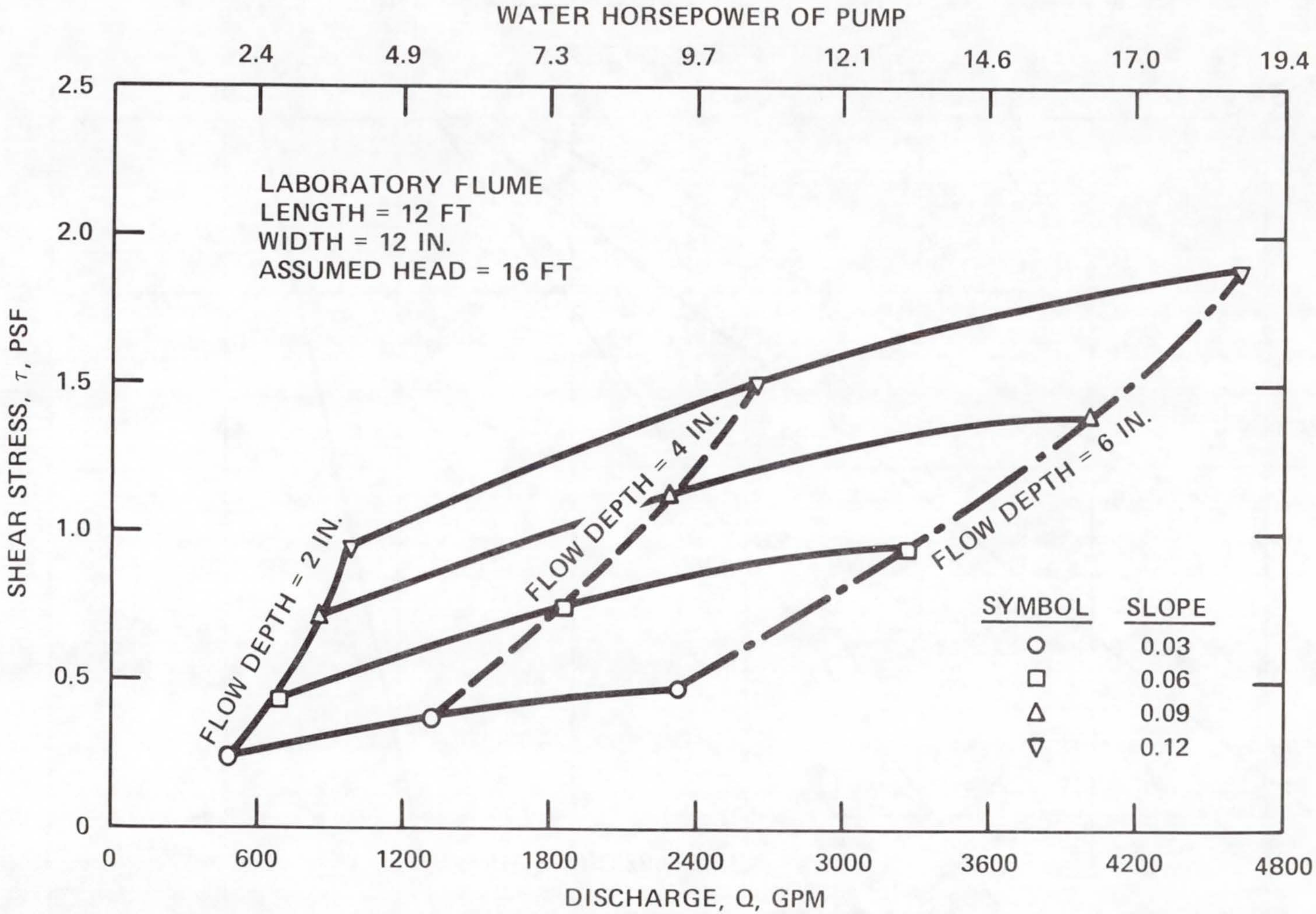


Figure C35. Theoretical relationship between tractive shear stress, discharge, and water horsepower, as a function of flow depth and bed slope for uniform flow conditions

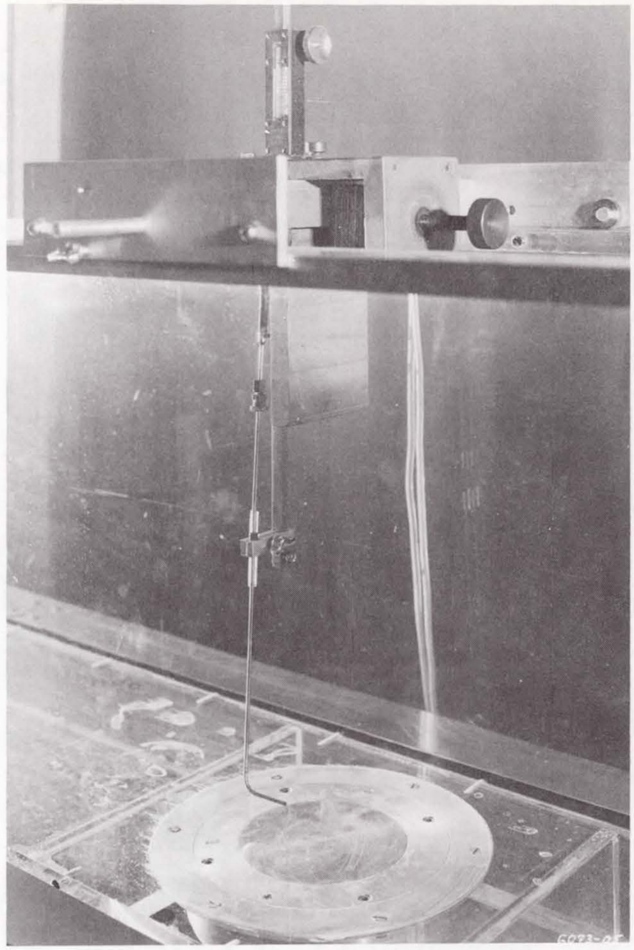


Figure C36. Pitot tube used to measure stagnation pressure and piezometric pressure in calibrating the flume

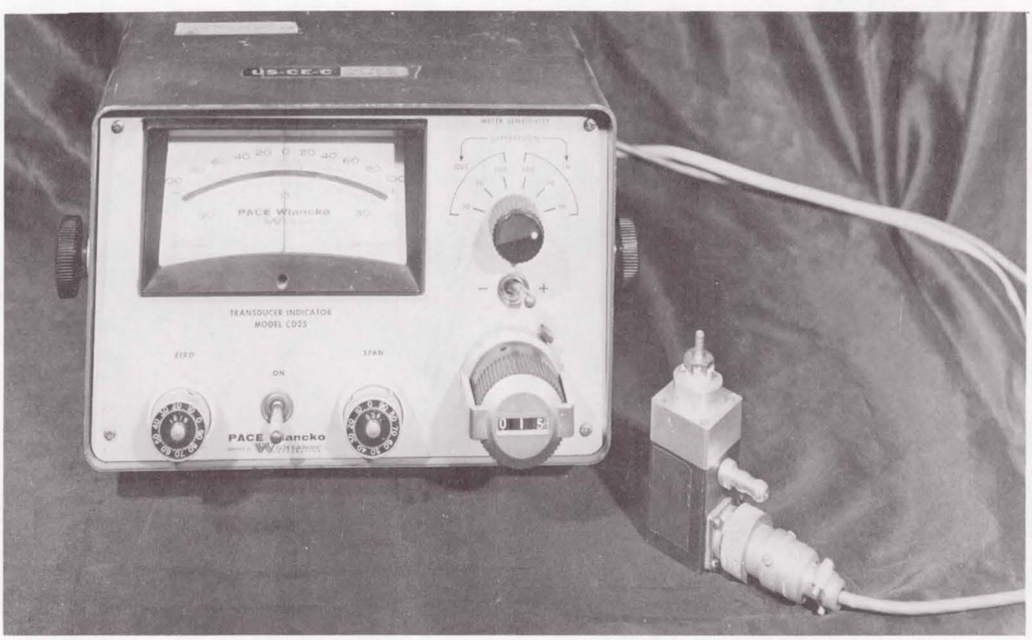


Figure C37. Variable reluctance differential pressure transducer and indicator used in calibrating the flume

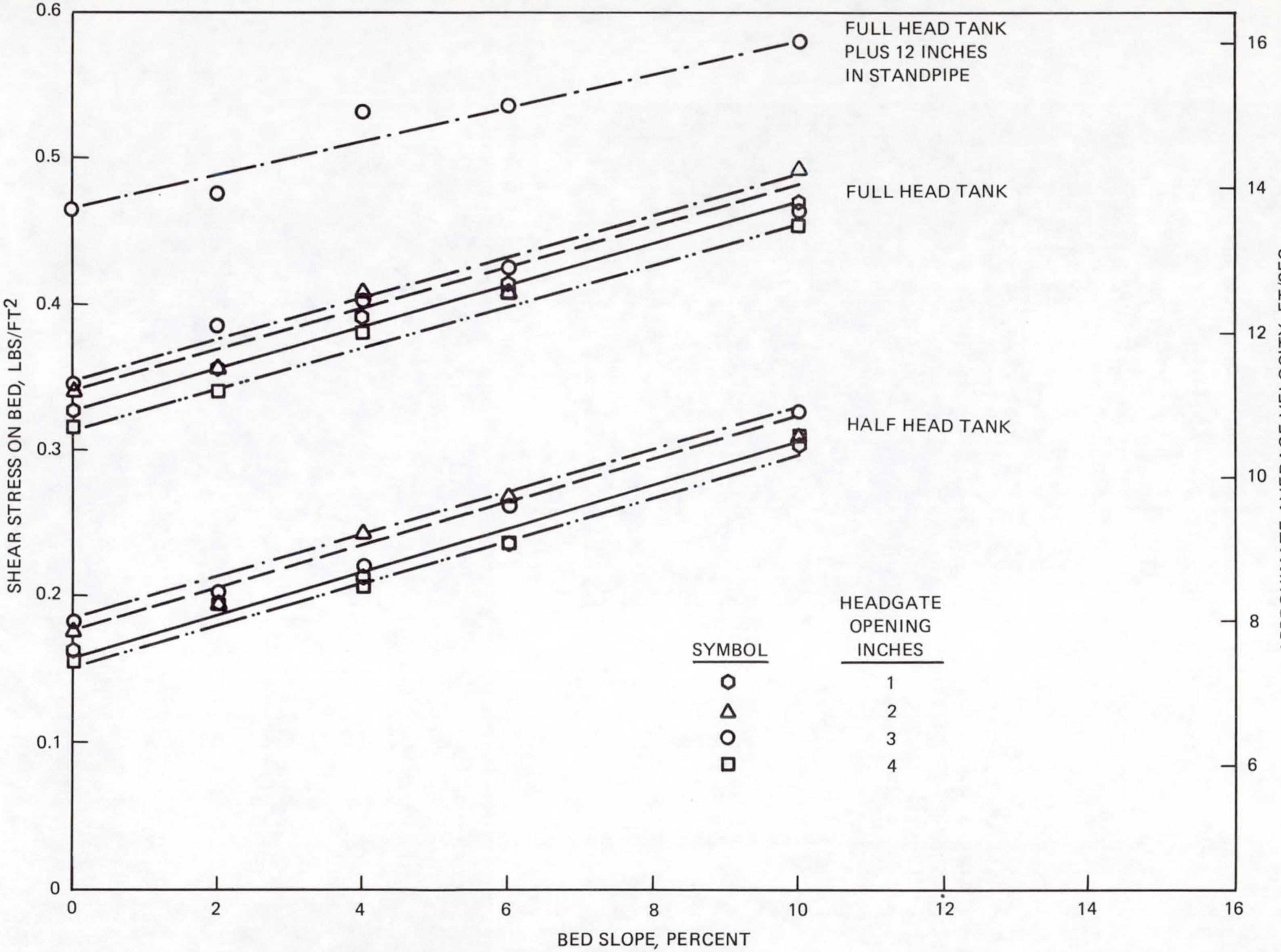


Figure C38. Calibration curves relating tractive shear stress and bed slope, as a function of headgate opening and water level in headtank for water at 70°F

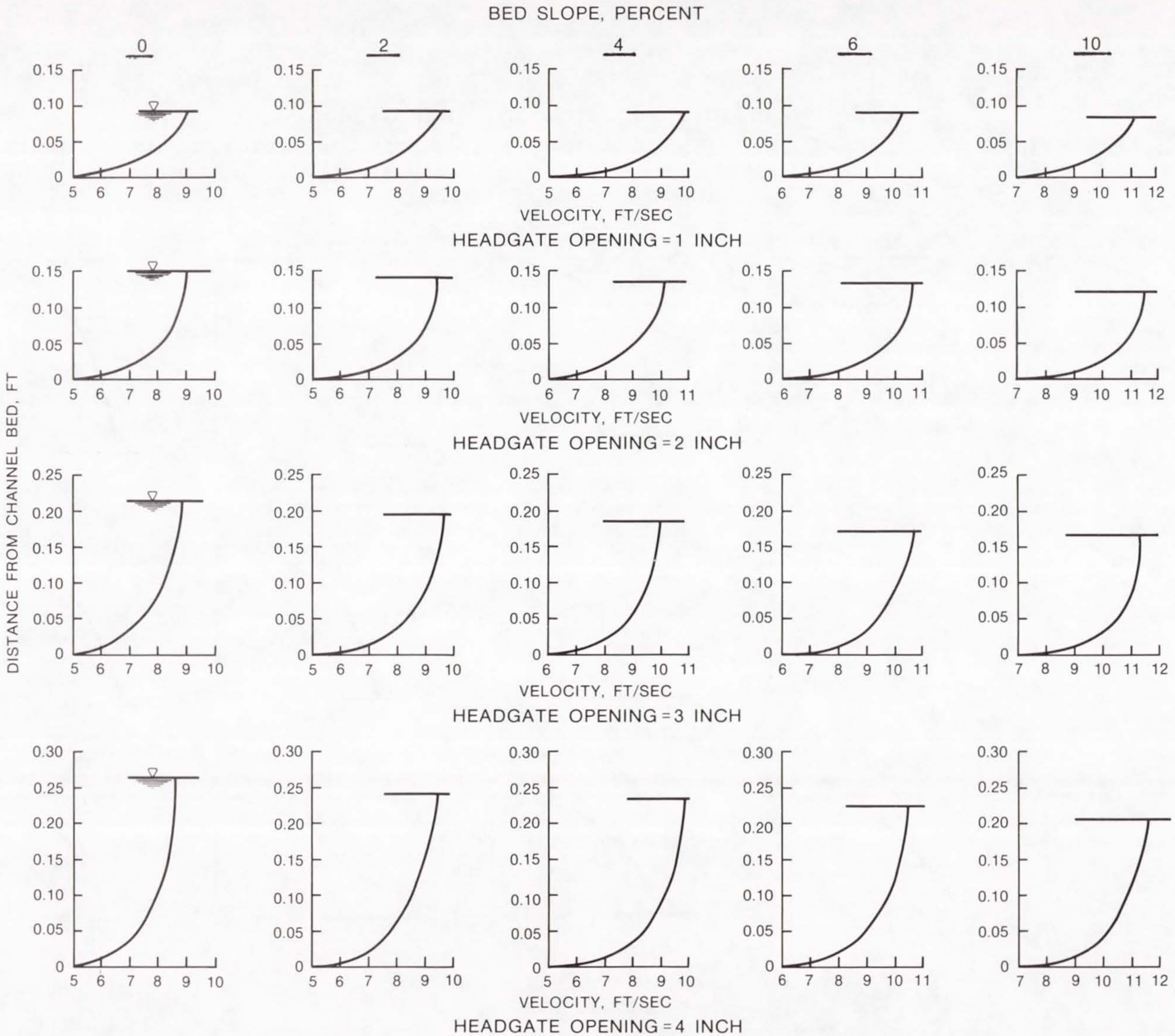


Figure C39. Calibration curves of velocity profiles at location of soil sample on center line for half headtank of water

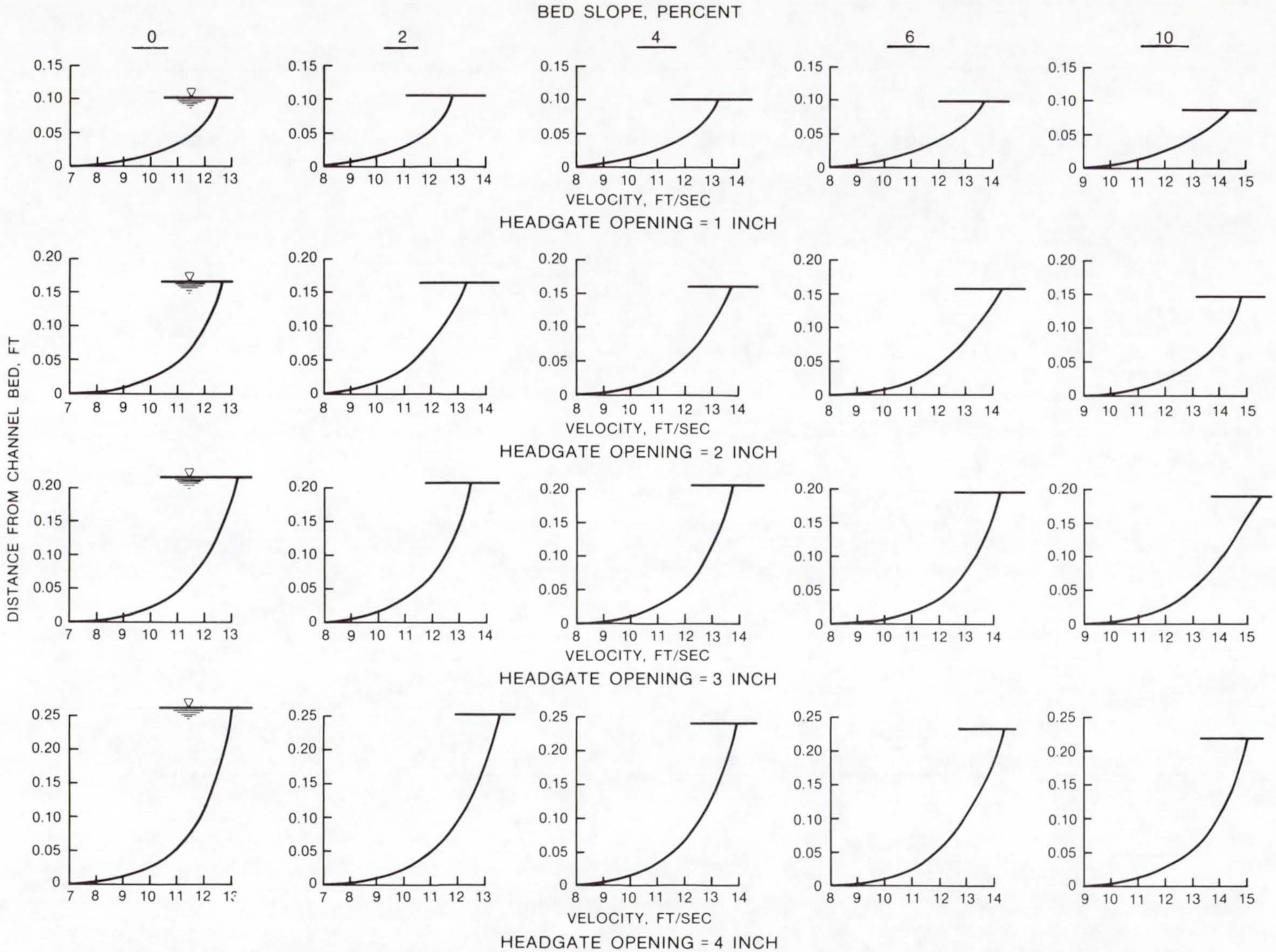


Figure C40. Calibration curves of velocity profiles at location of soil sample on center line for full headtank of water

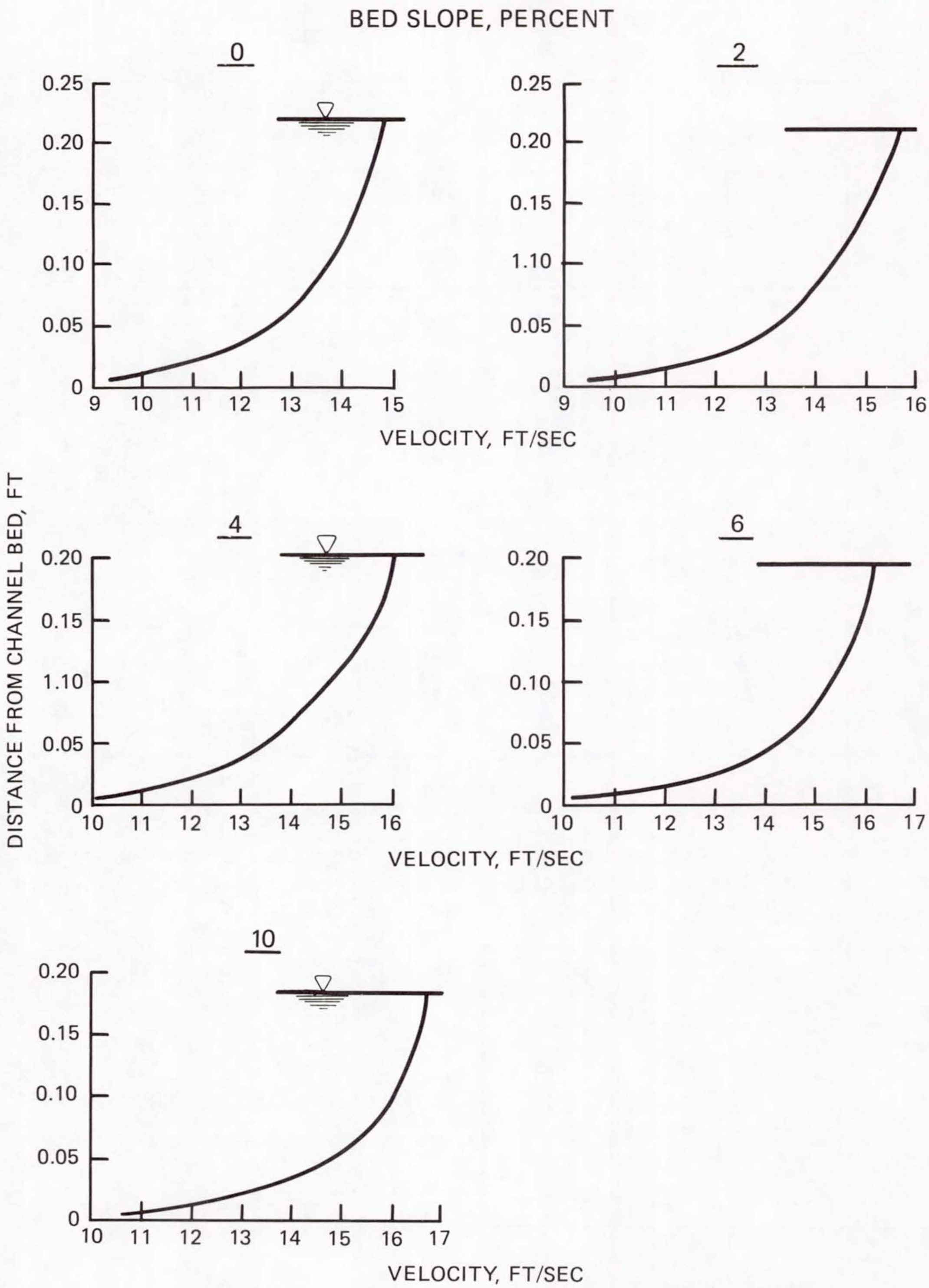


Figure C41. Calibration curves of velocity profiles at location of soil sample on center line for headgate opening of 3 in. and full headtank plus 12 in. of water in standpipe

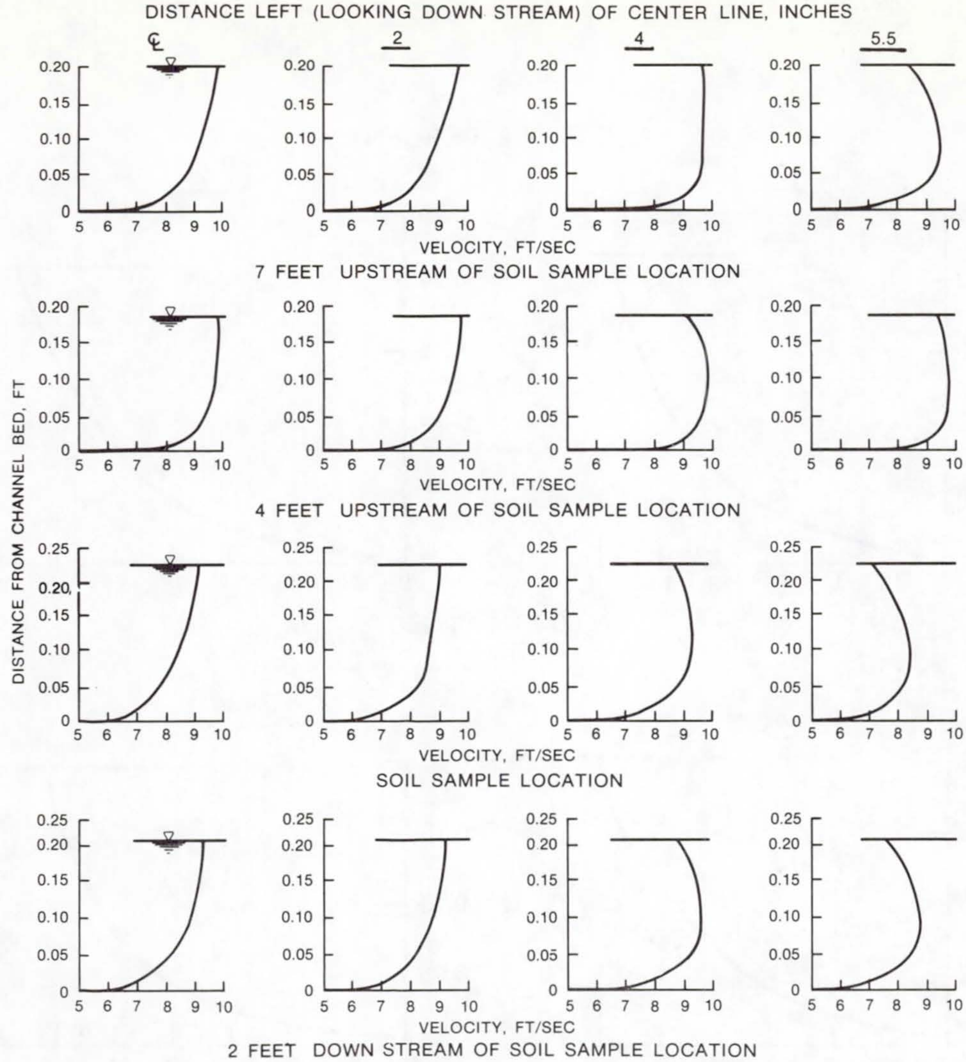


Figure C42. Calibration curves of velocity profiles at various locations and distances from the center line for zero bed slope, headgate opening of 3 in., and half headtank of water

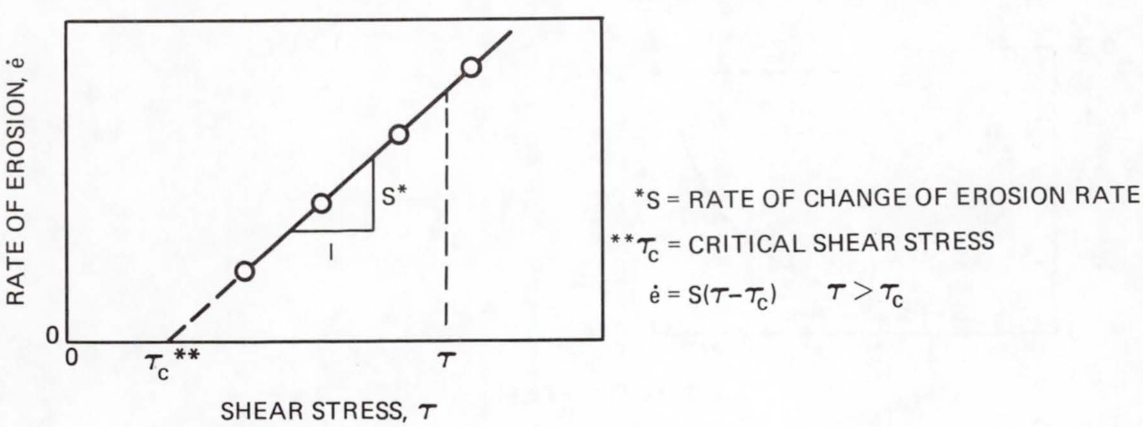


Figure C43. Definition of critical tractive shear stress, rate of change of erosion rate, and rate of erosion

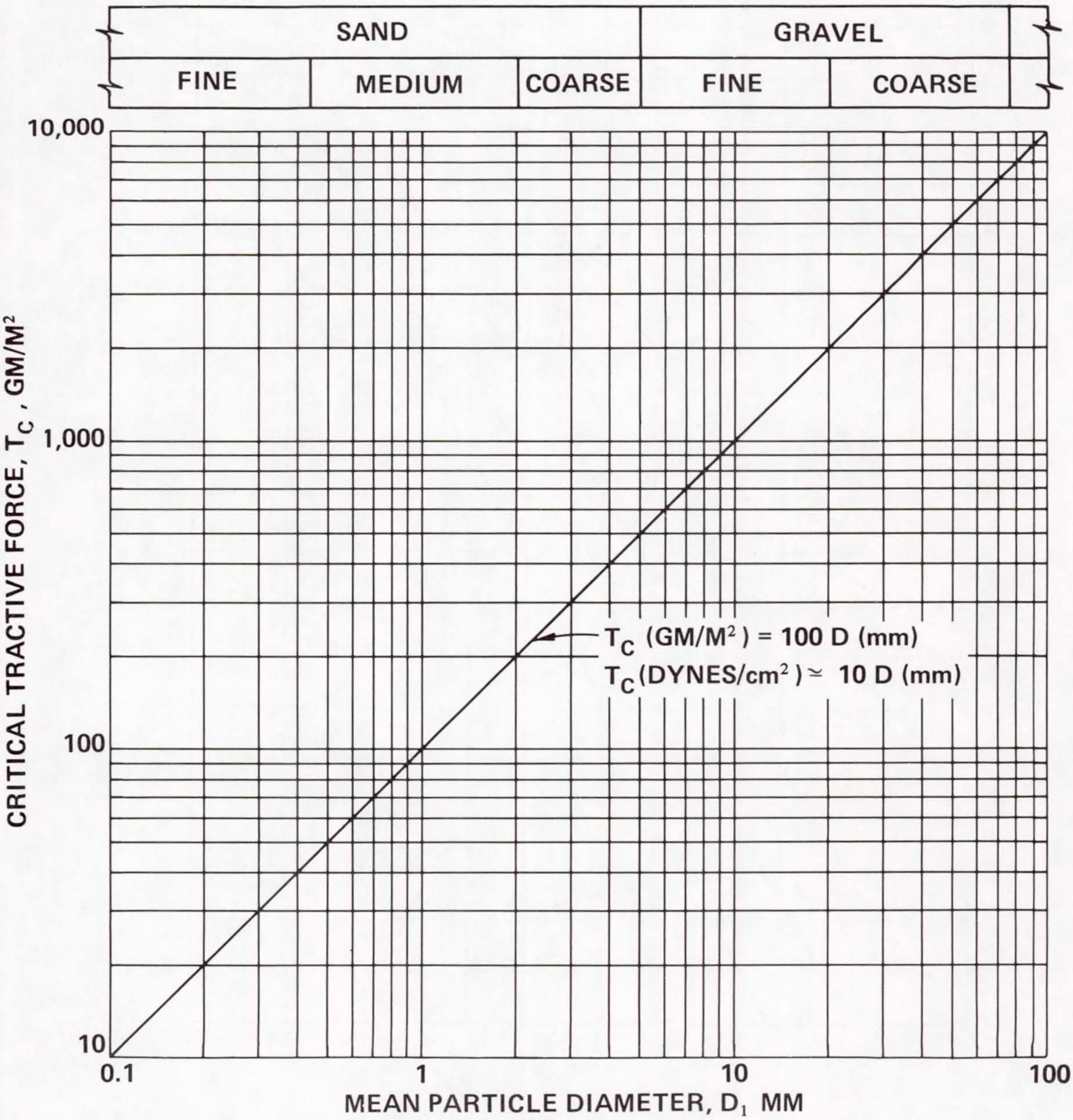


Figure C44. Relationship between critical tractive shear stress and mean particle diameter for sand and gravel (from Lane 1952)

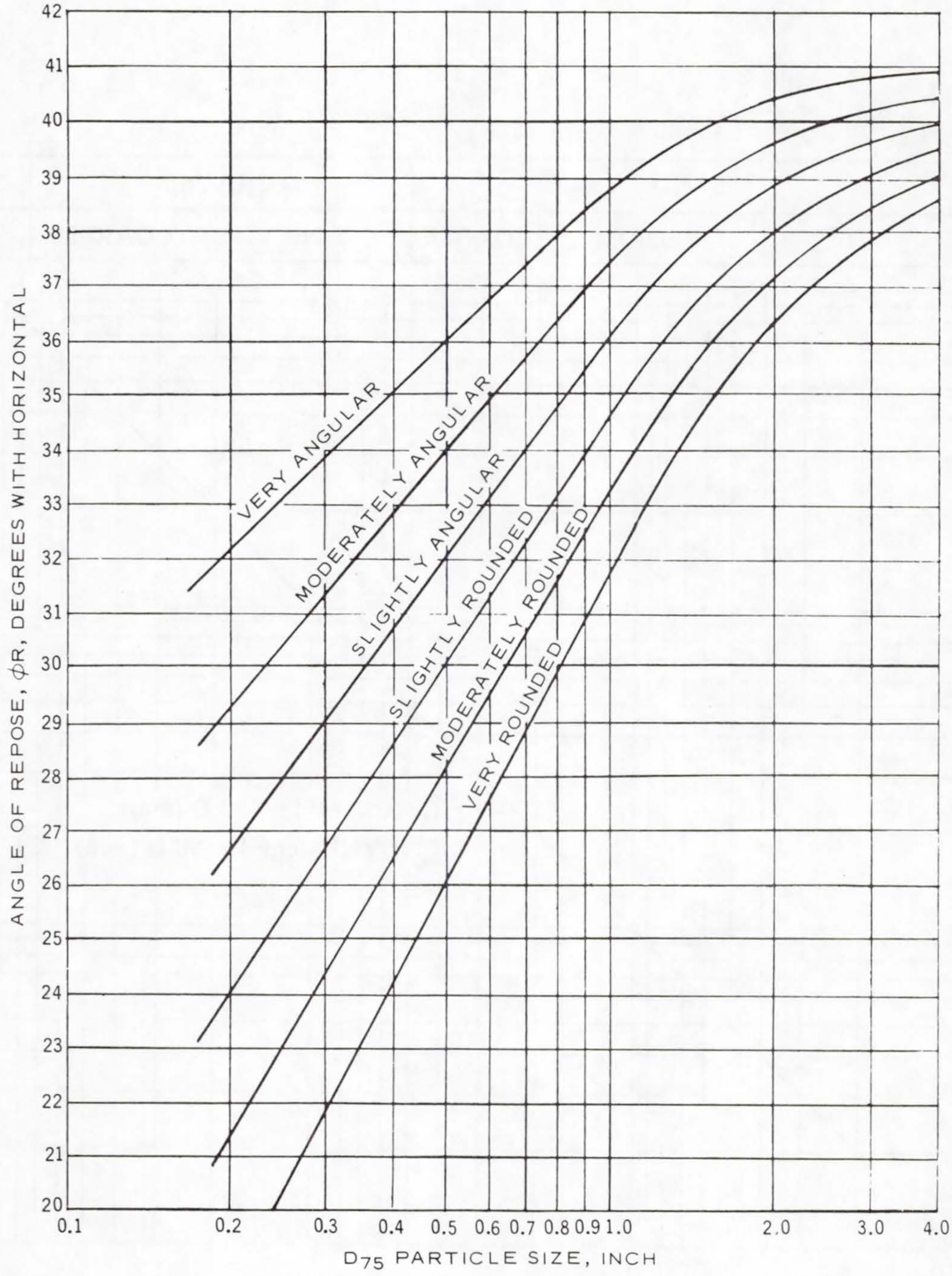


Figure C45. Relationship between angle of repose and D_{75} particle size for cohesionless soil (from Lane 1952)

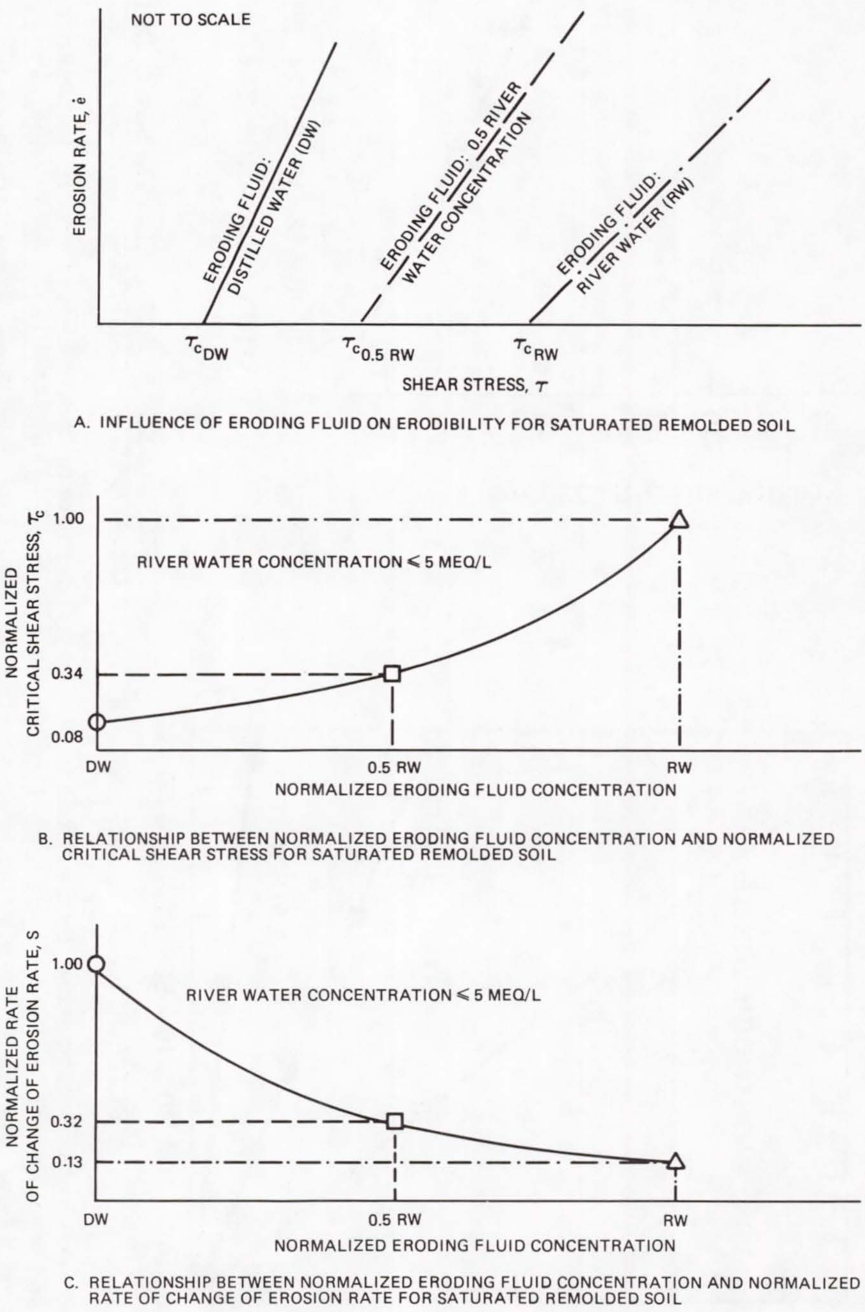


Figure C46. Average influence of eroding fluid concentration on critical tractive shear stress and rate of change of erosion rate for saturated remolded soils (from Arulanandan, Gillogley, and Tully 1980)

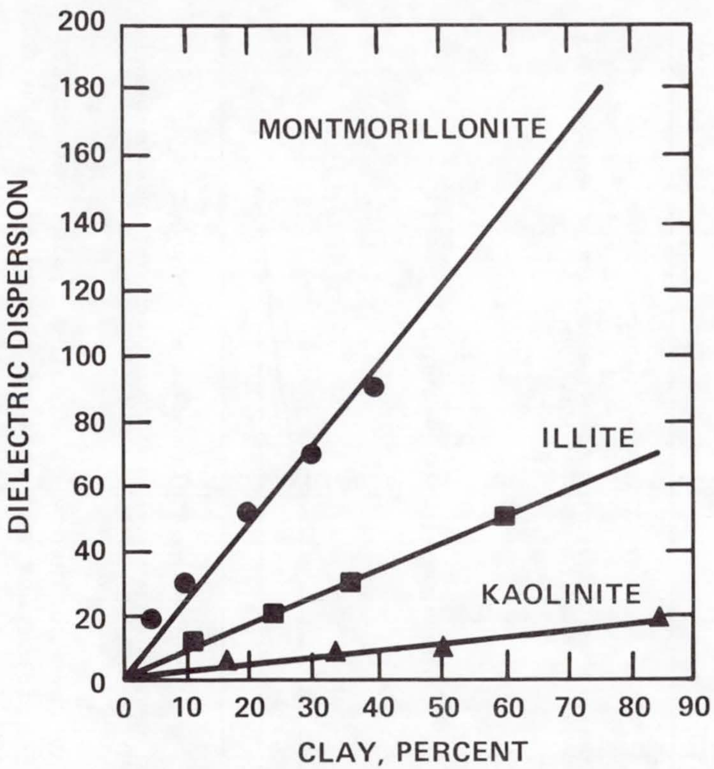
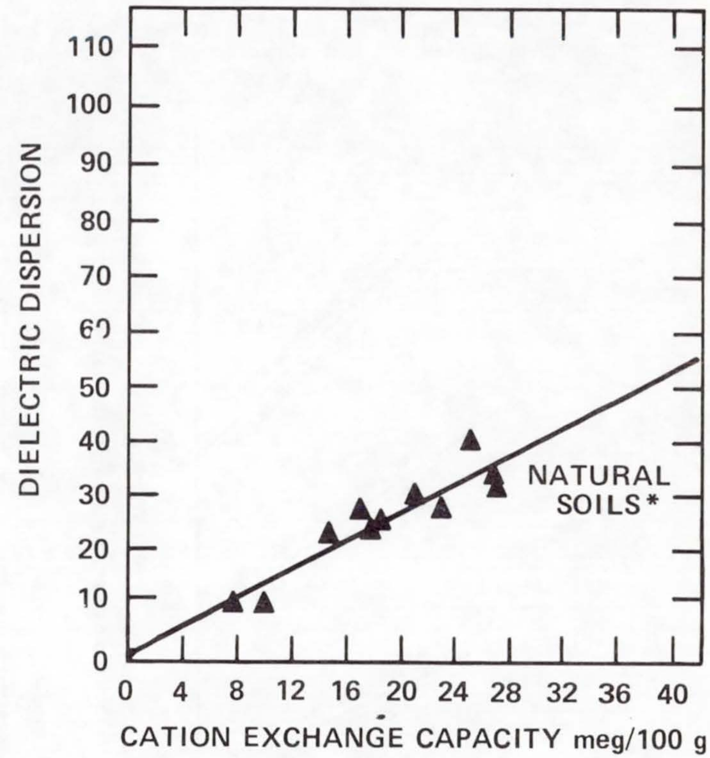


Figure C47. Influence of clay mineral type and amount of dielectric dispersion (from Alizadeh 1974)



*NATURAL SOILS WERE ELEVEN SOILS OBTAINED FROM VARIOUS LOCATIONS IN CALIFORNIA

Figure C48. Relationship between cation exchange capacity and dielectric dispersion (from Fernando, Burau, and Arulanandan 1977)

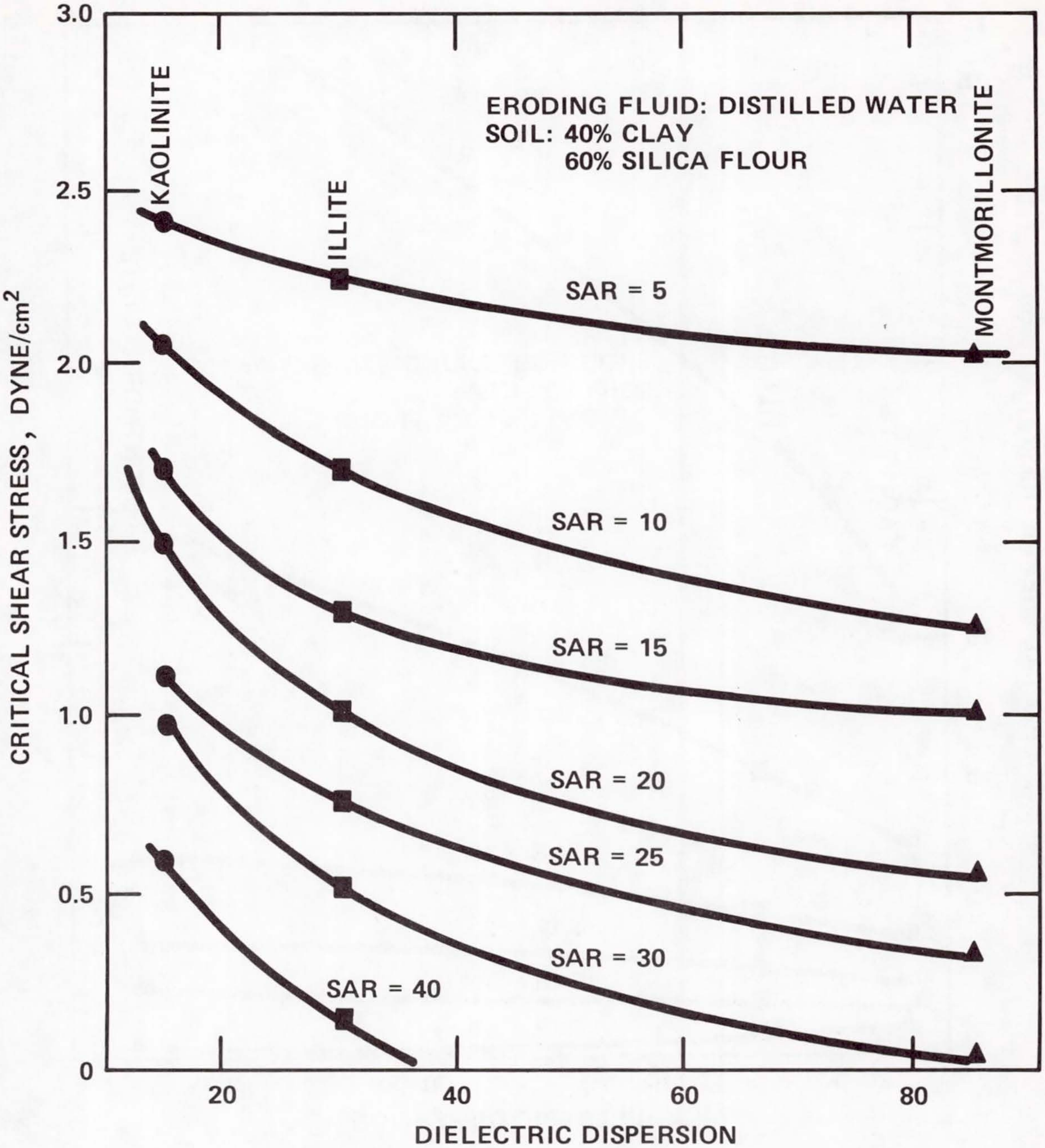


Figure C49. Relationship between critical tractive shear stress, sodium adsorption ratio, and dielectric dispersion for saturated remolded soil with distilled water as eroding fluid and soil pore fluid concentration of 5 milliequivalents/liter (from Alizadeh 1974 and Heinzen 1976)

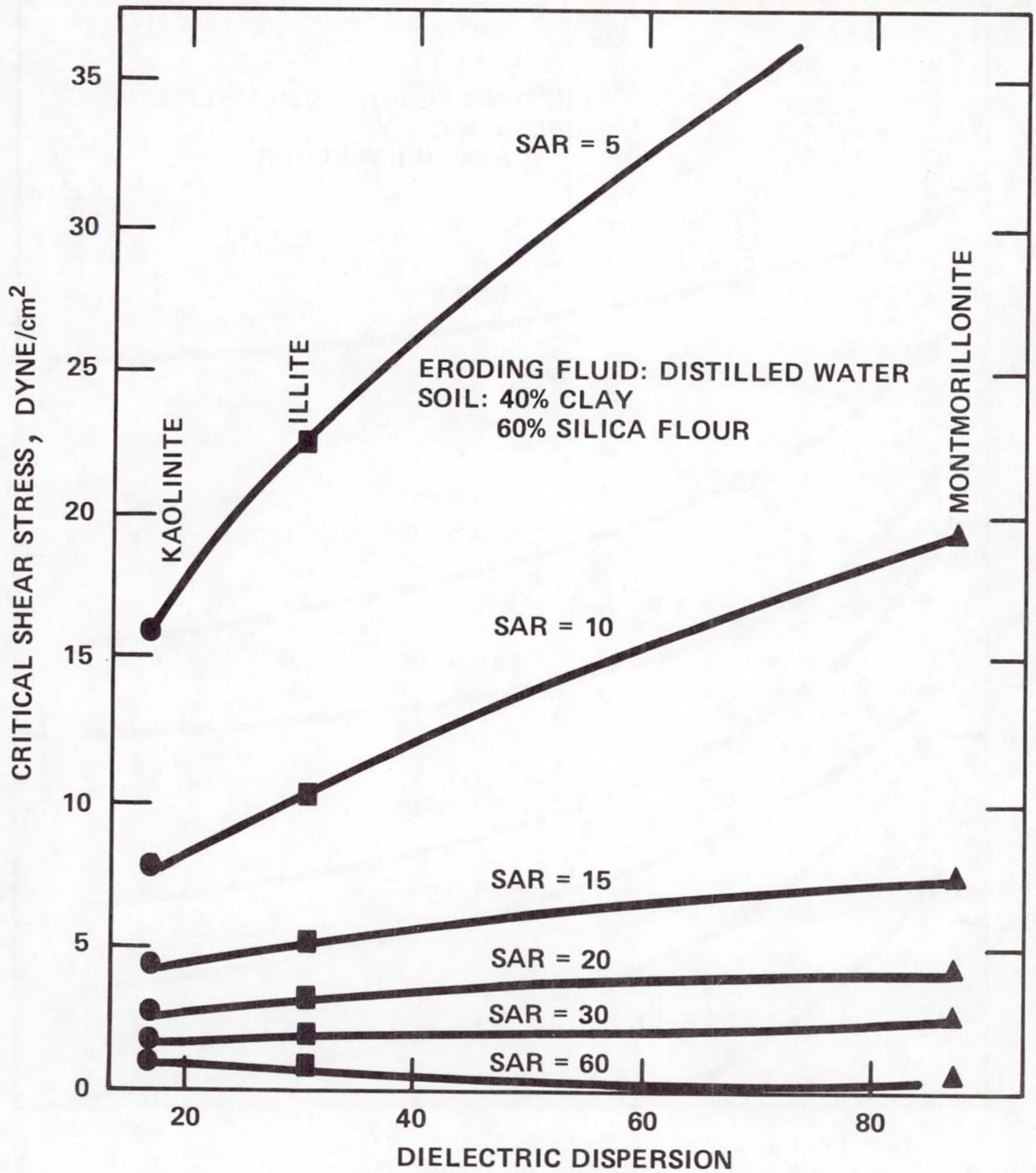


Figure C50. Relationship between critical tractive shear stress, sodium adsorption ratio, and dielectric dispersion for saturated remolded soil with distilled water as eroding fluid and soil pore fluid concentration of 50 milliequivalents/liter (from Alizadeh 1974 and Heinzen 1976)

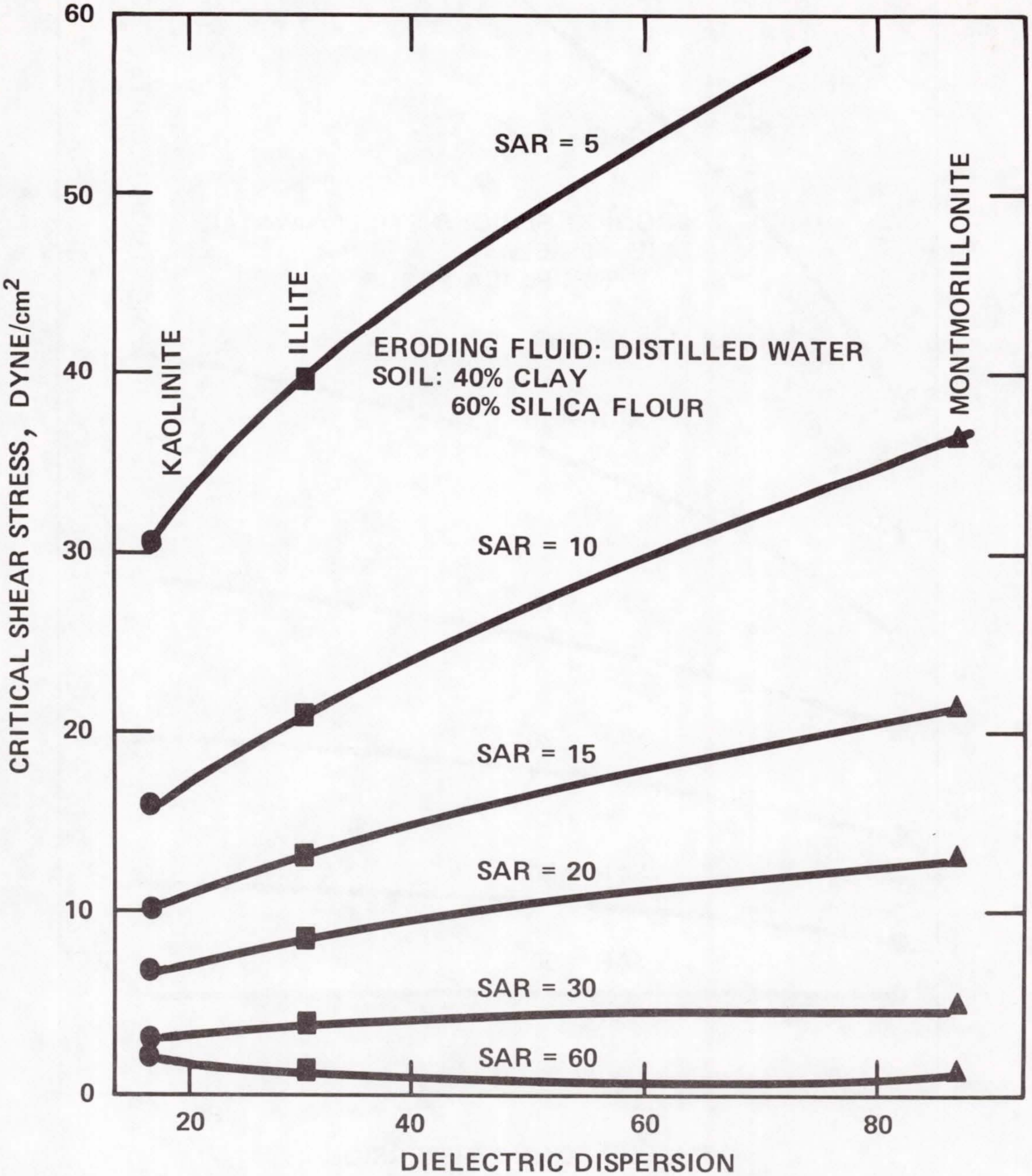


Figure C51. Relationship between critical tractive shear stress, sodium adsorption ratio, and dielectric dispersion for saturated remolded soil with distilled water as eroding fluid and soil pore fluid concentration of 125 milliequivalents/liter (from Alizadeh 1974 and Heinzen 1976)

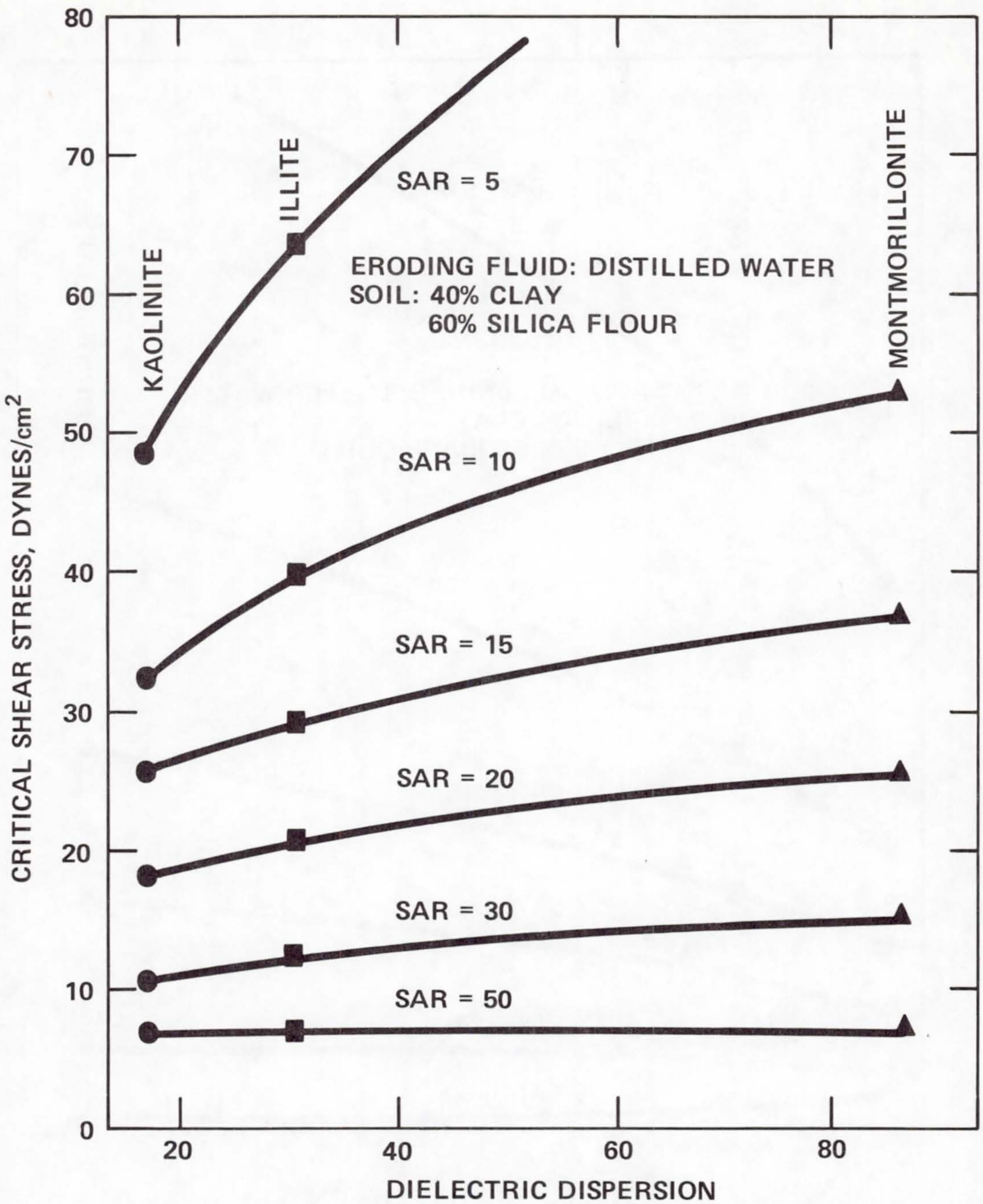


Figure C52. Relationship between critical tractive shear stress, sodium adsorption ratio, and dielectric dispersion for saturated remolded soil with distilled water as eroding fluid and soil pore fluid concentration of 250 milliequivalents/liter (from Alizadeh 1974 and Heinzen 1976)

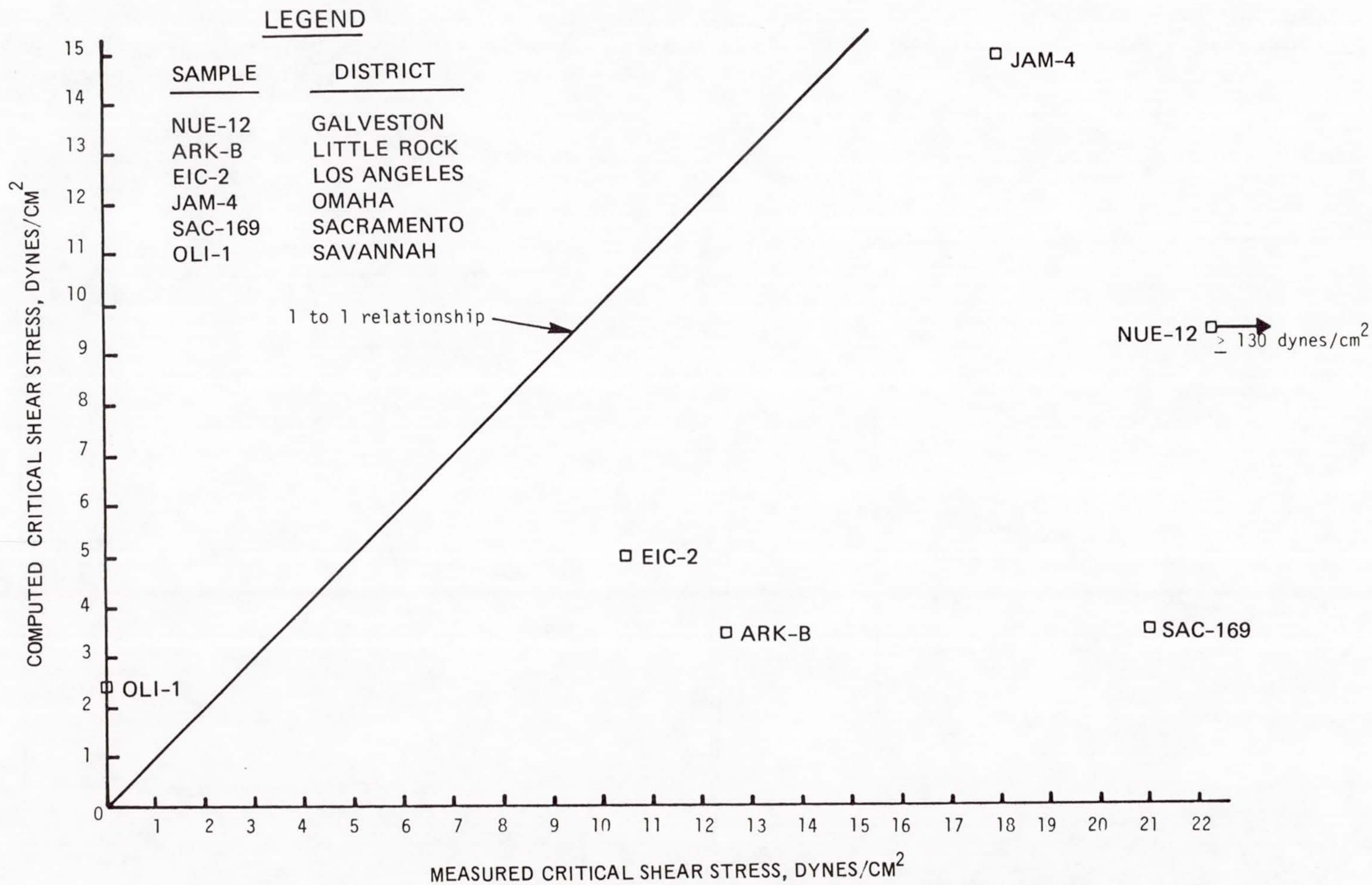


Figure C53. Predicted critical tractive shear stress from sodium adsorption ratio, dielectric dispersion, and soil pore fluid concentration versus measured critical tractive shear stress for saturated remolded soils with distilled water as eroding fluid (from Arulanandan, Gillogley, and Tully 1980)

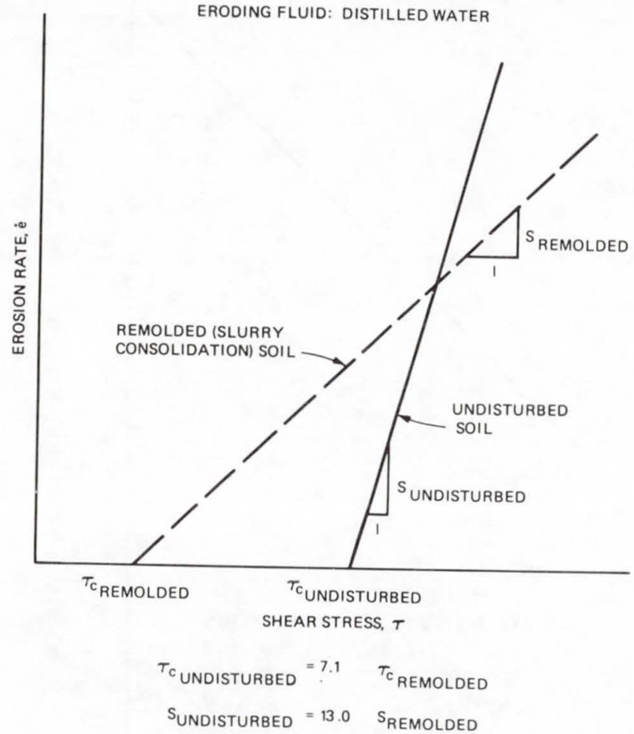


Figure C54. Average influence of remolding on critical tractive shear stress and rate of change of erosion rate for saturated soil using distilled water as eroding fluid (from Arulanandan, Gillogley, and Tully 1980)

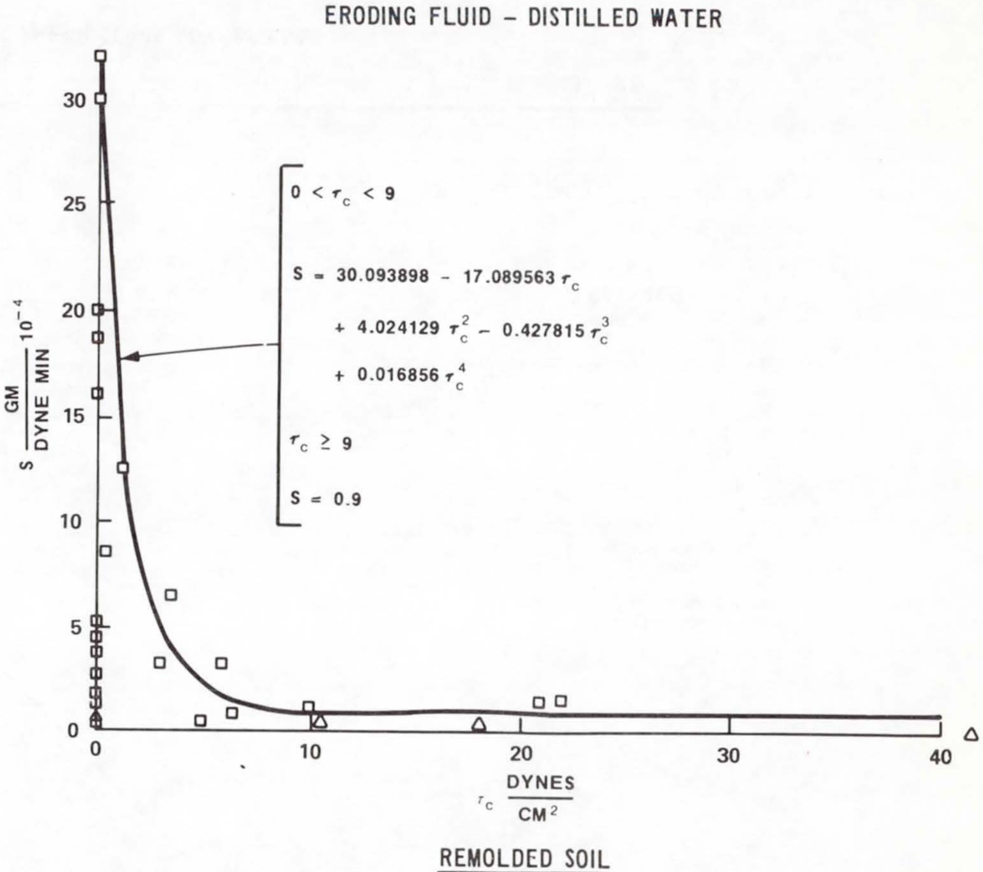
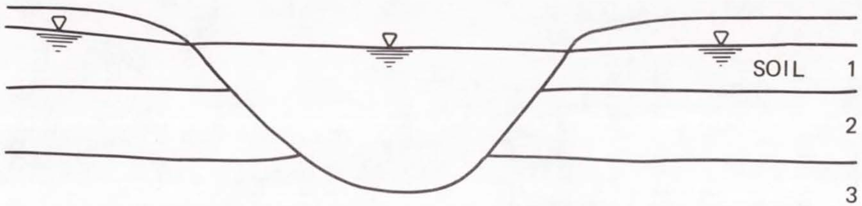
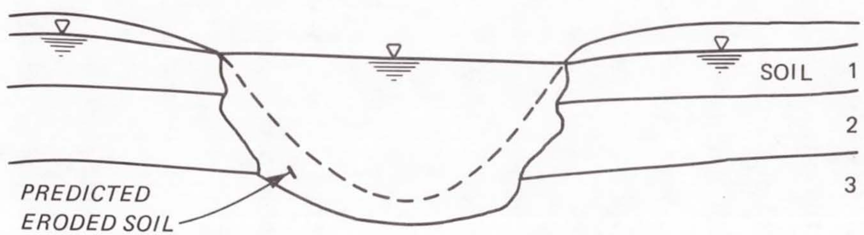


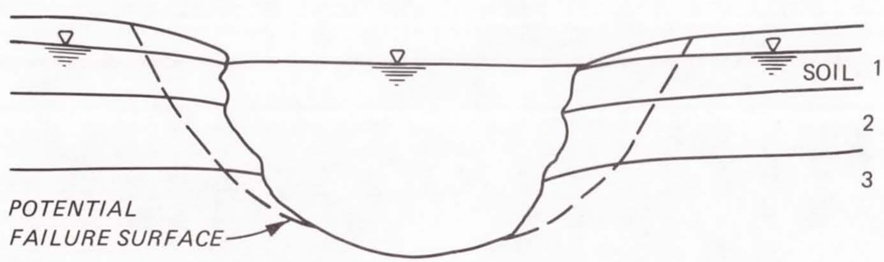
Figure C55. Relationship between rate of change of erosion rate and critical tractive shear stress for remolded soil soaked in distilled water and tested in the University of California, Davis, flume with distilled water as eroding fluid (from Arulanandan, Gillogley, and Tully 1980)



A. INITIAL CONDITIONS

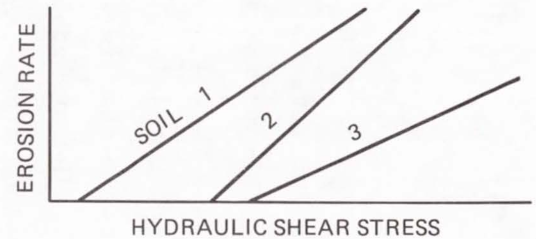


B. CONDITIONS AT SELECTED TIME

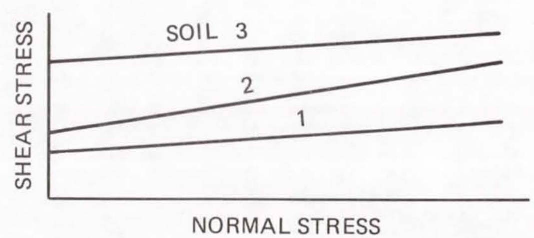


C. SLOPE STABILITY ANALYSIS FOR THE PREDICTED CONDITIONS AT THE SELECTED TIME

1. OBTAIN UNDISTURBED SOIL SAMPLES
2. DETERMINE EROSION RATE VERSUS HYDRAULIC SHEAR STRESS



3. DETERMINE STRENGTH PROPERTIES FOR SLOPE STABILITY ANALYSIS



4. PLOT CHANNEL PROFILE AT SELECTED TIME INTERVALS (SEE B)
5. COMPUTE SLOPE STABILITY FOR NORMAL WATER LEVEL AND RAPID DRAWDOWN (SEE C)

Figure C56. Procedure for evaluating streambank stability

PART III: GEOTECHNICAL RESEARCH FOR NEW METHODS AND TECHNIQUES FOR BANK PROTECTION

Research Plan

135. The planning objectives for this study were to conduct studies of various applications of new materials, construction methods, and techniques in geotechnical engineering for the protection of streambanks. Additionally, materials and construction techniques developed and used previously as temporary expedient-type surfacings, dustproofers, soil stabilizers, and film formers were also investigated as to their adaptability for restoring and protecting streambanks. Materials were selected, tested, and screened by laboratory tests, small test plots, channel model tests, and field tests. Placement of materials was made on small test areas to determine their suitability for construction using hand-labor methods and to identify any special techniques and equipment required for installation. Methods for securing and anchoring materials in place were investigated to ensure rapid placement of materials and prevent displacement by flood waters.

136. During this study, materials and techniques were investigated for applications to protect upper and lower banks on streams and rivers where there were considerable fluctuations in the depth of water. The various systems and material applications along with material descriptions, tests, test results, and recommendations covered in these investigations are discussed in subsequent paragraphs.

Evaluation of Materials

137. An investigation was conducted of spray-on stabilizers, metal landing mats, and expedient prefabricated membranes to determine their applicability for streambank protection. These materials and methods were developed previously for all-weather surfacings, waterproofers, and pavements.

Spray-on stabilizers

138. During construction or repair of streambanks, large upper

bank areas are stripped of their natural vegetation. Therefore, some means of protecting these denuded areas from erosion by wind and rainfall are needed until vegetation can be reestablished. Five spray-on type materials (Oldham 1979) were examined on field installations to determine if they were capable of controlling erosion during this period without having an adverse effect on the reestablishment of vegetation.

139. The materials examined included four manufactured in the United States and one material furnished by the U.S.S.R. These materials are described below:

- a. Aerospray 70 (U.S.) - a polyvinyl acetate, latex water emulsion that cures into a durable surface film.
- b. Soil Seal (U.S.) - a copolymer emulsion of acrylate and methacrylates that also cures into a durable surface film.
- c. DLR (U.S.) - an acrylic that forms a thin hard surface.
- d. Peneprime (U.S.) - a penetrating grade of cutback asphalt that penetrates into the soil and leaves a tough hard surface.
- e. Nerozin (U.S.S.R) - a dark brown fluid that is based on resin from the semichoking of fuel shale and caustobioliths (lignite, peat, etc.) and has adhesive properties.

140. Test plots using these materials were constructed on flat and sloping areas. Five test plots and a control plot (seeded with no spray-on material) were constructed on a flat area, and ten test plots and a control plot were constructed on a 1V on 4H slope. Various application rates of the different materials were used over Bermuda grass seed and fertilizer to determine the effectiveness of these materials in aiding the establishment of vegetation. Meteorological data and soil temperatures were collected and recorded periodically using automatic recording devices. These test plots were monitored from 24 April to 22 June 1978.

141. From these tests, it was observed that three of the materials tested, Aerospray 70, Soil Seal, and DLR, were effective in establishing vegetation, with Aerospray 70 and Soil Seal being the most effective in controlling erosion during the test period. These materials

showed no adverse effect on germination as the Burmuda grass in sections sprayed with these materials emerged and propagated better than that in the control plot. Aerospray 70 and Soil Seal should be incorporated into some of the Section 32 Program demonstration projects for field testing (Appendix A of Investigation Report 1 (Oldham 1979) gives the general guidelines on application rates and procedures), and spray-on stabilizers should be considered for general use to inhibit erosion while enhancing plant emergence and early growth.

Rigid and flexible materials

142. Expedient surfacing materials have been developed at the U. S. Army Engineer Waterways Experiment Station (WES) for use in forward military areas as landing surfaces for aircraft operations. Initial testing of these rigid and flexible surfacing materials (Styron 1979) was made at the WES in a hydraulic model flume to determine their effectiveness in protecting channel banks against erosion.

143. In the flume, sand banks of a sinuous channel were shaped and sloped approximately 1V on 2H. The bank area selected for protection was located along the outside edge of a curve in the channel, where erosion is usually most severe. The model channel was approximately 5.5 ft wide at the bottom, and the water was up to 1 ft deep. The channel slope averaged 0.0009 ft/ft. Discharges were successively increased, with each discharge being maintained for 1 hr in order to establish conditions under which the test materials failed. As the discharge was increased, the velocities associated with these flow conditions increased proportionally. The maximum discharge produced was 12.5 cfs. At the maximum discharge, the actual velocity measured near the toe (depth = 0.80 ft) was 4.2 fps. The sand channel was shaped, test materials placed, and then the flume was filled slowly to the desired depth. When the channel was full and the sand saturated, flows were initiated.

144. The rigid materials, a rolled aluminum mat panel weighing 2.0 psf and an M8A1 steel mat panel weighing 7.5 psf, were simulated using lightweight aluminum plates. The M8A1 steel mat panel and the

rolled aluminum mat panel were simulated by using 0.025- and 0.008-in.-thick aluminum plates, respectively. Individual sheets of each thickness were tied with copper wire to form rectangular sections large enough to surface bank areas approximately 2 by 6 ft. These sections were placed on the bank of the sand channel in the model. The bottom and side edges of each section were anchored with +1/2-in. crushed rock,* and 24 in. of crushed rock separated the two sections. Curved wires (hairpins), approximately 2-1/2 in. long, were used for anchors. The panels were subjected to various discharges and velocities both with and without a filter cloth (fine mesh nylon curtain backing) beneath them.

145. Seven membranes were placed along the streambank in the channel model and subjected to various discharges and velocities. These membranes are described below.

- a. T15 - vinyl-laminated coated nylon (impervious).
- b. T16 - neoprene-coated nylon (impervious).
- c. Bidim C-38 - direct-spun polyester filament.
- d. Mirafi 140 - two continuous filaments in random arrangement: 100 percent polypropylene and a polypropylene core surrounded by nylon sheath.
- e. Griff Weave 10 - reinforced plastic laminate consisting of a nonwoven grid of polyethylene ribbons (impervious).
- f. Griffolyn - reinforced plastic laminate consisting of a nonwoven grid of polyethylene ribbons (impervious).
- g. Sackurity Bag - vinyl-coated polyester.

146. In order to prevent ballooning of the very lightweight impervious Griffolyn and Griff Weave 10, 3-3/8-in.-long nails were forced through the membrane into the bank slope at intervals both parallel and perpendicular to the streamflow. The bottom and sides of each membrane were anchored with +1/2-in. crushed rock.

147. Based on the results of these tests, the following conclusions are believed warranted:

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* The +1/2-in. rock which passes the 3/4-in. sieve but is retained on the 1/2-in. sieve was used to simulate riprap.

a. Filters should be used beneath rigid protective materials to prevent erosion of streambanks.

b. Heavy, rigid materials were used successfully in this study, but actual costs ($5-$10/sq ft) of these materials for streambank protection may be considered excessive.

c. Anchoring systems are required for all materials used in the tests.

d. Pervious membranes, such as Bidim C-38, Mirafi 140, and Sackurity Bag, permitted the sand banks to erode.

e. Impervious membranes, such as T15 and T16 membranes, should prevent erosion of streambanks provided adequate anchoring systems are developed.

f. When compared with most streambank protection methods used today, membranes are the most cost-effective materials (Table C6).

148. It was recommended that field tests be conducted with prototype T15 and T16 membranes on actual streambanks to validate and verify construction techniques and methods for anchoring these materials. Three anchoring systems proposed for the field tests were: light-duty protection, the membrane blanket concept, as used in the channel model where the membrane would be secured with anchors placed in a 12- by 12-ft grid pattern; medium-duty protection, the membrane encapsulated soils layer (MESL) concept (Webster 1974) where 6 to 12 in. of encapsulated compacted soil is anchored to the streambank; and heavy-duty protection, a stepped MESL concept where 18 to 36 in. of encapsulated compacted soil would partially overlay each underlying layer. The maximum size for prototype test sections should be based on sizes of prefabricated membranes produced currently by commercial manufacturers and specifically that size found to be capable of being handled and placed rapidly by hand labor. Ideally, each section should be constructed in a dry environment from the top of the streambank to the toe and in approximately 50-ft widths along the bank. Each section should be separated by a suitable transition zone in order that the behavior of one section does not influence the adjacent section. Based on the availability of funds, and verification of anchoring systems discussed above, construction of the prototype tests should be undertaken during

the summer of 1979 on the Big Black River.

Grid confinement systems

149. Tests were conducted on aluminum grids to determine the suitability of these materials as a potential bank protection system (Spivey and Styron 1979). Specifically, tests examined a grid/vegetation system in combination as a possible means for controlling bank erosion. The system was evaluated for effectiveness and durability in controlling erosion, ease of placement, and cost. It was envisioned that this system might be employed where something more durable than vegetation, but less durable than riprap, was believed necessary.

150. An aluminum grid system made in a honeycomb design was used. Each section, 20 by 8 ft, was fabricated from 0.014-in.-thick aluminum sheets formed by bonding into 6-in.-wide cells that are 2 in. deep. Each section had a total weight of 27-1/2 lb or 0.17 lb/sq ft.

151. The test material was embedded on a sloped (1V on 4H) area that was open and unprotected. The area covered by the grid, as well as an equal area adjacent to the grid, was fertilized and seeded with rye grass on 25 October 1978. The grass began to germinate on 27 November 1978. In the area that had only rye grass for protection from water runoff, rills began to form on 30 November and continued during the observation period (1 November 1978 - 31 March 1979). The rills were 8 to 12 in. wide and deep. On 12 March 1979, however, the area with the embedded grid showed little or no erosion.

152. Based on the results of the investigation, it was concluded that:

- a. Aluminum grids with induced vegetation provide considerably more protection against erosion than vegetation used alone.
- b. Vegetation inhibits erosion considerably although in some cases grass growth alone may not be enough to stop all erosion.
- c. Denuded lean clay sloped as little as 1V on 4H will experience severe erosion if left unprotected.

153. The combination of a grid/vegetation system was recommended for transition areas where something more substantial than simply

vegetation growth is necessary and the more expensive erosion control measures are not justified.

Experimental Field Test Sites

154. As the results of model tests (Styron 1979), experimental field tests were conducted at Durden Creek and the Big Black River (Plate C1). In addition to the membranes (T15 and T16) recommended for field testing, two additional experimental membranes, Hypalon- (synthetic rubber) coated 5x5 polyester scrim and Hypalon-coated 10x10 polyester scrim, were selected (White 1981). Riprap sections were used as the standards for comparison purposes. Two filter fabrics, Bidim C-34 and C-38 (spunbonded continuous polyester filaments) were selected for use beneath the riprap sections. Table C7 presents the costs of membranes, filter fabrics, riprap, and other materials used for these field tests. Some of these costs are different from the costs of the same materials listed in Table 1 (Styron 1979, and Spivey and Styron 1979). These variations in cost resulted because of differences in the quantities procured, size of sections, availability of materials, or economic conditions that existed at the time of procurement.

Durden Creek test site

155. The bank along Durden Creek (see Plate C2 for site location) selected for the installation of test items had been eroded previously by streamflows (Photos C1 and C2). Banks in this area were identified as silt (ML). A view of the creek test area covered by water after a heavy rain is shown in Photo C3. This area had been observed to remain underwater for as long as 6 hr. The water level fluctuated as much as 7 ft during periods of heavy rain, and this condition existed many times during the period the test materials were monitored. The stream in this area was curved to the extent that it permitted the construction of a diversion channel to drain the water away from the area where materials were to be installed (Photo C4). The materials were installed along the creek bank from just below low-water level to approximately 2 ft over

the top bank. Seven different test items (Photo C5 and Plate C3) were installed with each item being approximately 17 ft wide (parallel to streamflow) and 20 ft long (perpendicular to streamflow). These items included: (a) a stair-stepped MESL with T15 membrane as the encapsulating material (Item 1) installed along the bank in an area where the bank was caving vertically; (b) four "blanket" items, the T15 (Item 2), T16 (Item 5), Hypalon 5x5 (Item 4), and 10x10 (Item 3) membranes draped over the slope of the bank and anchored in ditches with the ditches being partially backfilled with soil and covered with sandbags; (c) a MESL item with the T15 membrane as the encapsulating material (Item 6); and (d) Bidim C-34 filter fabric covered with riprap (Item 7). The riprap-covered filter blanket was used as the standard for comparing the performance of all test materials. Photo C5 shows the material emplaced and anchored.

156. Construction of the project was initiated in June 1979 and was completed in August 1979. Photo C6 presents a view of the test area after the dams were removed.

157. Observations, monitoring, and data collected. The performance of these materials was monitored from August 1979 through December 1980. Various test data including photographs (Photos C7-C9), cross sections (Plate C4), stream velocities, and discharge measurements were collected. Stream velocities up to 3.91 fps and discharges up to 280 cfs were recorded.

158. The materials on all items at the Durden Creek test site performed satisfactorily during the period they were monitored. There were only two problem areas with the materials. Some of the membrane (T15) of the second step of the stepped item (Item 1) "ballooned" out (Photo C6). This condition occurred after the first few times the water rose in the creek. The "ballooned" area was approximately 3 ft wide and 8 ft long (Photo C9) at the end of the monitoring period. No other damage to this item resulted nor did this condition cause any damage to the other items. The other problem area involved the sandbags that were used in the anchor ditches and for ballast on the membrane. The bag

material deteriorated, and rain as well as streamflows eroded the sand from the deteriorated bags. The first problem was eliminated later at the Big Black River test site by having the membrane stretched tight on each step, and the ballast of sacked concrete was placed at the face of each step to prevent "ballooning" of the membrane. The second problem was solved by using sacked concrete mix in the anchor ditches and areas where ballast was required. The bags of sand in the Durden Creek test site anchor ditches were replaced in October 1980 with bagged concrete mix, and the ballast of the sacked concrete mix was placed at the face of each step in the stepped MESL item (Item 1). The air entrapped beneath the membrane (Items 5 and 6, Photo C8) during high water levels in the creek did not cause any problem. In fact, it helped to raise the height of the top bank and prevented the water from overtopping the bank in this area. As the water receded, the membrane flattened to the slope of the bank. The bank in the test area of Durden Creek remained stable as a result of the protection from the materials.

159. Cost. The total cost of the experimental test on Durden Creek was $31,300, which included $6,800 for materials. The costs were high due to the large number of heavy rains that occurred during construction. As the result of heavy rains, water overflowed the temporary dams that blocked the creek from the test area and flooded the test site. Consequently, trapped water between the dams had to be pumped out each time the creek flooded the site.

Big Black River test site

160. The permit for installation of materials for full-scale field testing on the Big Black River (see Plate C5 for test location) was approved on 28 September 1979. All test materials were procured expeditiously; then construction on the project was initiated on 9 October 1979, and material installation was completed on 3 November 1979.

161. The view of the right bank of the Big Black River looking upriver before materials were installed (Photo C10) is located approximately at the midpoint of the test area. The test site was in a

straight reach of the river. Note that most of the bank is denuded of vegetation and trees as a result of rapid and frequent large fluctuations of river stages. Small trees and some vegetation can be seen near the top bank. The major portion of the bank is sloped approximately 20 deg (note the slope indicator (33 percent) in the left portion of the photograph). The uppermost part of the bank was vertical with a height that varied from 6 to 10 ft. In situ soils identified at the surface and down to a depth of 3 ft consisted primarily of the following: (a) top bank - clay (CL), (b) 20 ft below top bank - sandy clay (CL), and (c) 40 ft below top bank - sandy clay (CL).

162. Test materials emplaced on the test site are shown in Photo C11 and Plate C6. The slope of the entire test area was approximately 30 percent after shaping for installation of the materials. All test items, which were approximately 22 ft wide (parallel with streamflow) and 42 ft long (perpendicular to streamflow), are identified as follows:

Item 1 - riprap placed on Bidim C-38 filter fabric. (Since heavier riprap was required at this test site, the stronger and more puncture resistant C-38 fabric was used.)

Item 2 - blanket of Hypalon-coated 5x5 polyester scrim membrane.

Item 3 - blanket of Hypalon-coated 10x10 polyester scrim membrane.

Item 4 - blanket of T15 membrane.

Item 5 - blanket of T16 membrane.

Item 6 - MESL constructed with T15 membrane.

Item 7 - riprap placed on Bidim C-38 filter fabric (standard of comparison item).

Item 8 - stepped MESL constructed with T15 membrane.

163. The bank area below the toe anchor ditches approximately 6.5 ft wide and 200 ft long was covered with 10-12 in. of riprap placed on Bidim C-38 fabric. The distance from the lower edge of this riprap to the normal low water level was about 20 ft. The edges of Items 2 through 5, which were draped over the bank as "blankets," were anchored in ditches. Sand drains were constructed in the anchor ditches between

these items to relieve the hydrostatic pressure that might develop behind these materials and cause them to balloon and blow out during rapid drawdowns of the river. The sand drains consisted of poorly graded (SP) sand encapsulated with Bidim C-38 filter fabric. Approximately 6 in. from the bottom of the encapsulated sand-filled ditches, perforated plastic drainpipe wrapped with Bidim material was placed for the full length of the drainage ditch. Near the end of each ditch, the polyvinyl chloride plastic perforated pipe was closed with a perforated cap and covered with washed gravel to allow the water to drain into the river without causing localized erosion of the banks. The encapsulated sand was used to fill the ditches to within 12 in. of the surface; at this point, soil obtained locally was backfilled, compacted, and then overlaid with riprap. Plate C6 (sheet 3 of 9) shows the materials emplaced and anchored.

164. The areas upstream and downstream of the test section contained holes where the bank had washed and sloughed prior to installation of the test materials. Photo C12 shows a typical example of this condition along the riverbank.

165. Observations, monitoring, and data collected. The performance of these materials was monitored from November 1979 through December 1980. Cross sections in Plate C7 were obtained prior to emplacement of test items and during the period materials were observed. Plates C8 and C9 present gage readings and discharge measurements as well as discharge measurements for typical wet, moderate, and dry years that occurred before the project year 1980.

166. Two piezometers were located in the vicinity of the test area, one about 10 ft from the top bank adjacent to Item 2, and the other about 200 ft southwest of the top bank of the test area. Table C8 presents the level readings obtained periodically from the piezometers. As the river rose, the groundwater level was usually within a foot or so of the level of the river. However, the groundwater level did not recede as quickly as the level in the river.

167. In mid-November 1979, the river began a slow rise with some

fluctuation until the latter part of November, at which time it rose to the top bank during the first week in December (Photo C13). The water level fell slowly after reaching the top bank and then fluctuated from about half-bank down to below the toe of the materials until 10 January 1980. From this time until the latter part of February, the water level was such that at least 50 percent or more of the test bank was covered with water because of heavy local and upstream rains. During the latter part of February 1980, the water level dropped slowly several days, and then there was a sudden drop of 10.7 ft in 48 hr. The water level at this time was below the toe of the materials. Some shifting and sloughing of the bank occurred at the toe of the materials as well as along the river in areas not associated with the test area (Photos C14-C16). No damage to the test items was observed even though riprap at the toe anchor ditches had shifted.

168. The water level remained below the toe of the materials for about 10 days. Then a sustained slow rise began, and eventually the water overtopped the bank because of heavy local and upstream rains (Photo C17, 31 March 1980). The maximum discharge and stage recorded during the period experimental materials were on the bank exceeded those recorded previously for the past 10 years (1970-1980). The water remained at this level or near the top bank for about 15 days. A slow fall began until the level reached about half-bank. The level fluctuated between half-bank and top bank until 9 May 1980 (Photo C18). Between 9 and 12 May, the water level dropped 13.9 ft (72-hr period). Photo C19 illustrates the condition of the test area on 12 May. Photos C20 and C21 show the areas above and below the test area, respectively. The test materials in all items were damaged as a result of this drop in the water level. The bank behind the test materials was saturated; when it slipped and slumped toward the river, the test materials became unanchored at the toe. The riprap on Item 7 (standard for comparison) also shifted considerably toward the river.

169. The water level remained at or below the toe of the test materials until 19 May. Then a slow rise began until about two thirds of the test bank was covered on 26 May 1980. The level then dropped

14.2 ft in 72 hr at which time the water was below the toe of the materials. Only minor additional shifting of the bank occurred as a result of this rapid drawdown.

170. The water level during the summer months rose only twice to the point where one third of the bank was covered with water. These changes in the water level were slow and caused no additional damage to the bank. Photo C22 shows the condition of the bank in July 1980. Photo C23 is a view of the riverbank approximately 3 miles below the test area where shifting and settlement of the bank occurred around a bridge pier on Mississippi Highway 27.

171. The level of the water remained well below the toe of the materials until late October 1980. Then the level rose until about one third of the bank was covered with water. The fluctuations between the one-third bank level and below the toe of the test items continued to the end of December 1980.

172. Cost. The initiation of the project was delayed for several weeks as the result of a hurricane that caused heavy rains in the area and high stages of the river. Normally, membrane-type materials are installed rapidly with a minimum labor force and equipment; however, because of the short time remaining before the normal rainy season occurred in the area, additional labor and several pieces of heavy equipment were used to expedite completion of all test items before sustained high stages occurred in the river. Therefore, additional labor and equipment contributed to the higher-than-normal cost of installation of these test materials. The material cost was $24,800, and the total cost for installation of all test items was $52,600.

Findings

173. The following findings are believed warranted as the result of geotechnical research for new methods and techniques for bank protection:

a. Spray-on stabilizers that were used to inhibit erosion enhanced plant emergence and early growth. Aerospray 70 and Soil Seal were most effective in establishing vegetation for top bank applications. These materials showed no adverse effect on germination as Bermuda grass in these sections emerged and propagated better when used with these materials than when used alone.

b. Heavy, rigid expedient surfacing materials were used successfully in this study; however, present costs ($5-$10/sq ft) of these materials for streambank protection were considered excessive. Filters used beneath rigid protective materials prevented erosion of streambanks. Anchoring systems are required for all materials used.

c. When compared with most streambank protection methods used today, membranes are the most cost-effective materials available. Impervious membranes, such as T15 and T16 membranes, prevent erosion of streambanks provided adequate anchoring systems are used. Pervious membranes, such as Bidim C-38, Mirafi 140, and Sackurity Bag, permitted sand banks to erode.

d. Aluminum grids with induced vegetation provided considerably more protection against erosion than vegetation used alone. Vegetation inhibits erosion considerably although in some cases grass growth alone may not be enough to stop all erosion.

e. All membrane materials used in the small-stream tests (Durden Creek) performed satisfactorily in protecting the bank from erosion. Each type of installation of the membrane materials performed satisfactorily, i.e., blanket, stepped MESL, and MESL items.

f. All membrane materials evaluated at the river test site (Big Black River) performed satisfactorily by protecting the bank from failure during normal flows of the river. However, when heavy rains produced flood conditions, the test site was submerged, areas adjacent to the top bank became saturated, and unstable bank conditions occurred along vast reaches of the river. Flood stages of the river were followed by rapid drawdowns that produced scouring and extensive bank failures not only in the immediate area of the test site but throughout the river basin.

g. Membrane materials protected streambanks and riverbanks from failure as long as the banks remained stable. It is doubtful that any existing materials or construction techniques will prevent bank failures for extended periods of time when exposed to flood conditions that saturate banks followed by rapid drawdown conditions such as those produced by the Big Black River.

Recommendations

174. Spray-on soil stabilizers, particularly the synthetic latex and emulsion materials which were the most effective, should be considered for use to aid the initial establishment of vegetation on denuded top bank areas. Aluminum grids in conjunction with induced vegetation are recommended when more expensive erosion control measures are not justified, but where something more substantial than vegetation alone is required.

175. Impervious membrane materials, such as laminated vinyl-coated nylon, are easily constructed with hand labor and light equipment, are readily available from commercial sources, are cost-effective, and should be considered suitable for erosion protection by private landowners and others having limited resources available. The blanket method should be considered where the banks require a light protective surface to prevent erosion by current and wave action, and the MESL slabs as a medium-type protection when loose surface conditions exist on banks. The stepped MESL can be used as heavy duty protection in areas where severely eroded and caved banks are nearly vertical as this method eliminates extensive grading and shaping of the banks.

<u>References</u>

Oldham, J. C. 1979. "Section 32 Program, Streambank Erosion Control Evaluation and Demonstration, Work Unit 4 - Research on Soil Stability and Identification of Causes of Streambank Erosion; Evaluation of Spray-on Stabilizers for Bank Protection," Investigation Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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Webster, S. L. 1974. "Construction of MESL Demonstration Road at Fort Hood, Texas, 1972," Miscellaneous Paper S-74-13, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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Table C6

In-Place Cost Summary
for the Streambank Protection Methods

Streambank Protection Method	Cost/Unit, $	Unit
	1976 Costs*	
Stone riprap	3.50 - 30.00	yd^3
Concrete pavement	90 - 125	100 ft^2
Articulated concrete mattresses	84	100 ft^2
Transverse dikes:		
Pile board	40 - 55	lin ft
Untreated clumps	1400 - 2300	clump (three 60-ft piles)
Stone	40 - 65	lin ft
Fences	25 - 50**	lin ft
Asphalt mix (upper bank)	60 - 80	yd^3
Kellner jack field	16 - 47†	lin ft
Vegetation (grass)	1.15 - 1.49 (500 - 650)	100 ft^2 (acre)
Gabions	40 - 47	yd^3
Erosion-control matting	5.56 - 7.22 (0.50 - 0.65)	100 ft^2 (yd^2)
Bulkheads	14 - 105	lin ft
	1978 Costs	
T15	0.41	ft^2
T16	0.44	ft^2
M8A1 mat	5.00††	ft^2
Rolled aluminum mat	10.00††	ft^2

Note: This table is the same as Table 2 (Styron 1979) and Table 1 (Spivey and Styron 1979).

* Cost figures supplied by Corps of Engineers Divisions and Districts.

** Range applies to new materials.

† Range applies to used and new materials.

†† Estimated costs.

Table C7

Materials and Cost

Material	Size	Weight oz/yd^2	Thickness in.	Cost (1979)
T15 vinyl-coated nylon	50' x 50'	19.1	0.0261	$ 0.29/ft^2
T16 neoprene-coated nylon	50' x 50'	16.0	0.0194	0.5775/ft^2
Hypalon-coated 5x5 polyester scrim	50' x 50'	33.4	0.0370	0.535/ft^2
Hypalon-coated 10x10 polyester scrim	50' x 50'	31.0	0.0340	0.585/ft^2
Bidim C-34	13' 10" x 984'	7.7	0.081	0.099/ft^2
Bidim C-38	17' 5" x 984'	8.1	0.093	0.124/ft^2
Rock (riprap)	*	--	--	21.00/ton
Sand	--	--	--	5.06/ton
Sandbags	18" x 26"	**	--	0.324/bag
Sakrete	80-lb bag	--	--	2.10/bag

* Limestone aggregate size

a. Durden Creek test site:

Standard Square Mesh, in.	Cumulative, % passing
7	100
6	80-100
5	45-65
4	0-20

The riprap used at Durden Creek was already on hand at the WES. It was procured for $10.66/ton in 1975.

b. Big Black River test site:

125 - 300 lb - 10% maximum

6 - 125 lb - 80% maximum

Spalls under 6 lb - 10% maximum

The cost shown in the table for the riprap is for the material used at the Big Black River test site.

** Ten-ounce weight burlap fabric.

Table C8

Piezometer and River Stage Data

Date	Piezometer P_1, ft (msl)*	Piezometer P_2, ft (msl)	Big Black River Test Site Gage ft msl	Big Black River, Bovina Gage, ft msl**
11/07/79	29.0 (83.5)	24.1 (86.5)	87.5 (E)†	93.0
11/27/79	10.5 (102.0)	10.2 (100.4)	105.4	110.7
12/04/79	3.4 (109.1)	††	112.3	122.3
12/11/79	8.7 (103.8)	††	103.2	108.2
12/12/79	13.8 (98.7)	7.9 (102.7)	96.8	99.9
12/17/79	11.0 (101.5)	7.4 (103.2)	100.8	106.9
12/18/79	11.6 (100.9)	7.7 (102.9)	99.8	106.0
12/20/79	16.5 (96.0)	10.4 (100.2)	94.0 (E)	100.5
12/26/79	16.0 (96.5)	11.8 (98.8)	95.5 (E)	102.1
12/31/79	16.3 (96.2)	11.3 (99.3)	95.0 (E)	101.8
01/02/80	16.5 (96.0)	11.6 (99.0)	95.0 (E)	101.7
01/07/80	18.8 (93.7)	13.2 (97.4)	94.0 (E)	99.5
01/14/80	6.7 (105.8)	4.5 (106.1)	106.5	111.6
01/15/80	7.0 (105.5)	4.4 (106.2)	106.0	111.7
01/18/80	7.1 (105.4)	4.6 (106.0)	105.8	111.9
02/04/80	6.4 (106.1)	3.6 (107.0)	105.8	111.7
02/12/80	5.1 (107.4)	2.7 (107.9)	107.0	112.8
02/15/80	5.0 (107.5)	2.4 (108.2)	107.3	114.1
02/22/80	8.7 (103.8)	4.8 (105.8)	102.7	108.6
02/26/80	21.5 (91.0)	14.4 (96.2)	92.5 (E)	96.5
02/28/80	22.5 (90.0)	15.5 (95.1)	91.5 (E)	95.7
02/29/80	23.0 (89.5)	16.3 (94.3)	90.5 (E)	95.5
03/05/80	20.9 (91.6)	15.3 (95.3)	92.0 (E)	97.1
03/14/80	8.1 (104.4)	7.4 (103.2)	106.0	----
03/22/80	1.5 (111.0)	††	111.9	122.0
03/31/80	‡	‡	114.1	123.8
05/05/80	4.5 (108.0)	1.9 (108.7)	108.1	114.9
05/09/80	7.5 (105.0)	3.3 (107.3)	105.4	111.4
05/12/80	20.6 (91.9)	12.4 (98.2)	91.0 (E)	97.5
05/13/80	21.9 (90.6)	14.4 (96.2)	90.0 (E)	96.6
05/27/80	8.2 (104.3)	6.9 (104.3)	106.0	109.2
06/02/80	24.5 (88.0)	16.9 (93.7)	88.0 (E)	94.7
06/05/80	25.6 (86.9)	18.2 (92.4)	87.0 (E)	94.0
06/13/80	27.6 (84.9)	20.1 (90.5)	86.0 (E)	93.1
06/26/80	19.8 (92.7)	19.6 (91.0)	93.0 (E)	103.2
07/02/80	9.1 (103.4)	8.4 (102.2)	105.0 (E)	111.5
07/08/80	25.4 (87.1)	13.3 (97.3)	90.0 (E)	94.6
07/11/80	26.9 (85.6)	20.3 (90.3)	88.0 (E)	93.4
08/01/80	27.7 (84.8)	21.6 (89.0)	87.5 (E)	93.1
08/15/80	29.3 (83.2)	23.8 (86.8)	87.0 (E)	92.5
08/25/80	30.2 (82.3)	24.6 (86.0)	85.0 (E)	91.9
09/10/80	30.7 (81.8)	25.3 (85.3)	85.0 (E)	91.8
09/24/80	31.4 (81.2)	26.1 (84.5)	84.5 (E)	91.4
10/10/80	31.0 (81.5)	26.4 (84.2)	84.0 (E)	91.8
11/05/80	25.0 (87.5)	20.3 (90.3)	89.0 (E)	94.4

* P_1 located about 10 ft from top bank adjacent to Item 2. P_2 located about 200 ft southwest of the top bank of the test area. Numbers given represent distances from ground level to groundwater level. Number in ( ) is mean sea level (msl) water level. P_1 and P_2 at ground level are 112.5 and 110.6 ft msl, respectively.

** Bovina gage located at mile 61.7; gage at test site is located at approximately mile 53 above mouth of river.

† River stage estimated as lowest staff gage level was set at 96.0 ft msl.

†† No reading taken, piezometer surrounded by water.

‡ Piezometer covered with water.

Photo C1. General view (looking downstream) of creek area before installation of test materials (note sloughing of bank)

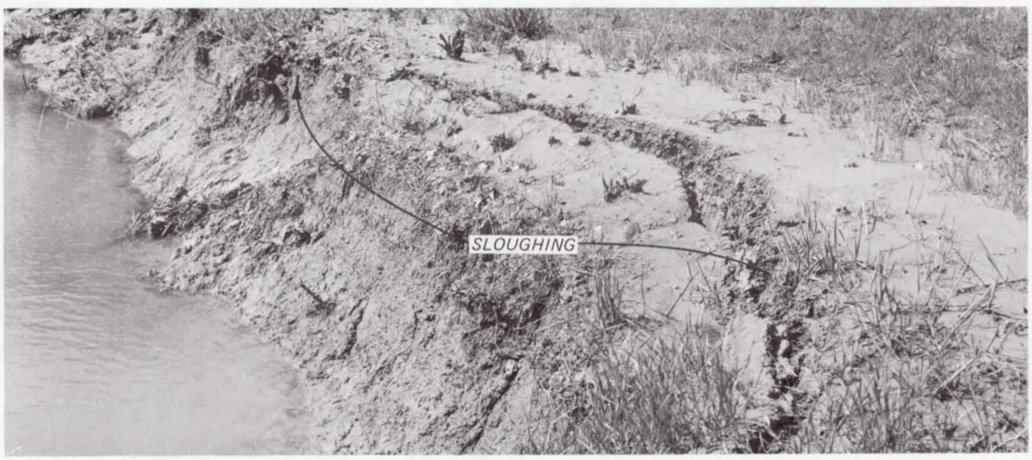


Photo C2. Closeup view (looking downstream) of maximum attack (note sloughing of bank)

Photo C3. View (looking downstream) of test area after a heavy rain

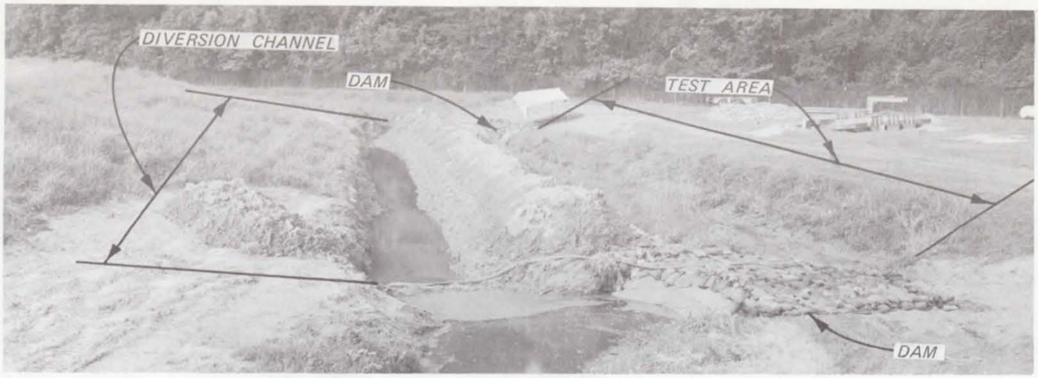


Photo C4. Diversion canal

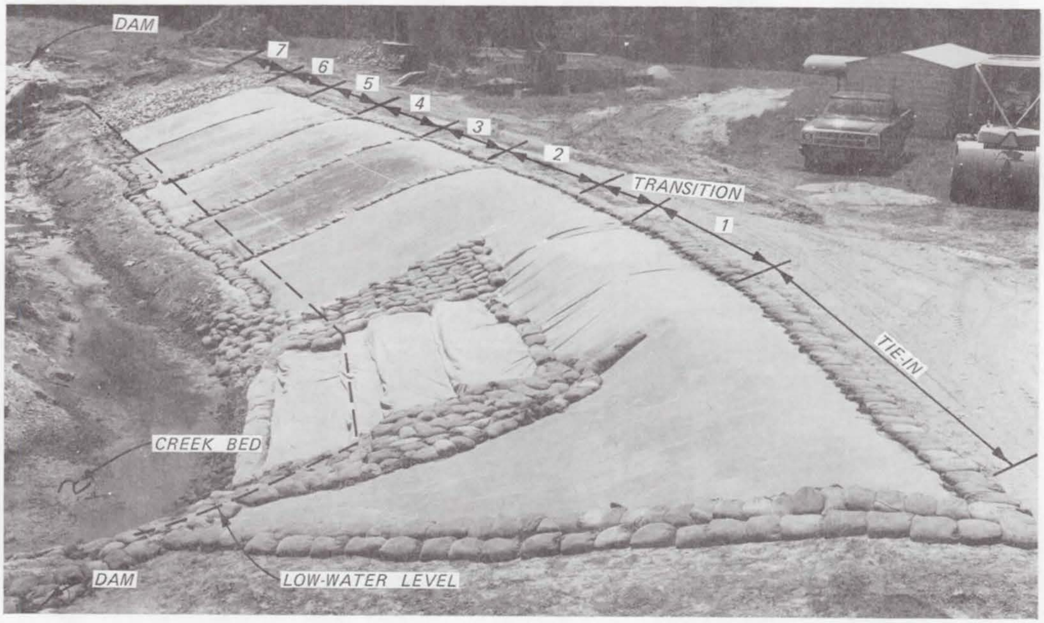


Photo C5. View (looking downstream) of test materials installed prior to removal of dams at each end of test area

Photo C6. View (looking downstream) of test area with water in creek channel

Photo C7. View (looking downstream) of test area during rain and high water level in creek (January 1980)

Photo C8. View (looking upstream) of test area during rain and high water level in creek (January 1980) (note membrane raised up in Items 5 and 6 because of air being entrapped)

Photo C9. View (looking downstream) of test area (September 1980)

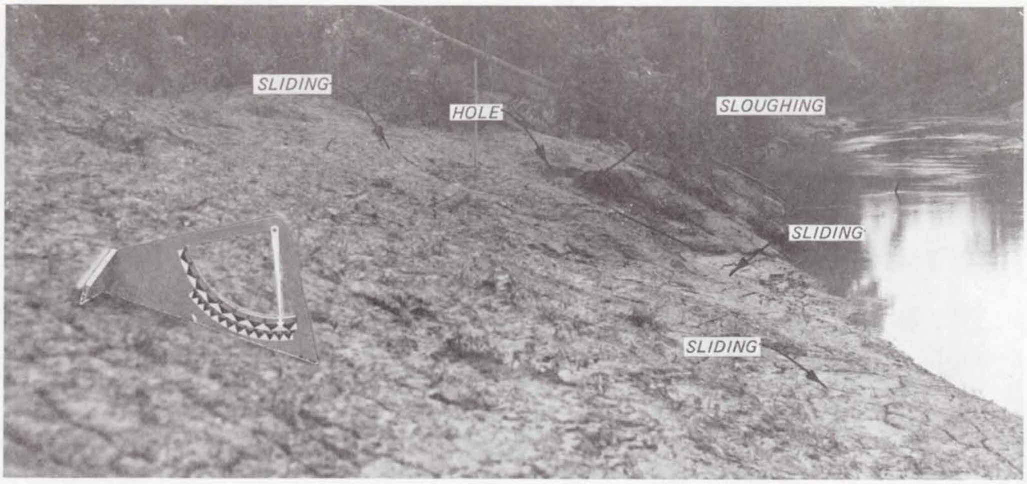


Photo C10. View looking upriver before installation of materials for bank protection

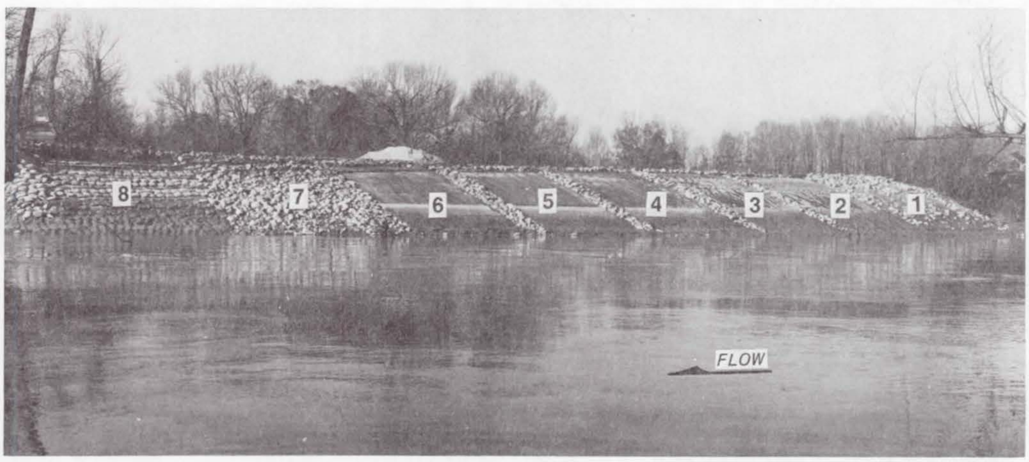


Photo C11. View from river of completed test area with water at toe of test materials

Photo C12. View of area below test materials where bank had sloughed and washed prior to the installation of the materials

Photo C13. View looking downstream from the top bank with water at the top bank

Photo C14. View (looking upriver) of bank below test area (note areas of shifting and sloughing)

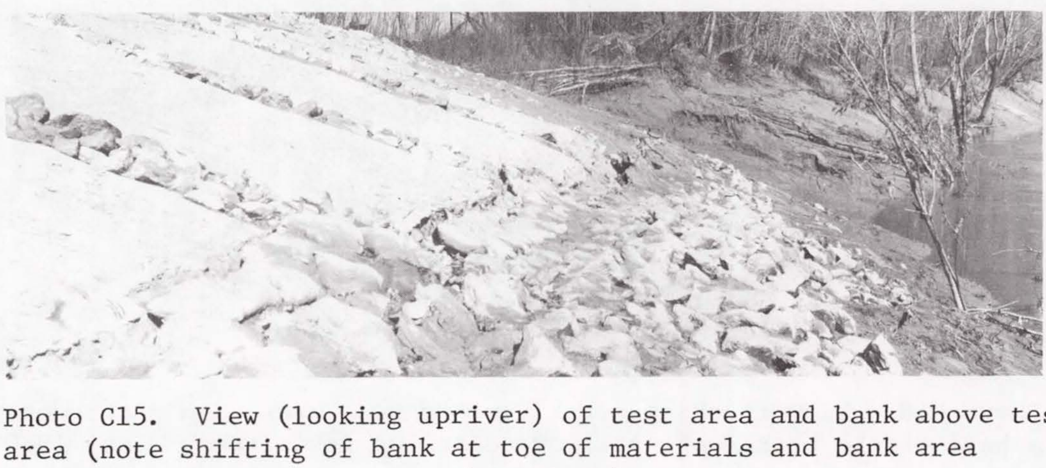


Photo C15. View (looking upriver) of test area and bank above test area (note shifting of bank at toe of materials and bank area above test)

Photo C16. View (looking downriver) of bank below test area (note shifting and sloughing of bank on both sides of the river)

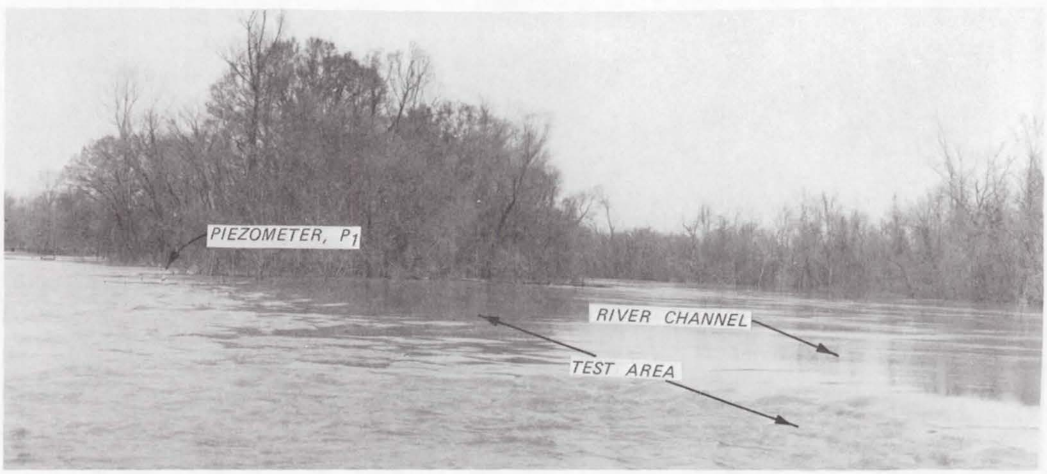


Photo C17. View (looking upriver) of test area covered by 2 ft o water, 31 March 1980

Photo C18. View (looking downriver) of test area with water covering half of the bank (note silt deposited on test items, 9 May 1980)

Photo C19. View (looking downriver) of test area with water level below toe of test materials, 12 May 1980

Photo C20. View (looking upriver on bank) of sloughing and sliding of bank due to sudden drop in water level of river, 12 May 1980

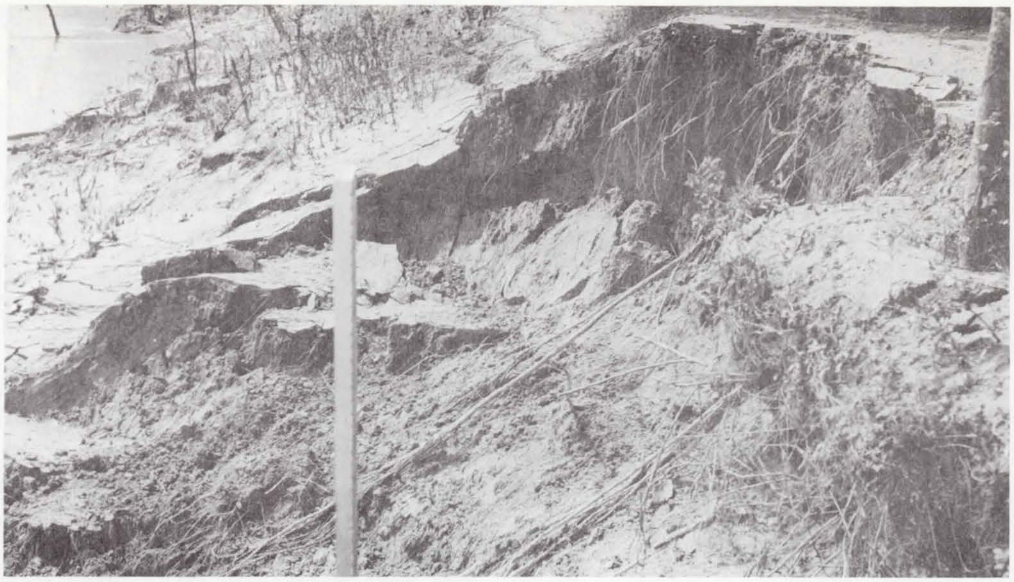


Photo C21. View (looking downriver) of sloughing and sliding of bank due to a sudden drop in the water level of the river, 12 May 1980

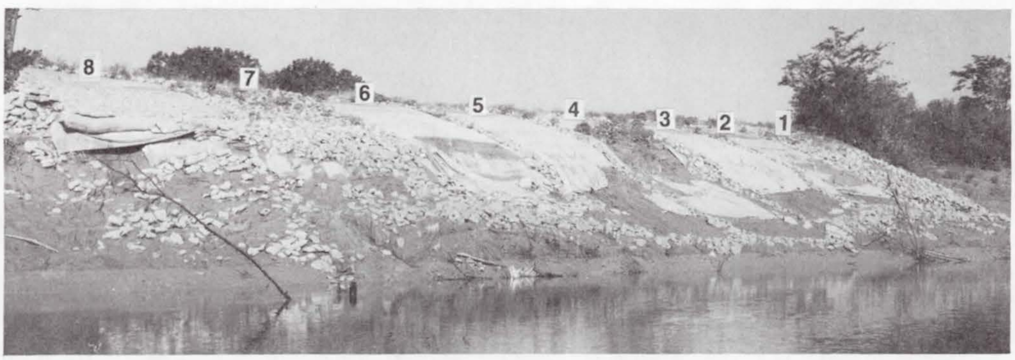


Photo C22. View (from river) of test area, July 1980

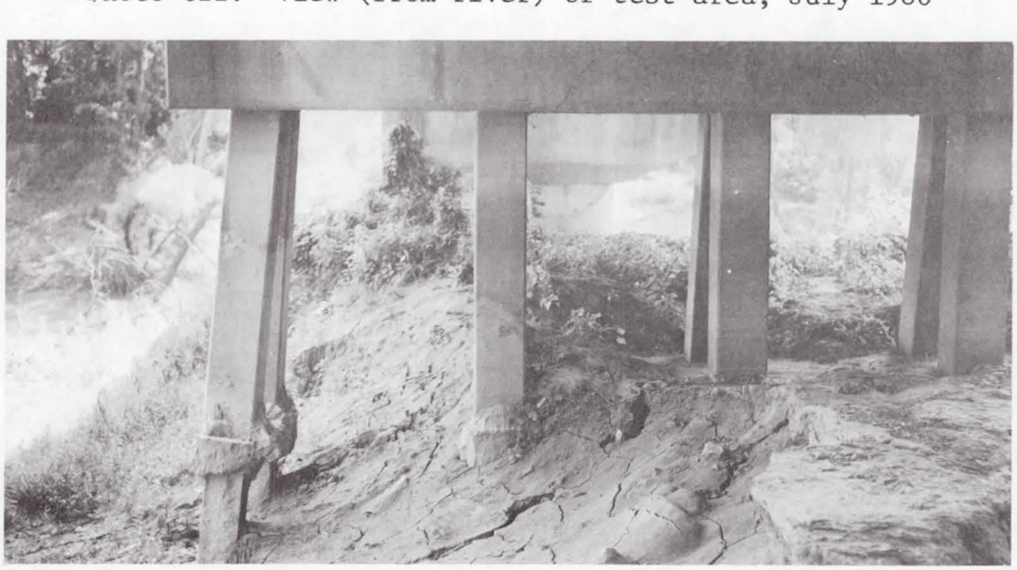
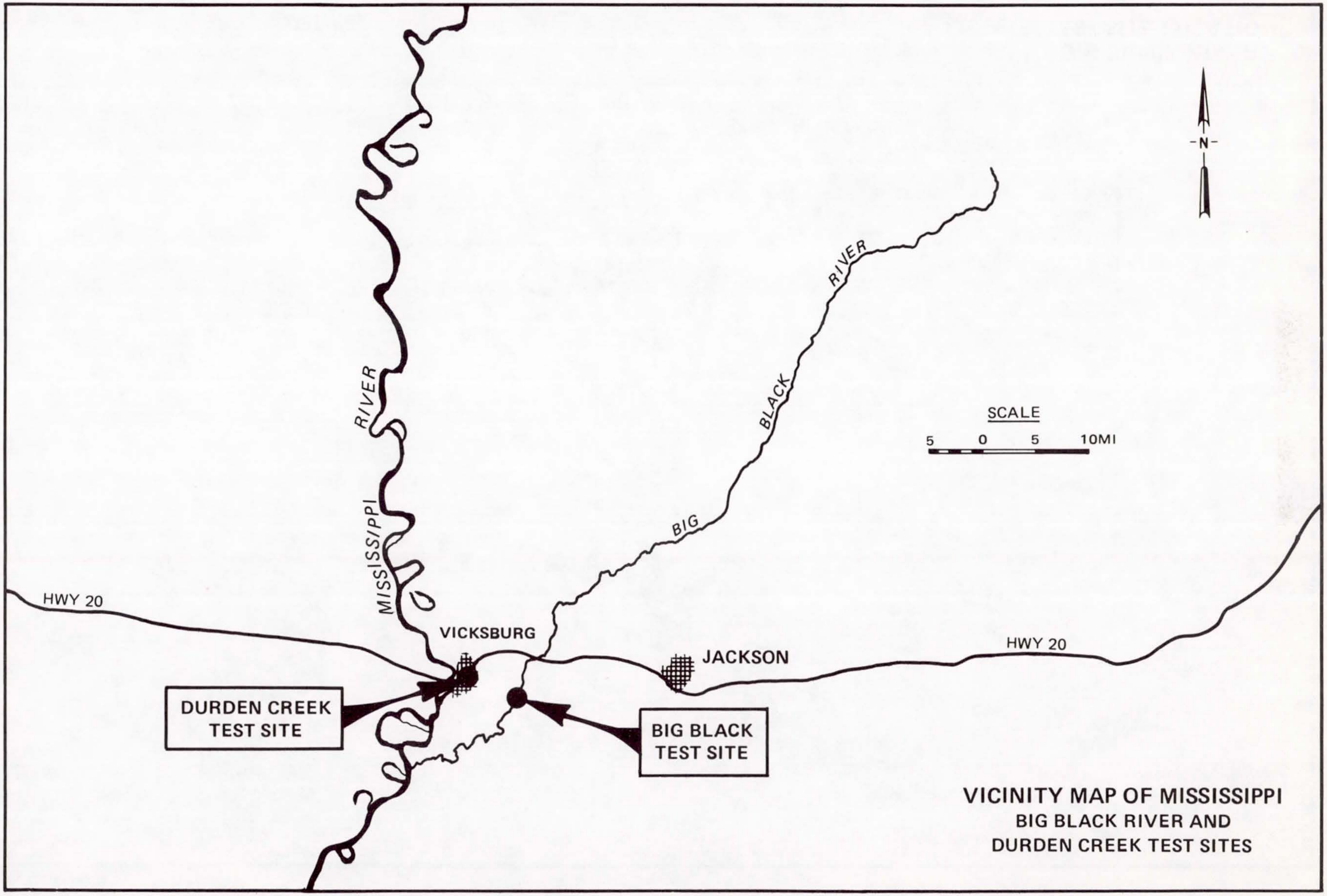


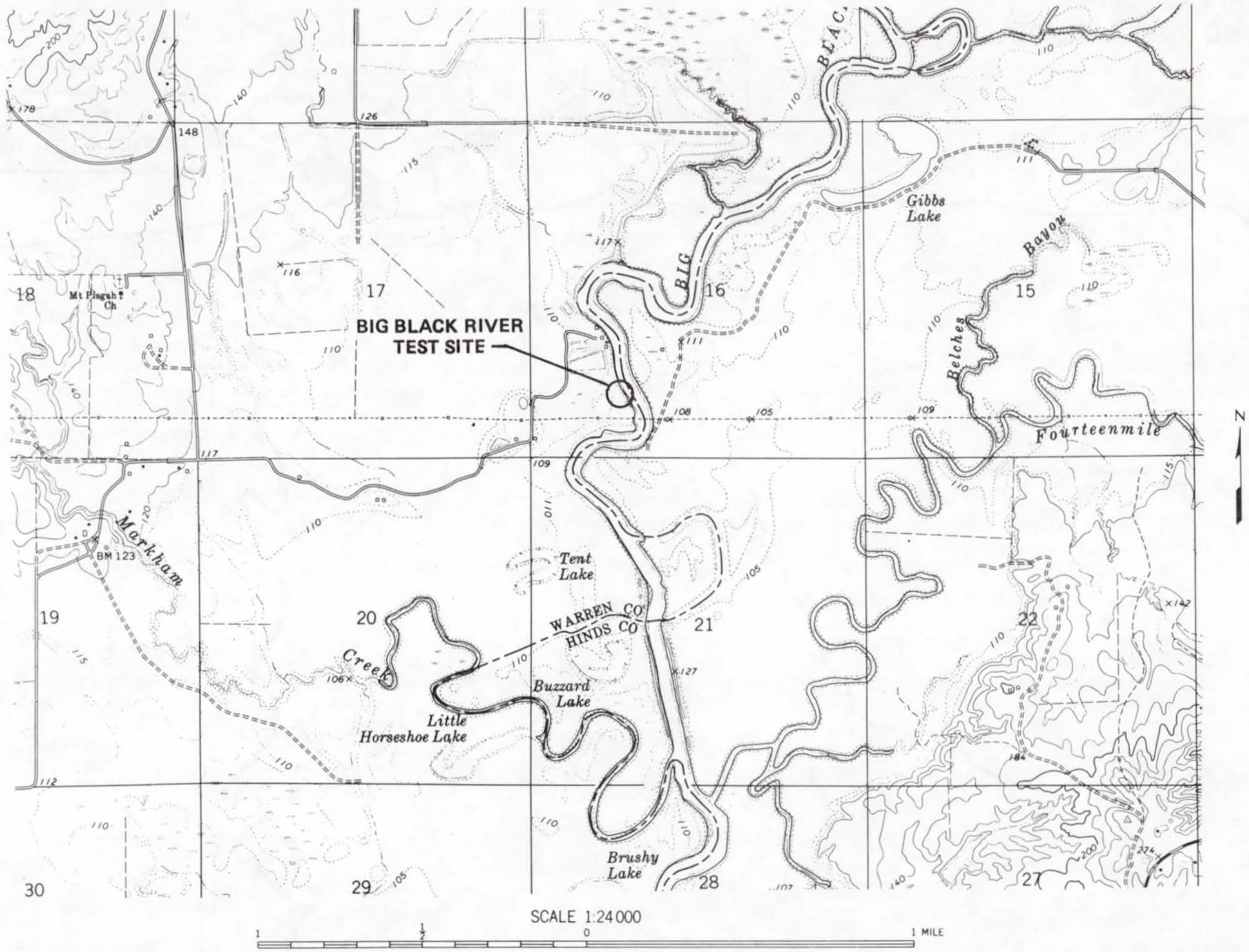
Photo C23. View of bank area that had shifted and washed approximately 3 miles below the test area around a Mississippi Highway 27 bridge pier



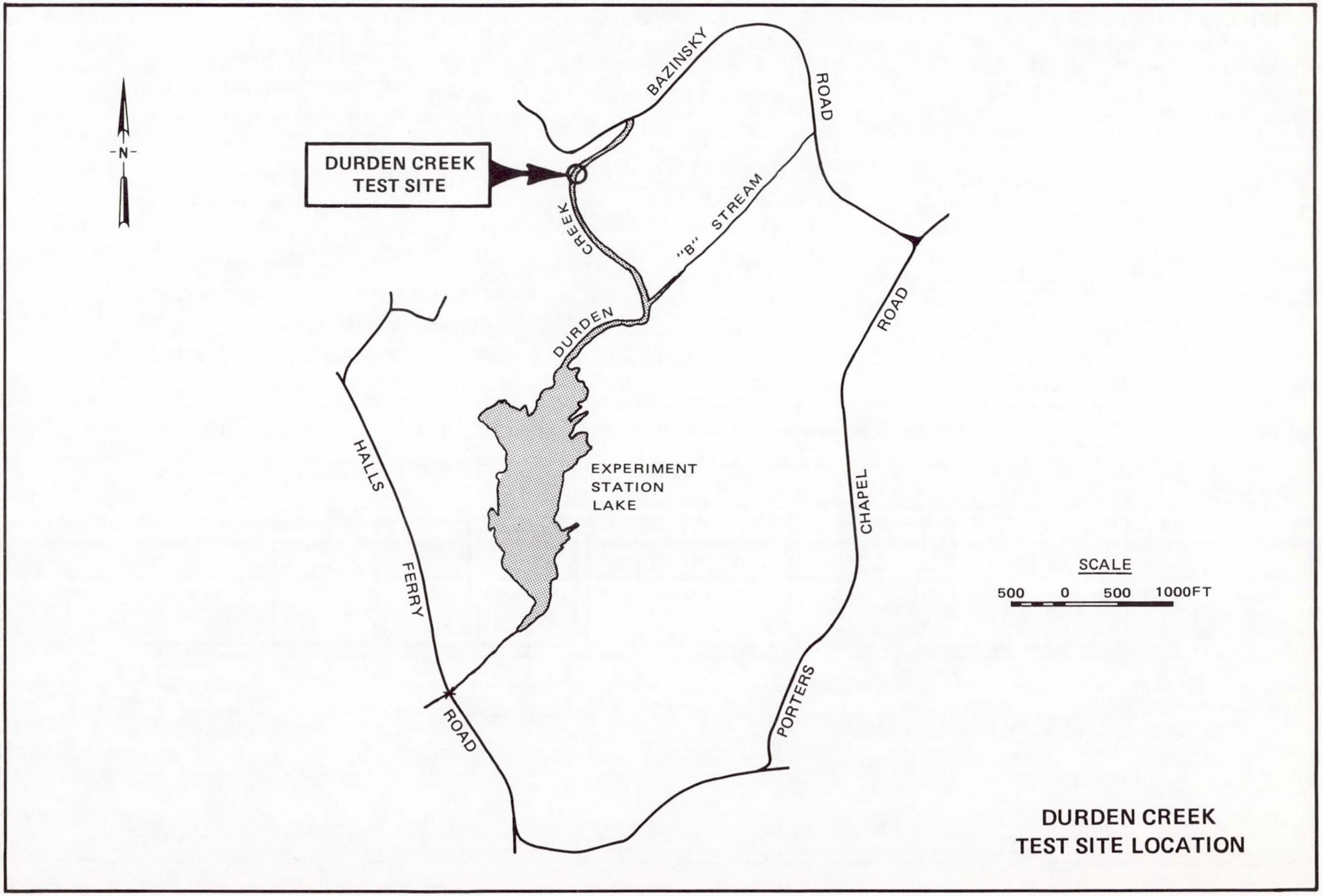
VICINITY MAP OF MISSISSIPPI
BIG BLACK RIVER AND
DURDEN CREEK TEST SITES

PLATE C1

PLATE C2

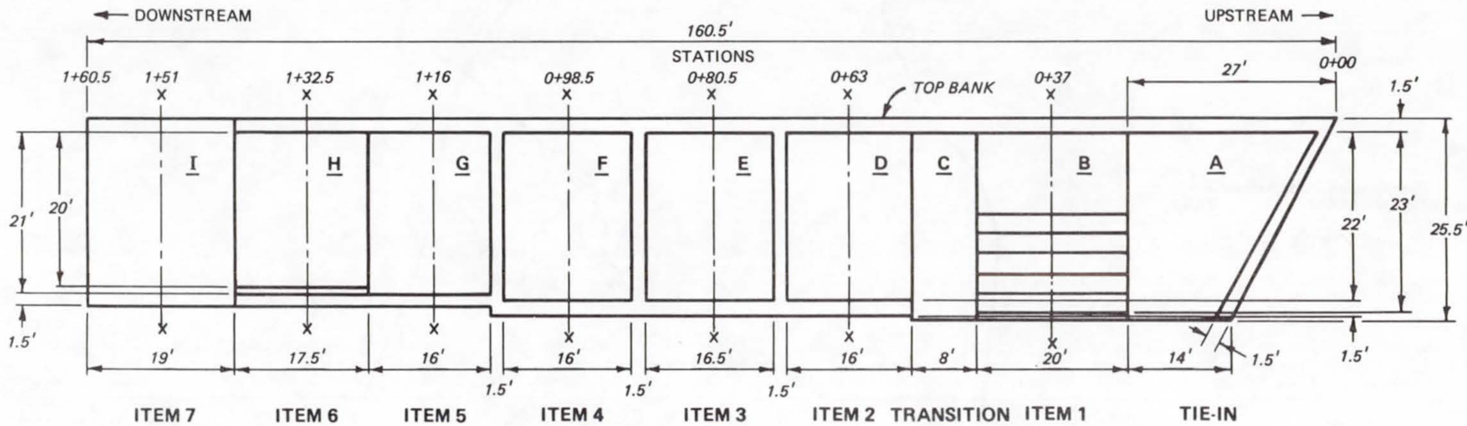


BIG BLACK RIVER TEST SITE LOCATION



DURDEN CREEK
TEST SITE LOCATION

PLATE C3



PLAN

LEGEND

A. T-15 MEMBRANE TIE-IN TO TEST ITEMS (SEE SHEET 2)

B. ITEM 1 – STEPPED T-15 MEMBRANE MESL (SEE SHEET 3)

C. T-15 MEMBRANE AND SAND BAG TRANSITION (SEE SHEET 4)

D. ITEM 2 – T-15 MEMBRANE (SEE SHEET 4)

E. ITEM 3 – HYPALON 10 x 10 MEMBRANE (SEE SHEET 5)

F. ITEM 4 – HYPALON 5 x 5 MEMBRANE (SEE SHEET 5)

G. ITEM 5 – T-16 MEMBRANE (SEE SHEET 6)

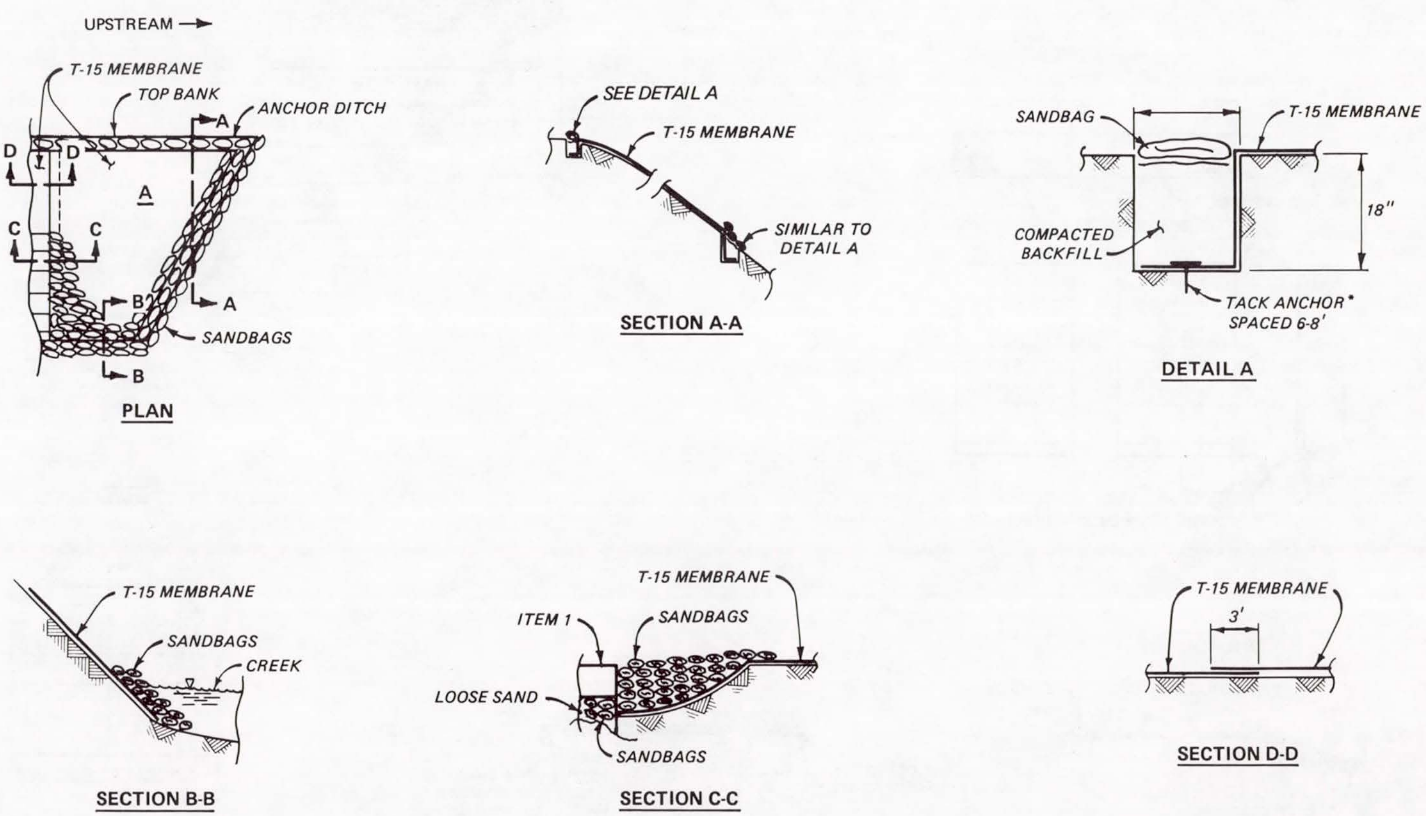
H. ITEM 6 – T-15 MEMBRANE MESL (SEE SHEET 6)

I. ITEM 7 – RIPRAP ON BIDIM C-34 FABRIC (SEE SHEET 7)

X—- -—X CROSS-SECTION DATA POINTS

NOTE: NO SCALE ON ANY OF THE SHEETS

STREAMBANK EROSION STUDY
DURDEN CREEK
TEST SECTION LAYOUT



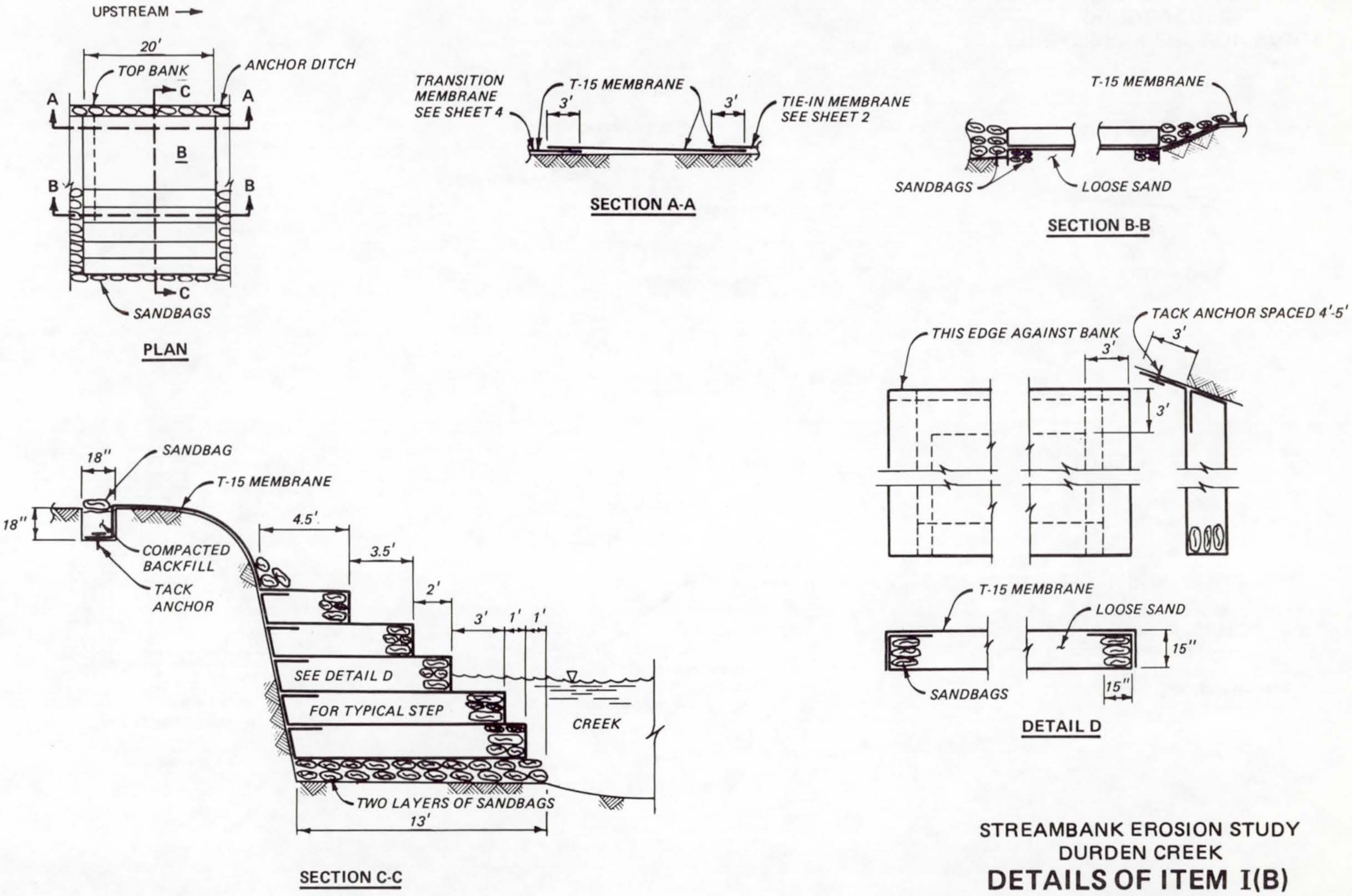
*TACK ANCHOR – ¾" REBAR, 12" LONG, 8" DIAMETER STEEL CAP

STREAMBANK EROSION STUDY
DURDEN CREEK

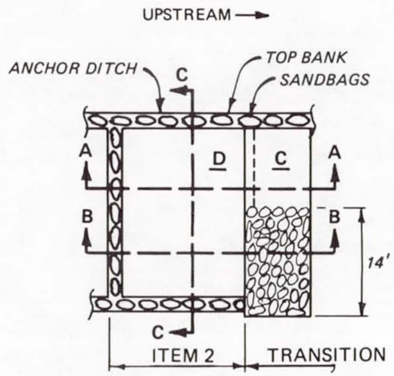
DETAILS OF T-15 MEMBRANE TIE-IN TO TEST ITEMS (A)

PLATE C4 (SHEET 2 OF 7)

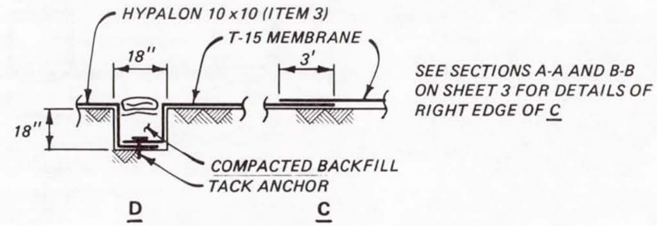
PLATE C4 (SHEET 3 OF 7)



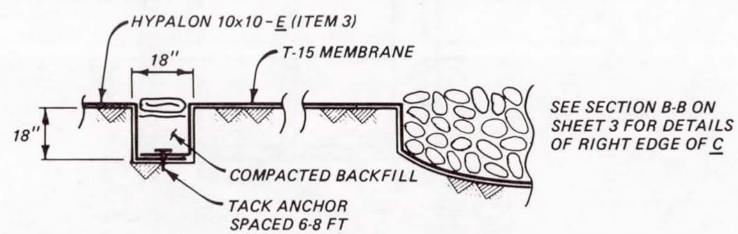
STREAMBANK EROSION STUDY
DURDEN CREEK
DETAILS OF ITEM I(B)
STEPPED T-15 MEMBRANE MESL



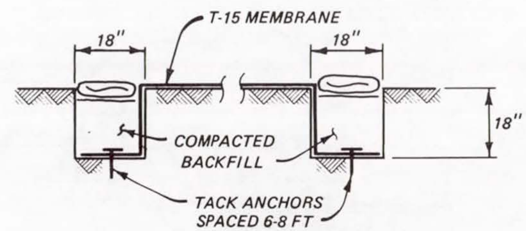
PLAN



SECTION A-A



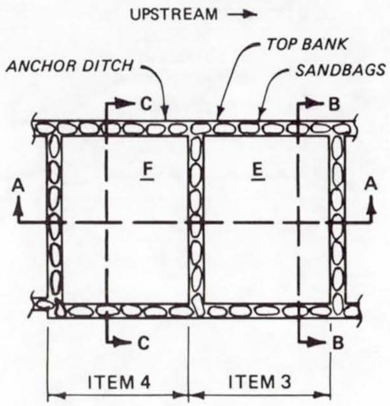
SECTION B-B



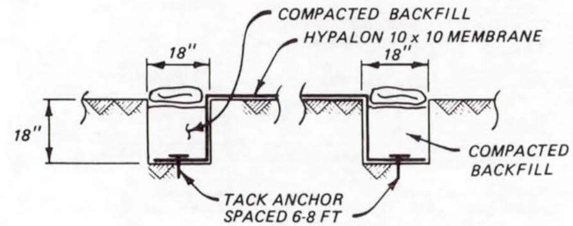
SECTION C-C

STREAMBANK EROSION STUDY
DURDEN CREEK

DETAILS OF T-15-SANDBAG TRANSITION AND ITEM 2(D) T-15 MEMBRANE BLANKET



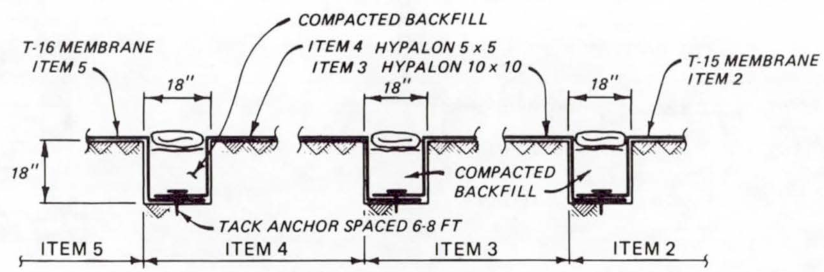
PLAN



SECTION B-B

SECTION C-C

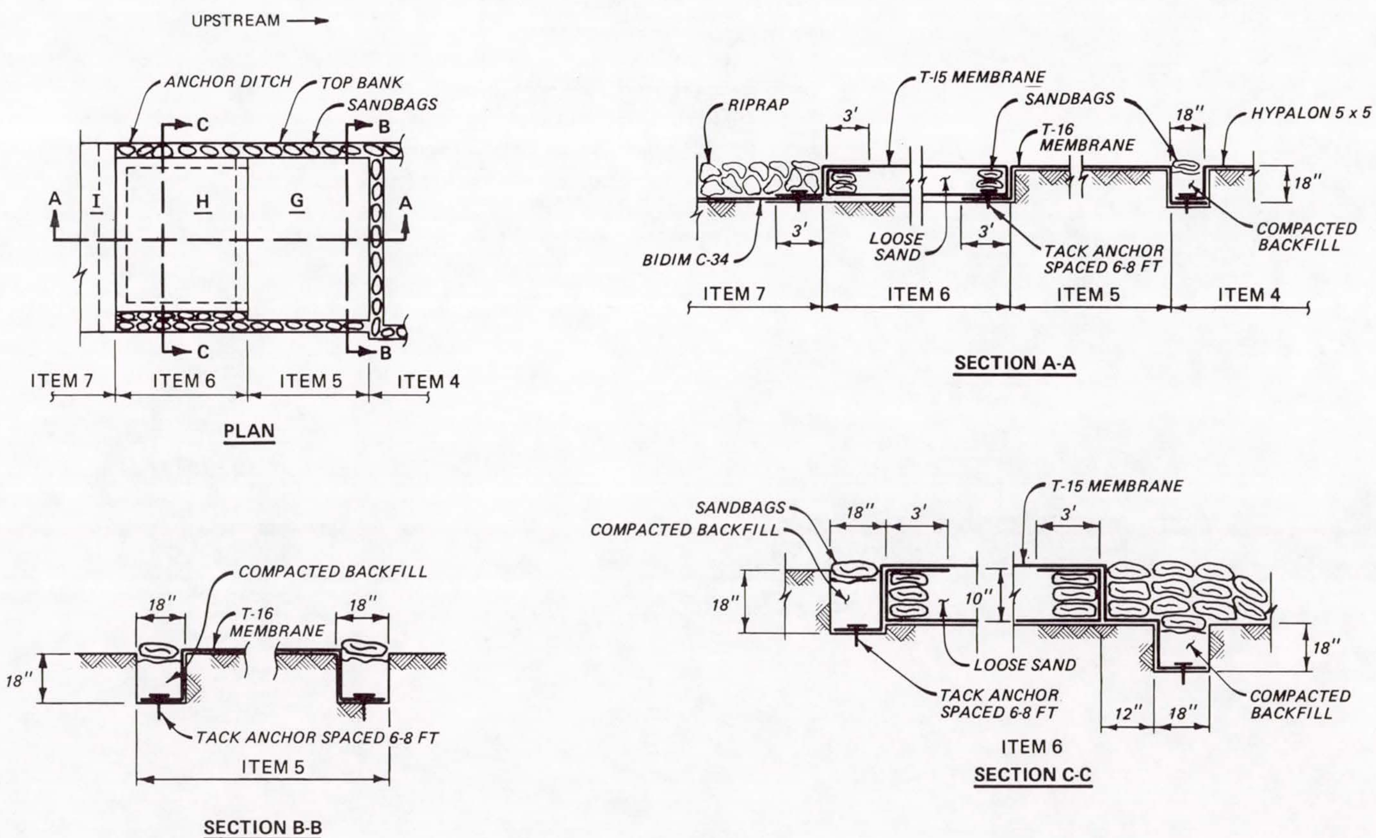
SAME AS SECTION B-B EXCEPT MEMBRANE IS HYPALON 5 x 5



SECTION A-A

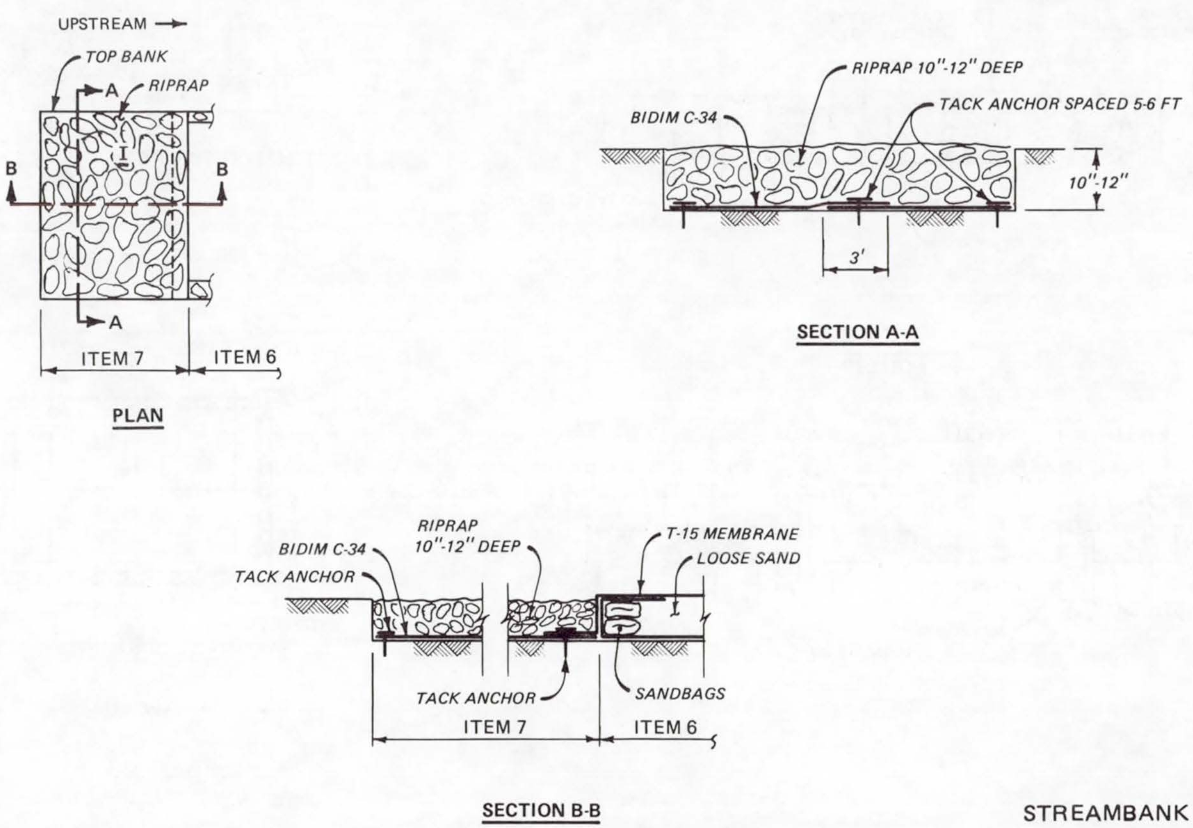
STREAMBANK EROSION STUDY
DURDEN CREEK

DETAILS OF ITEMS 3(E) and 4(F)
HYPALON MEMBRANE BLANKETS



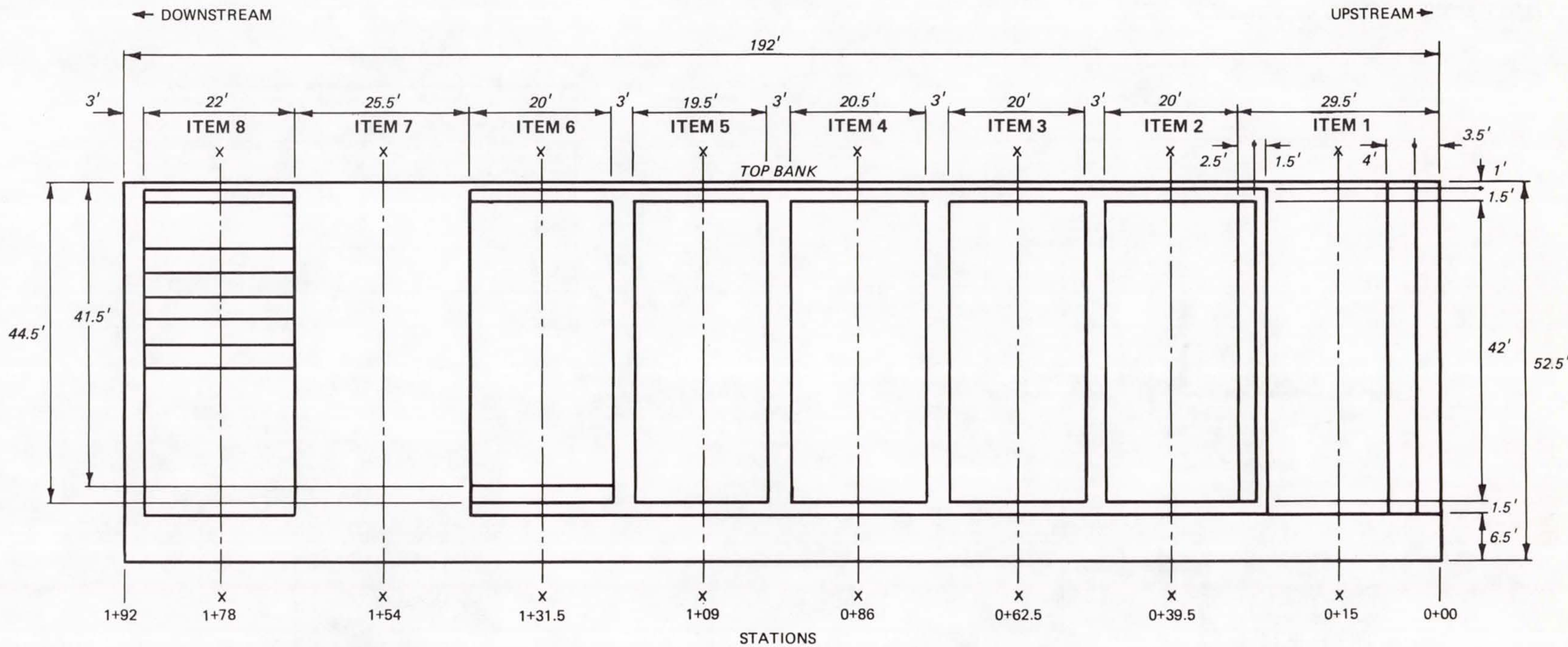
STREAMBANK EROSION STUDY
DURDEN CREEK
DETAILS OF ITEMS 5(G) and 6(H)

PLATE C4 (SHEET 6 OF 7)



STREAMBANK EROSION STUDY
DURDEN CREEK

DETAILS OF ITEM 7(I)
RIPRAP ON BIDIM C-34



PLAN

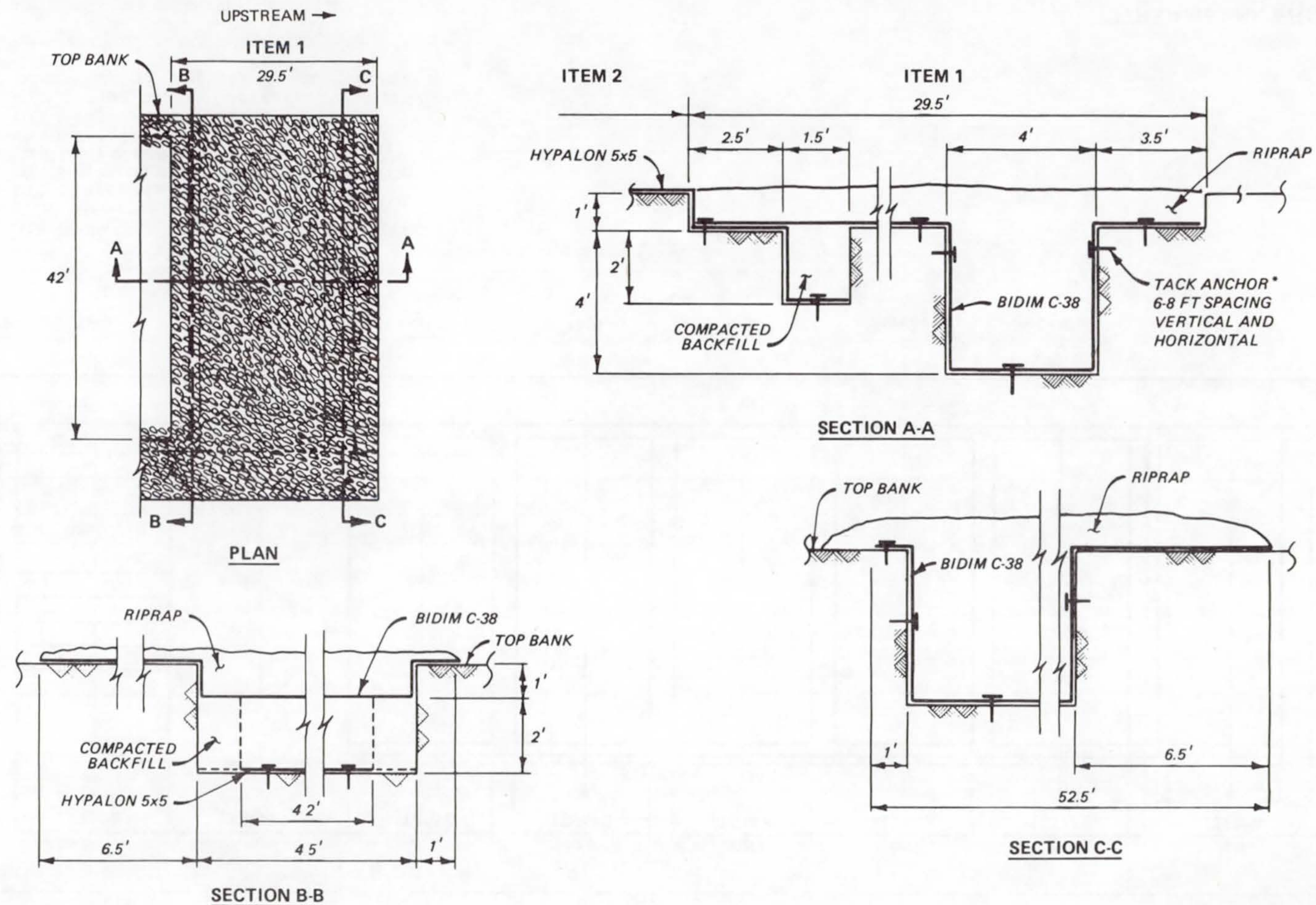
LEGEND

ITEM 1 RIPRAP ON BIDIM C-38 FABRIC–(SEE SHEET 2)
TIE-IN TO TEST ITEMS
ITEM 2 HYPALON 5x5 MEMBRANE–(SEE SHEET 3)
ITEM 3 HYPALON 10x10 MEMBRANE–(SEE SHEET 4)
ITEM 4 T-15 MEMBRANE–(SEE SHEET 4)
ITEM 5 T-16 MEMBRANE–(SEE SHEET 4)
ITEM 6 T-15 MEMBRANE MESL–(SEE SHEET 5)
ITEM 7 RIPRAP ON BIDIM C-38 FABRIC–(SEE SHEET 7)
ITEM 8 STEPPED T-15 MEMBRANE MESL–(SEE SHEET 8)

X—·—X CROSS-SECTION DATA POINTS

NOTE: NO SCALE ON ANY OF THE SHEETS

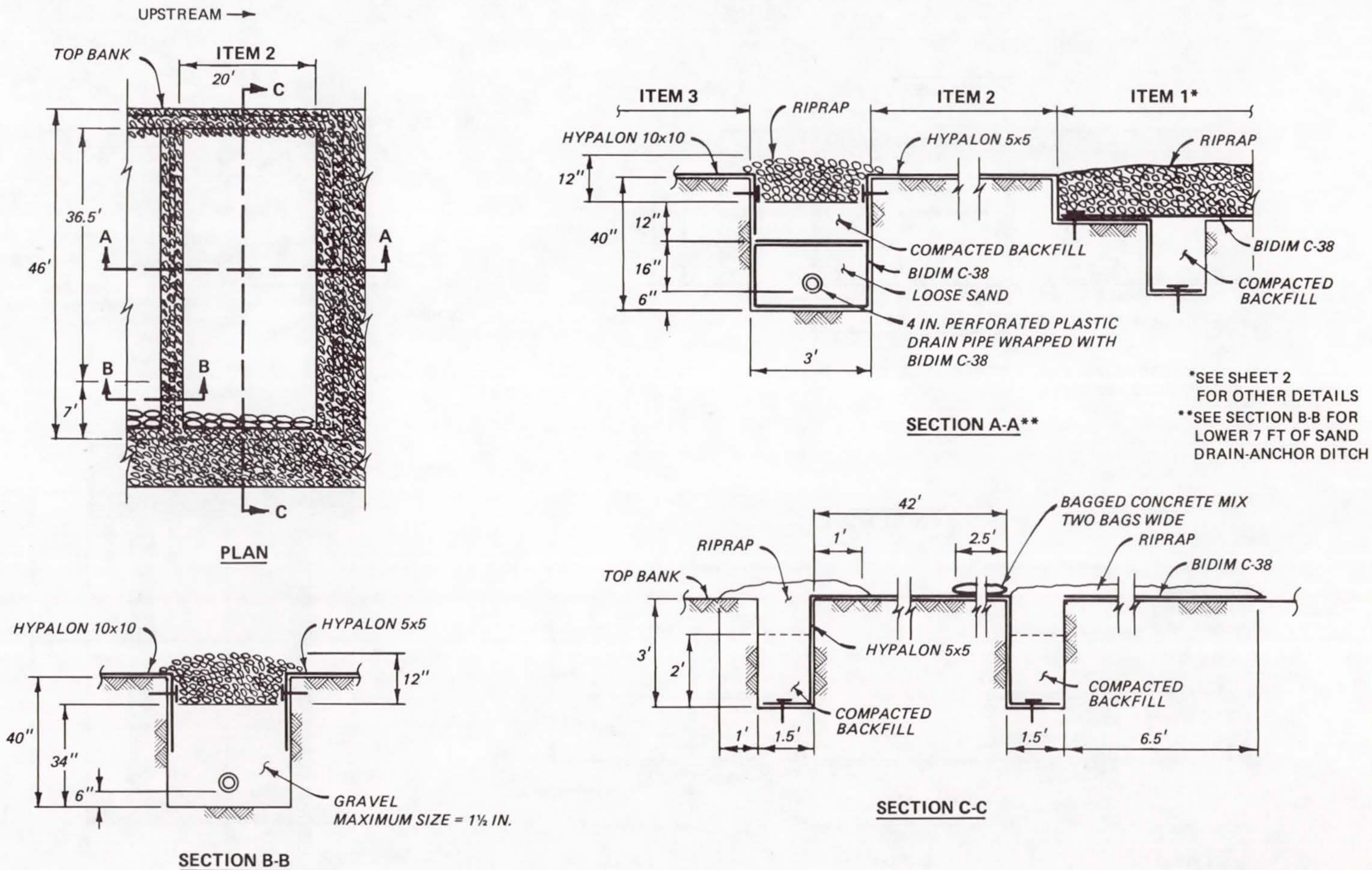
STREAMBANK EROSION STUDY
BIG BLACK RIVER
TEST SECTION LAYOUT



*TACK ANCHOR–¾ IN. REBAR, 12 IN. LONG, 8 IN. DIAMETER STEEL CAP–
WHERE SHOWN ON ALL SHEETS

STREAMBANK EROSION STUDY
BIG BLACK RIVER

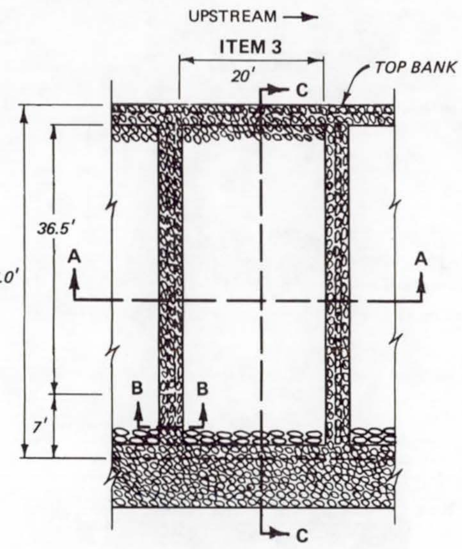
DETAILS OF ITEM 1
RIPRAP ON BIDIM C-38



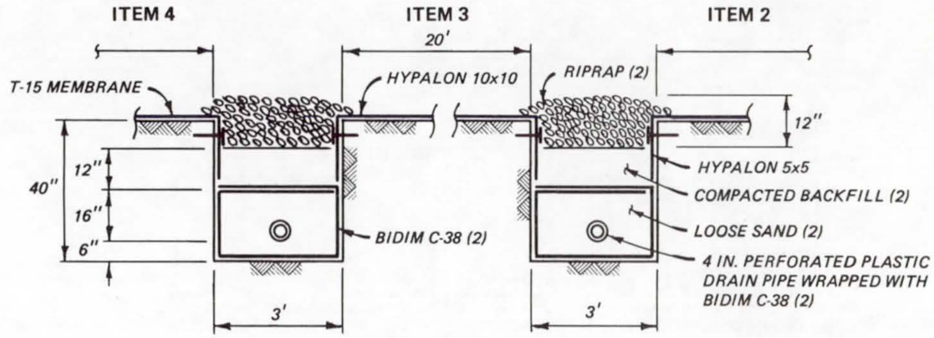
STREAMBANK EROSION STUDY
BIG BLACK RIVER

DETAILS OF ITEM 2
HYPALON 5x5 MEMBRANE

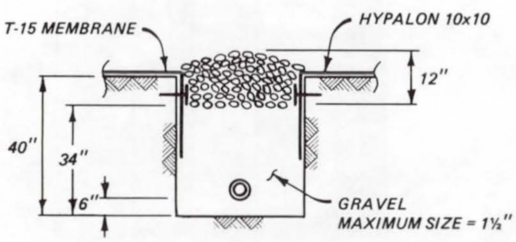
PLATE C5 (SHEET 3 OF 9)



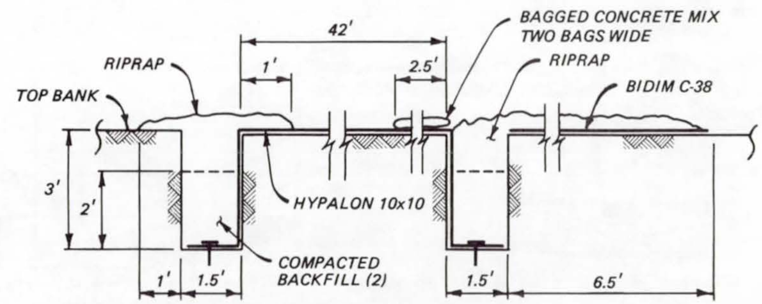
PLAN



SECTION A-A



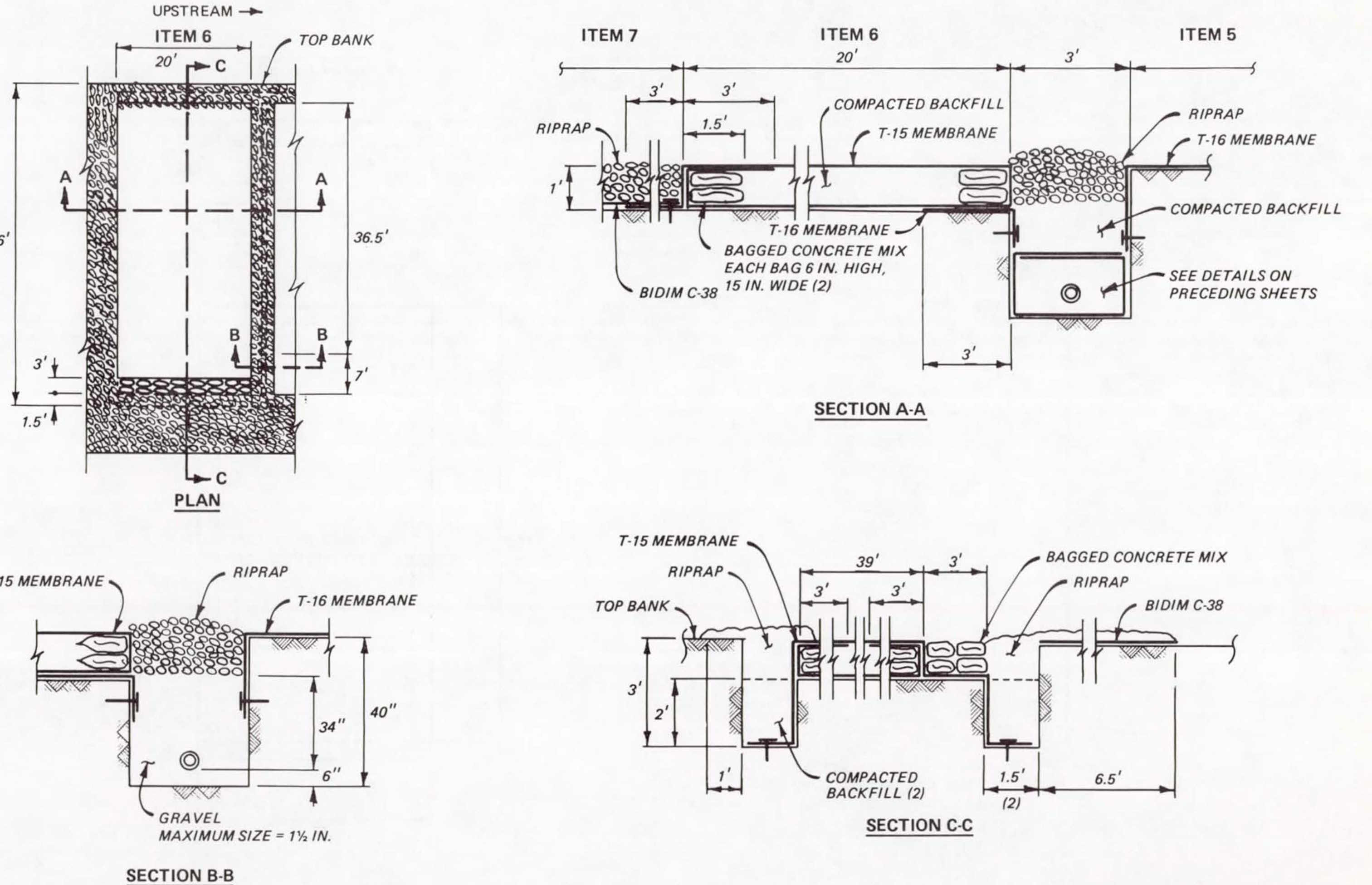
SECTION B-B



SECTION C-C

*DETAILS OF ITEMS 4 AND 5—SAME AS FOR ITEM 3 ABOVE EXCEPT WIDTH OF ITEM 4 IS 20.5 FT AND ITEM 5 IS 19.5 FT. MATERIAL ON ITEM 4 IS T-15 MEMBRANE AND ITEM 5 IS T-16 MEMBRANE.

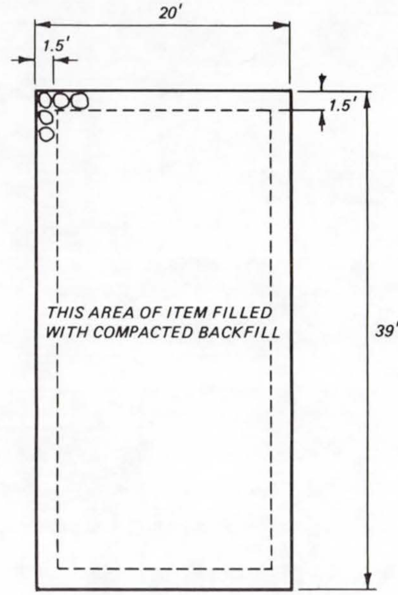
STREAMBANK EROSION STUDY
BIG BLACK RIVER
DETAILS OF ITEMS 3, 4*, AND 5*



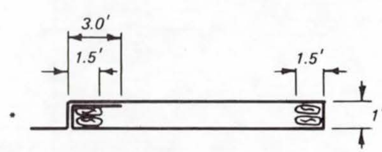
STREAMBANK EROSION STUDY
BIG BLACK RIVER

DETAILS OF ITEM 6
T-15 MEMBRANE MESL

PLATE C5 (SHEET 5 OF 9)

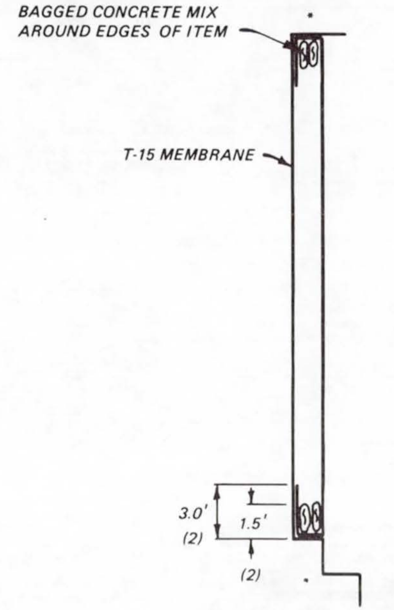


PLAN



FRONT VIEW

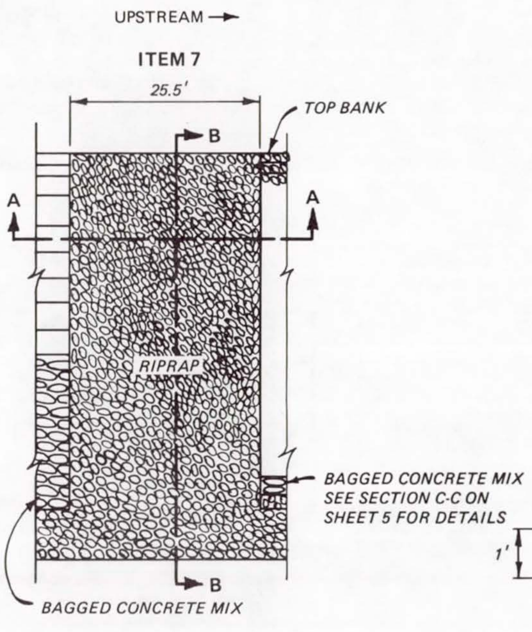
*SEE SHEET 5 FOR OTHER DETAILS



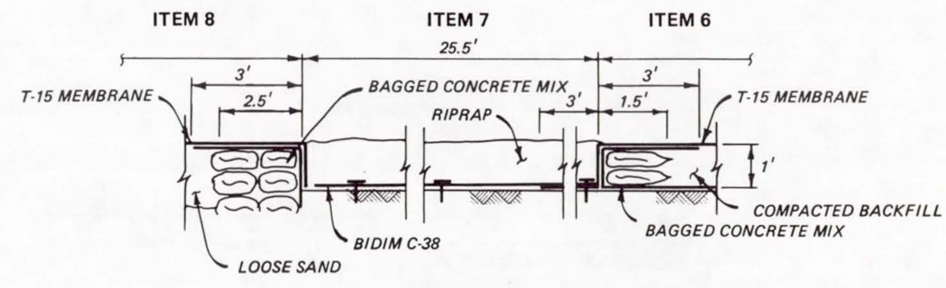
RIGHT SIDE VIEW

STREAMBANK EROSION STUDY
BIG BLACK RIVER
INTERIOR OF ITEM 6

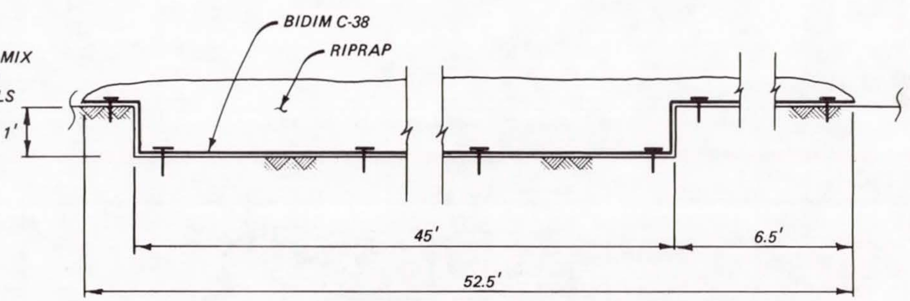
PLATE C5 (SHEET 6 OF 9)



PLAN



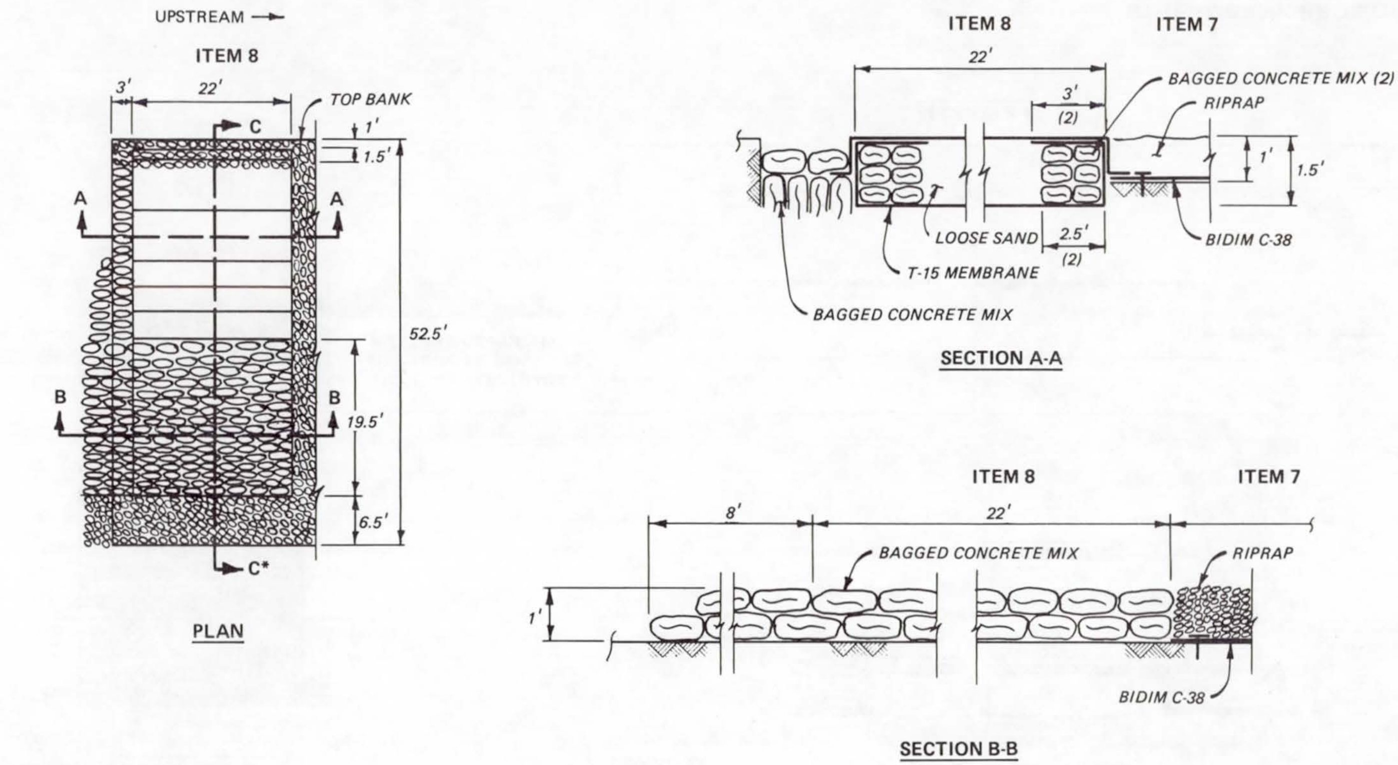
SECTION A-A



SECTION B-B

STREAMBANK EROSION STUDY
BIG BLACK RIVER

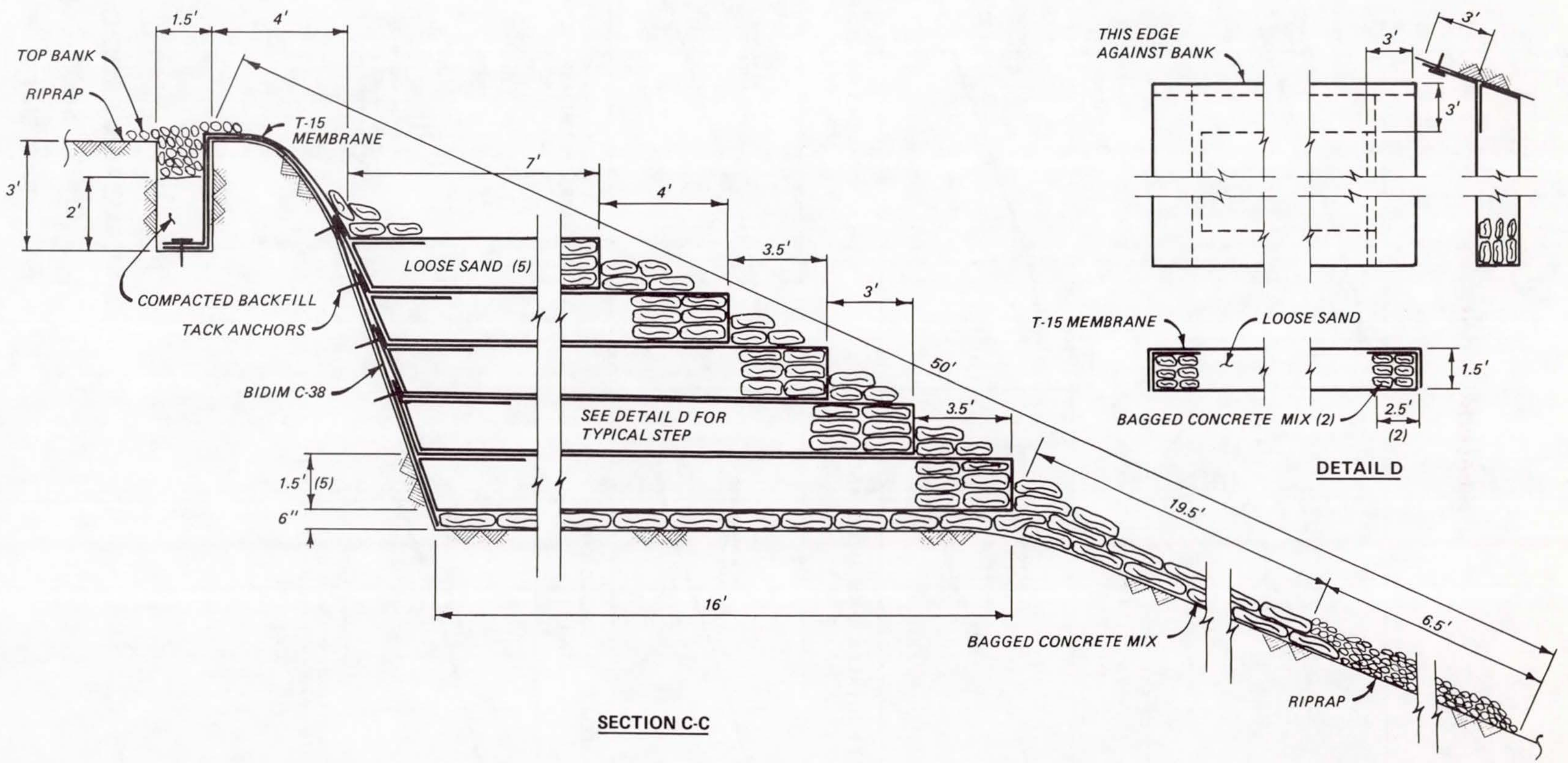
DETAILS OF ITEM 7
RIPRAP ON BIDIM C-38 FABRIC



*SEE SHEET 9 FOR SECTION C-C

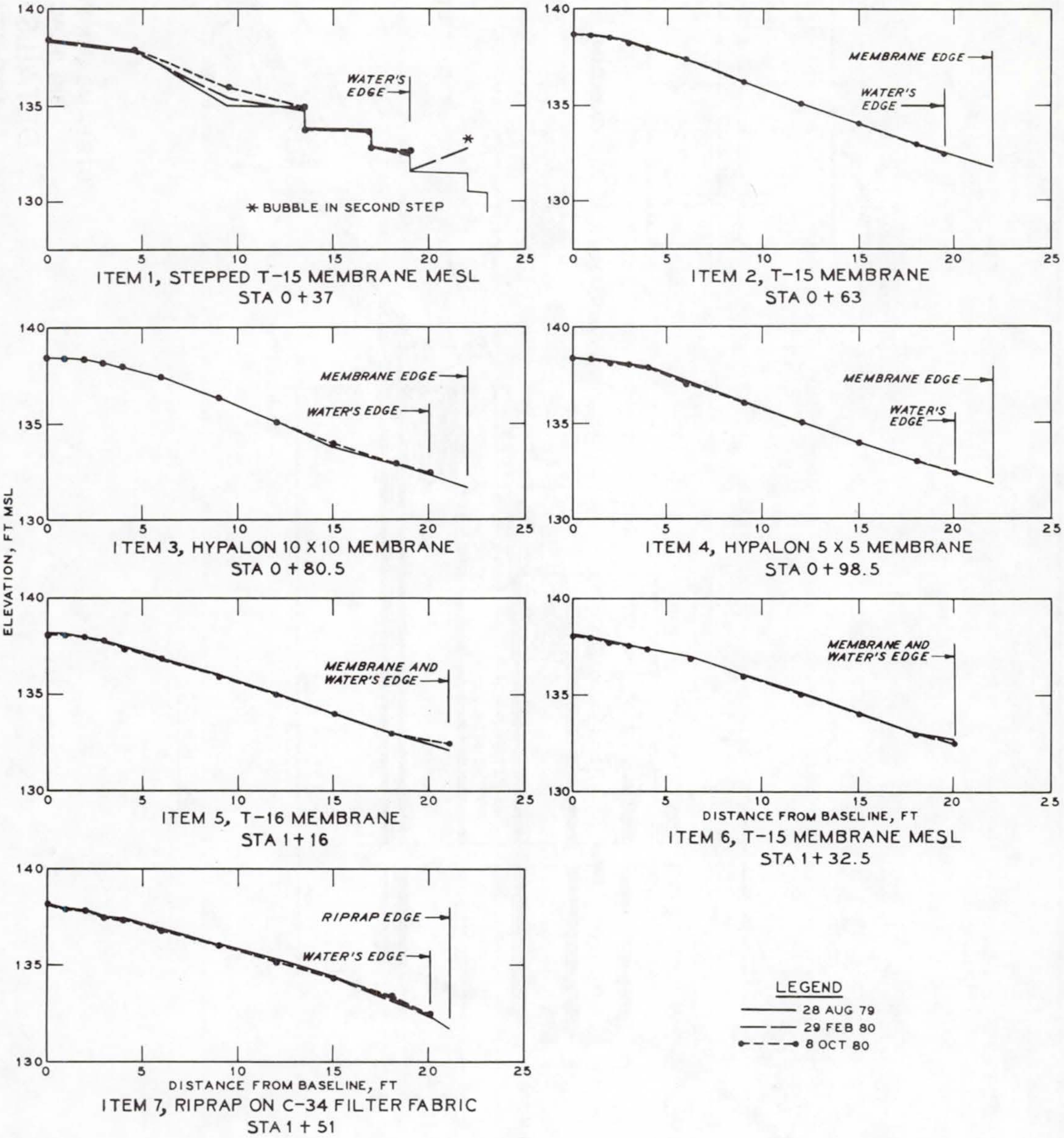
STREAMBANK EROSION STUDY
BIG BLACK RIVER

DETAILS OF ITEM 8
STEPPED T-15 MEMBRANE MESL



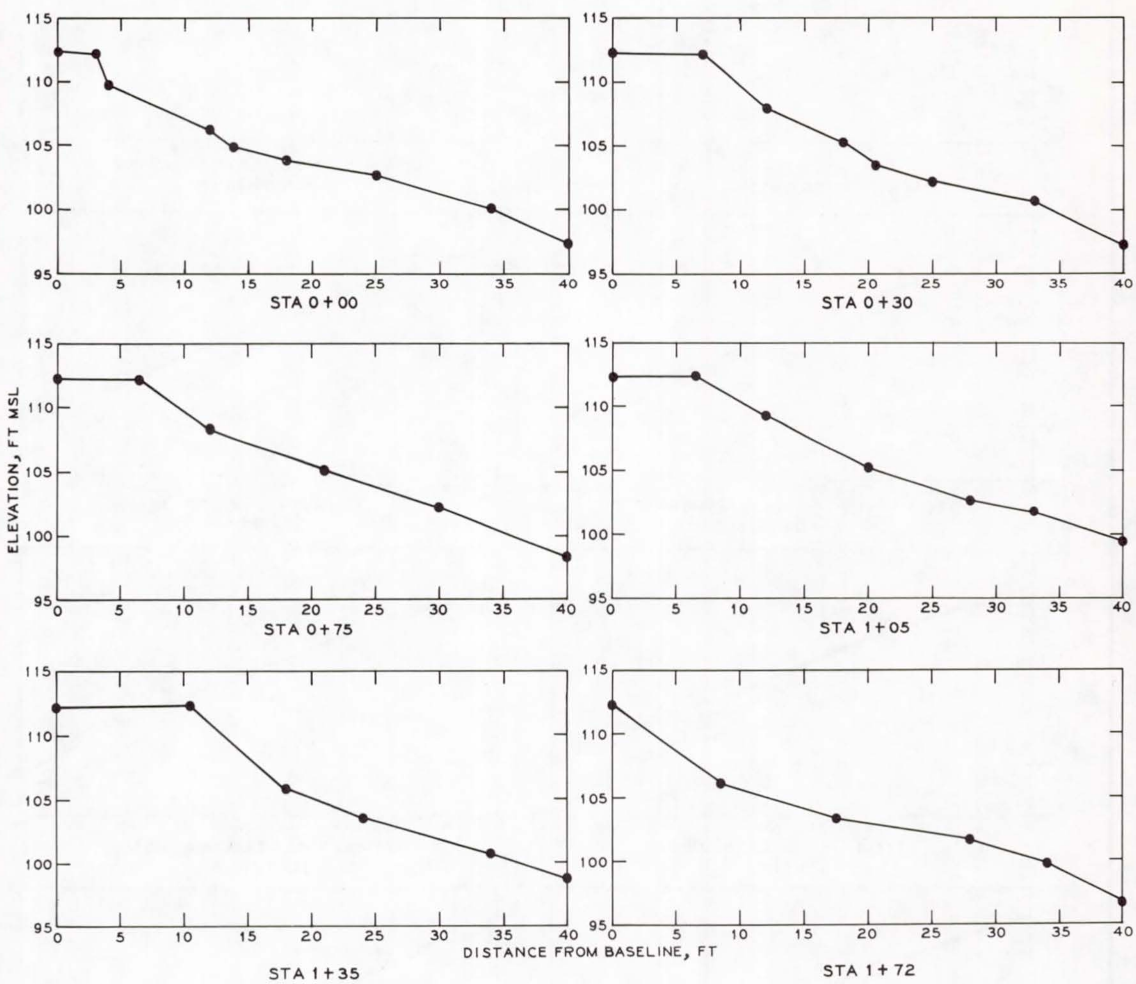
STREAMBANK EROSION STUDY
BIG BLACK RIVER

DETAILS OF ITEM 8
(CONTINUED)



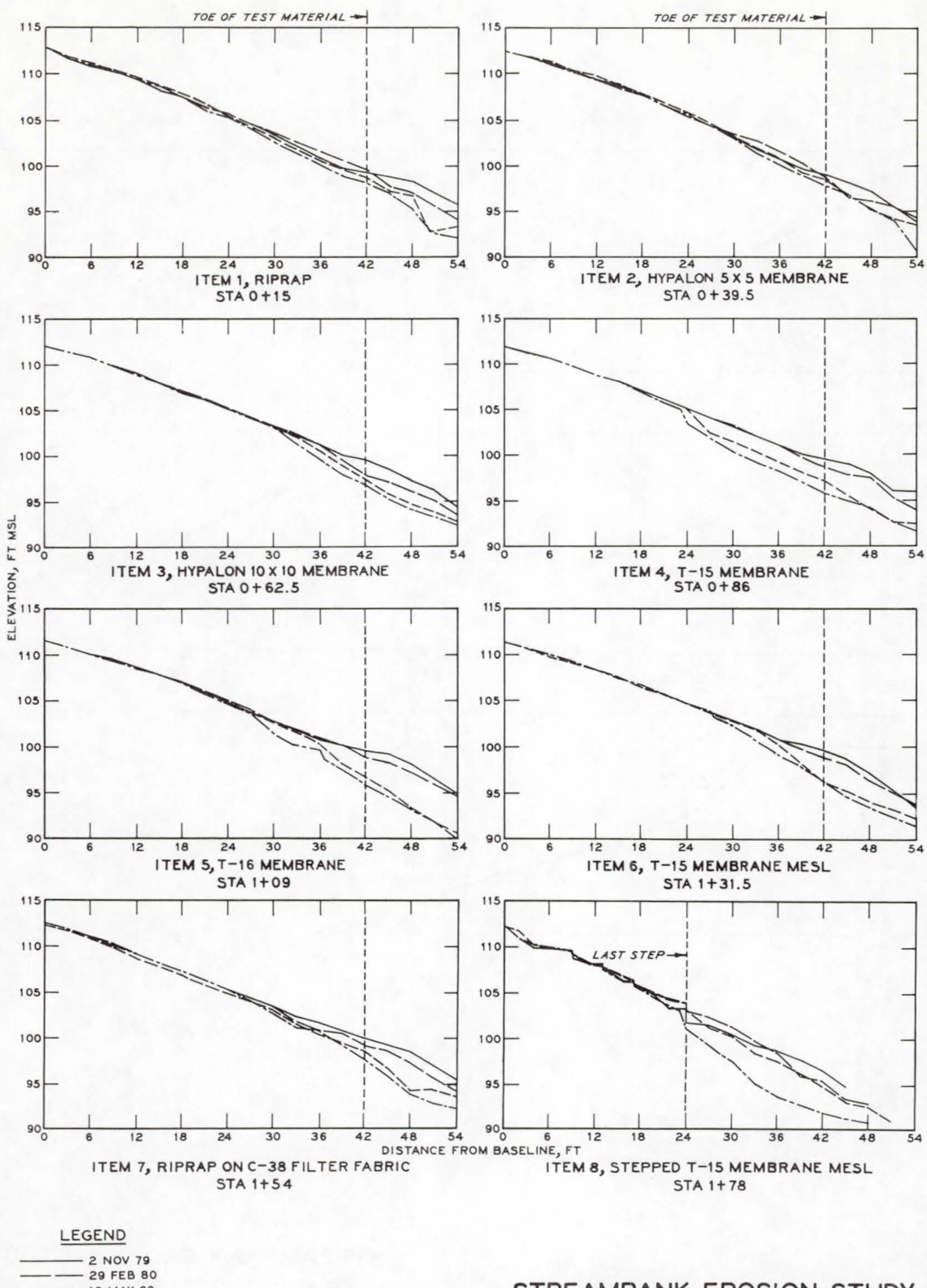
STREAMBANK EROSION STUDY
CROSS SECTIONS
DURDEN CREEK

PLATE C6



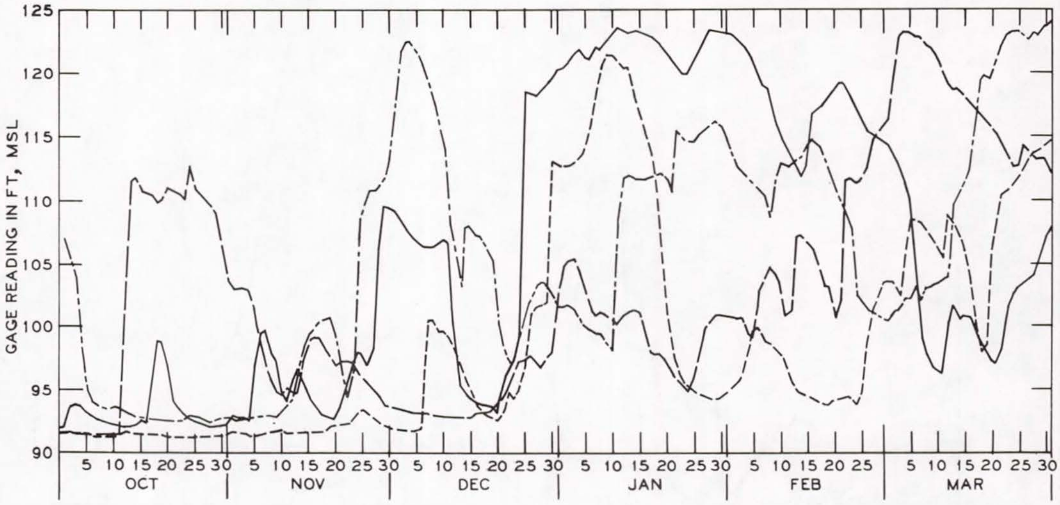
STREAMBANK EROSION STUDY
BANK CROSS SECTIONS
PRIOR TO CONSTRUCTION
BIG BLACK RIVER

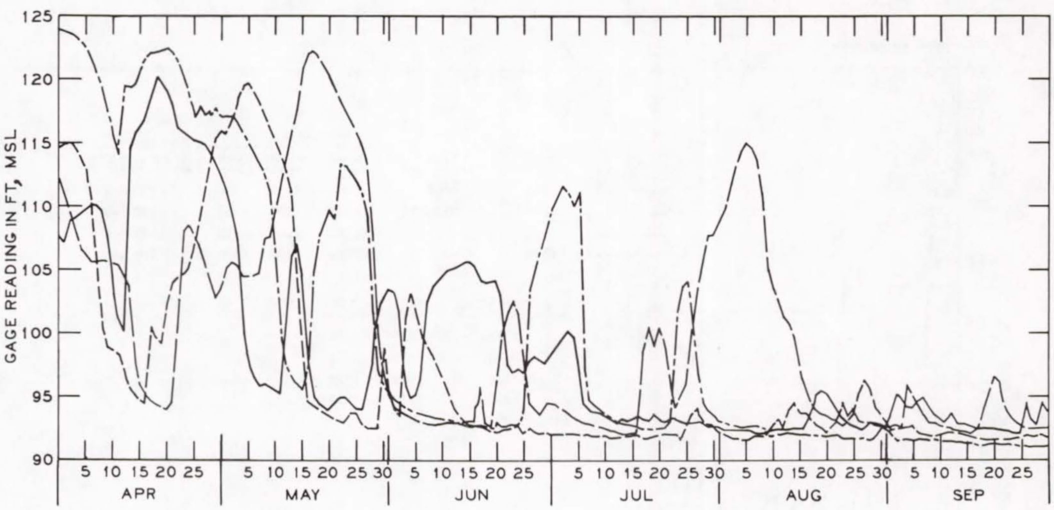
PLATE C7 (SHEET 1 OF 2)



STREAMBANK EROSION STUDY
CROSS SECTIONS
BIG BLACK RIVER

PLATE C7 (SHEET 2 OF 2)





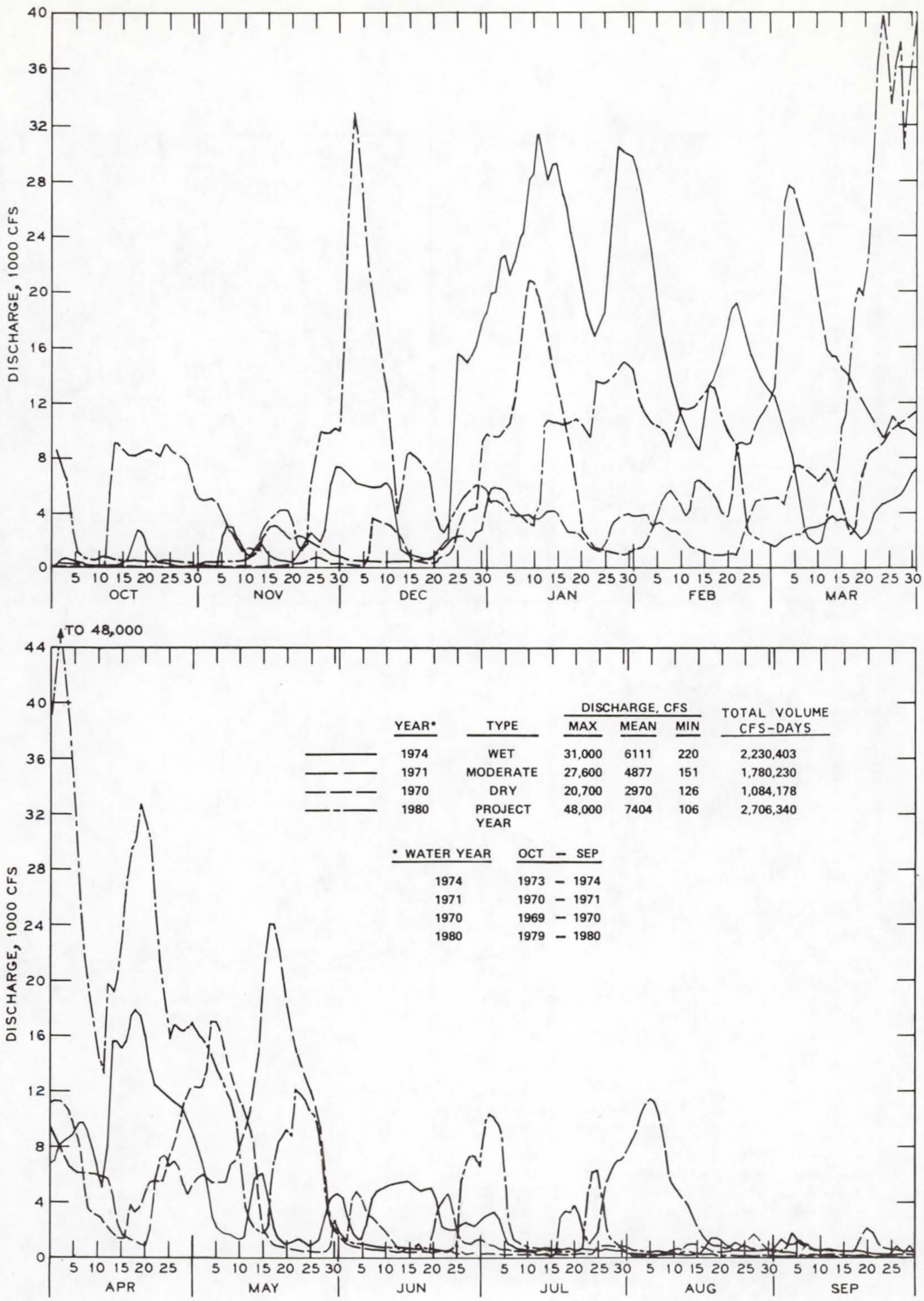
	YEAR*	TYPE	GAGE READING IN FT, MSL MAX	MEAN	MIN
——— (solid)	1974	WET	123.53	102.54	91.93
— — (long dash)	1971	MODERATE	123.13	101.54	91.53
– – – (dash)	1970	DRY	121.33	97.79	91.43
—·—·— (dash-dot)	1980	PROJECT YEAR	123.86	102.56	91.36

* WATER YEAR	OCT — SEP
1974	1973 — 1974
1971	1970 — 1971
1970	1969 — 1970
1980	1979 — 1980

BIG BLACK RIVER STAGE

BOVINA GAGE

PLATE C8



BIG BLACK RIVER DISCHARGE

BOVINA GAGE