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Prediction of the Effects of a Flood Control Project on a Meandering Stream

by

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PREDICTION OF THE EFFECTS OF A FLOOD CONTROL PROJECT ON A MEANDERING STREAM

D. Michael Gee* M.ASCE

ABSTRACT

The Arkansas River between Pueblo, Colorado, and John Martin Dam, a distance of about 125 river miles, is an alluvial, sand-bed river. It meanders between bluffs in a flood plain about one mile in width. During geologic time the downstream (eastern) portion of this reach has been migrating southward due to heavy sediment loads from northern tributaries. A local flood control project is being planned for the town of La Junta, which is in the downstream one-third of this reach.

A study was undertaken to evaluate the future performance of various flood control alternatives with regard to channel stability, sediment movement, and project maintenance. The alternatives considered were various channel and levee configurations. Evaluations were based on both long-term (100-year period) and short-term (single flood event) hydrologic scenarios.

The primary tool used in this study was the movable boundary mathematical model HEC-6 entitled "Scour and Deposition in Rivers and Reservoirs."(8) The hydrologic and sediment regimes of the study reach are complex due to four tributaries and eleven major irrigation diversions. This paper describes development of representative data for the long-term analysis, operation of the model, calibration and simulation strategies employed, interpretation of model results, and computational aspects of this application.

Introduction

The strategy used in this comprehensive study was to integrate both qualitative and quantitative analyses to best identify critical factors pertaining to the stream's behavior and, therefore, predict the stream's response to various channel modification plans. A major study component was the application of the mathematical model HEC-6 to simulate changes in the stream bed profile. This paper focuses on the procedures and techniques developed for utilization of the model and interpretation of simulation results. It is important to note that the process of assembling, interpreting and analyzing the field data necessary to apply the model led to a comprehensive understanding of the stream's behavior and contributed directly to the qualitative aspects of the study.

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A unique aspect of this study was the use of HEC-6 to simulate both the long-term (100 years) and short-term (single flood event) performance of the existing channel and the proposed flood control channel. The approach used was to recognize the basin-wide scale of long-term stream behavior and localized response of short period, high-flow events. Consequently, different data sets were employed for the different aspects of the study. The long-term simulations covered approximately 100 river miles and utilized historical observed water and sediment discharges. The single-event simulations focused on the stream channel in the vicinity of La Junta only, and utilized synthetic water discharge hydrographs and sediment load curves.

Historical Stream Behavior

The ancestral Arkansas River probably cut its first river valley during the earliest known geomorphic cycle in Quaternary time. Analysis of terrace gravel deposits reveals that this initial geomorphic cycle was followed by five more geomorphic cycles during the Pleistocene. In each geomorphic cycle, the Arkansas River cut a deeper valley and deposited gravel on its floor. During this downcutting, the Arkansas River also moved laterally. Geologic evidence indicates that the river between Fowler and La Junta, Colorado, has migrated northward as much as nine miles (2), (Fig. 1).

Migration of the river northward or southward across its valley probably resulted from a greater discharge of sediment into the river channel from one side of the valley than the other. Tributaries that discharge large volumes of sediment build alluvial fans at their junctions with the river. Unable to remove the sediment as quickly as it is deposited, the river flows around the edges of the fans. In so doing, the river cuts into the opposite wall of the valley and gradually moves away from the growing fan. Along the Arkansas river between La Junta and Kansas, for example, the tributaries from the north are long and flow over unconsolidated, erodible deposits. The tributaries from the south are shorter and flow over bedrock, which is less erodible. Due to these physical differences, the northern tributaries supplied a greater volume of sediment than did the southern tributaries, and the river migrated southward (2).

Measurements and reports by explorers in the early 1800's indicate that the Arkansas River was relatively straight, wide, shallow, braided, and intermittent, with sparse bank and floodplain vegetation (1). The river has changed dramatically during the past 150 years. Today it is narrower and more sinuous due to perennial stream flow. Large meander loops are evident, and there is a substantial increase in bank and floodplain vegetation, especially the phreatophytic salt-cedar.

Irrigated-agriculture practices eventually changed the natural hydrologic character of the river. By 1895 there were 20 major irrigation diversions between Pueblo and Kansas (1). These diversions also removed large volumes of sediment with the irrigation water. The effect of crop irrigation was to raise the water tables (via recharge)

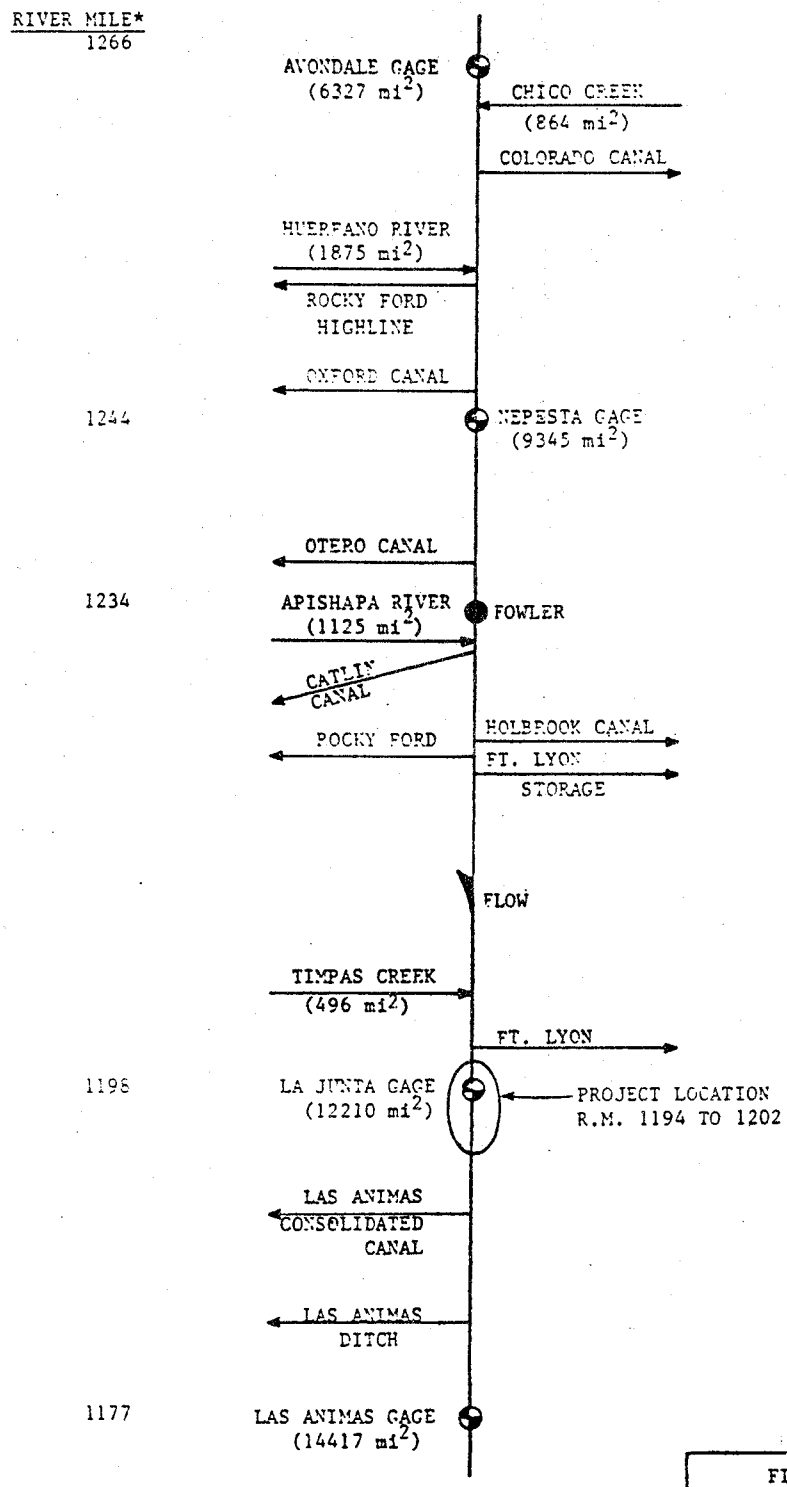

FIGURE 1
SCHEMATIC DIAGRAM
OF STUDY REACH

*Note: 1 mi = 1.6 km

Gee

above the river beds in late summer and to change streamflow from intermittent to perennial. The perennial river could support other types and amounts of riparian and floodplain vegetation. Areas of prairie decreased and shrubs and trees took hold. Salt-cedar, a phreatophyte native to the Mediterranean, was first observed in the the Arkansas Valley in 1913 and today thrives along the river. This increase in vegetation reflects an increase in soil moisture due to the higher water table, a result of increased irrigation. These hydrologic and vegetative changes produced major morphological changes along the river. Nadler (1) states that the river narrowed considerably between 1926 and 1952 (215m to 46m); the 1952 width was only 21% of the 1892 width. The sinuosity of every reach of the river was greater in 1977 (1.43) than it was in 1870 (1.15).

Droughts after 1900, in conjunction with the decrease in sediment discharge, also caused channel changes. During that time, salt-cedar was able to colonize the channel below mean high water level and stabilize the point bars. This process allowed meander loops to enlarge as channel width decreased.

Development of Geometric Data for HEC-6 Long-Term Simulations

Application of HEC-6 to predict future trends in the behavior of the Arkansas River required development of a geometric description of the river. A study reach of about 90 river miles from Las Animas to Avondale was identified. This reach was selected to avoid the need to simulate behavior of John Martin Reservoir (approximately 16 mi (26 km) downstream from Las Animas) and to avoid having to develop separate sediment load information for both the Arkansas River and Fountain Creek, a major tributary located approximately 17 mi (27 km) upstream from Avondale. Good flow records exist for both Las Animas and Avondale as well as at two intermediate locations: La Junta and Nepesta. Flow records were also available for all the irrigation diversions in this reach. The reach contains four significant tributaries and 11 irrigation diversions (Fig.1). The intervening drainage area between Las Animas and Avondale is 8090 mi^2 (20,950 km^2) of which 3730 mi^2 is (9660 km^2) ungaged.

The basic geometric information necessary for HEC-6 was developed from a set of river cross sections that cover the reach from Great Bend, Kansas, to Pueblo, Colorado. The sections are dated 1940 and 1945 with additional surveys in 1953 and 1977. The 1945 sections were selected for use because bed material size distribution information was available for 1946. The later data could then be used for calibration.

All 1945-surveyed cross sections for the study reach were digitized by hand into HEC-6 input format. Where additional spatial resolution was necessary, supplemental data were obtained from the 1953 survey. In some locations it was necessary to repeat cross sections for additional resolution or to provide unique entry or exit points for all tributaries and diversions. The surveyed sections were biased towards constrictions (bridges, diversion dams); therefore, when necessary, valley sections were used as repeated sections. The

resulting data set contained 41 cross sections. Channel lengths were based on section river mile and overbank lengths scaled from a river range location map that is part of the 1953 cross-section data. Manning's n values of 0.035 for the channel and 0.050 for the overbank were chosen.

Incorporation of Project Channel

The channel project being investigated directly affects about 8 miles (13 km) of the river in the vicinity of La Junta. The project condition was simulated by replacing the surveyed cross sections with those representing the proposed project design within this reach. The anticipated shortening of the river was captured through the new channel and overbank lengths. Thus, the interaction of the project channel with both the upstream and downstream reaches of the river could be simulated.

Development of Sediment Data for Long-Term Simulations

Bed material gradations for the study reach were obtained from 1946 surveys performed in conjunction with the construction of John Martin Dam (3,4). It was decided to use a single, average gradation for the entire study reach. This is the initial condition gradation and is updated continuously by the HEC-6 sediment sorting algorithm during the simulation. The average gradation curve was broken into 10 size classifications ranging from silt to coarse gravel (Fig. 2).

Measurements of instantaneous transport rates and size distributions were not available at the main stem gages and could not be obtained within the scope of this study. Based on field inspection, it was decided to develop an inflowing load that is in equilibrium with the transport capacity of the upstream end of the reach. This was accomplished by operating HEC-6 for a range of discharges, each with very short duration so that insignificant changes to the bed material size distribution or bed elevations would take place. An inflowing load curve with zero sediment load was then input to HEC-6. The calculated load passing each section (by grain size fraction) is equivalent to the equilibrium transport rate for those conditions. The inflowing load curve adopted was computed as an average of the calculated load curves at the three most upstream sections (Fig. 3).

Transport capacity was calculated using the Toffaleti procedure (11). The Toffaleti method was initially chosen because this reach of the Arkansas is similar to sand bed streams for which the Toffaleti method has worked well in past studies. The model performed satisfactorily with this method; therefore, no others were tried. As the Toffaleti function computes bed material load for sands and coarser grain sizes, wash load must be estimated from suspended load measurements. The wash load component was included in the inflowing load for completeness, but has an insignificant impact on channel behavior for this particular situation.

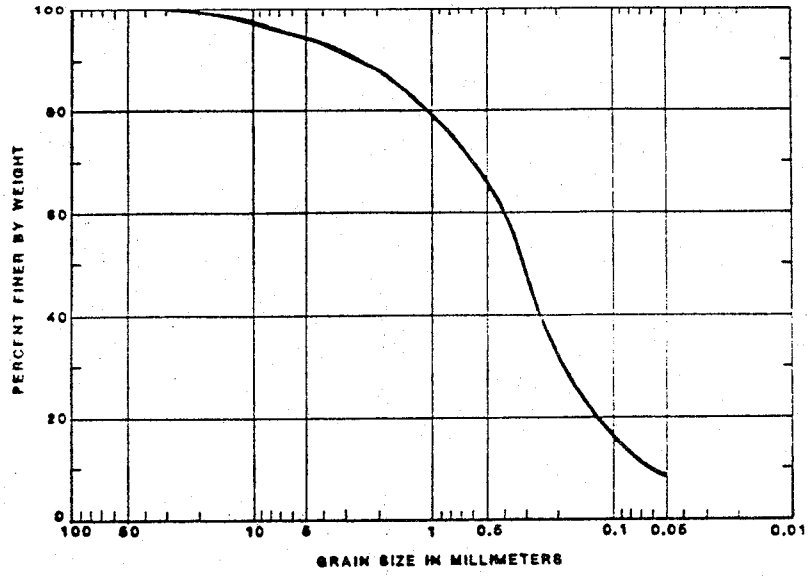

FIGURE 2. GRAIN SIZE DISTRIBUTION OF BED MATERIAL

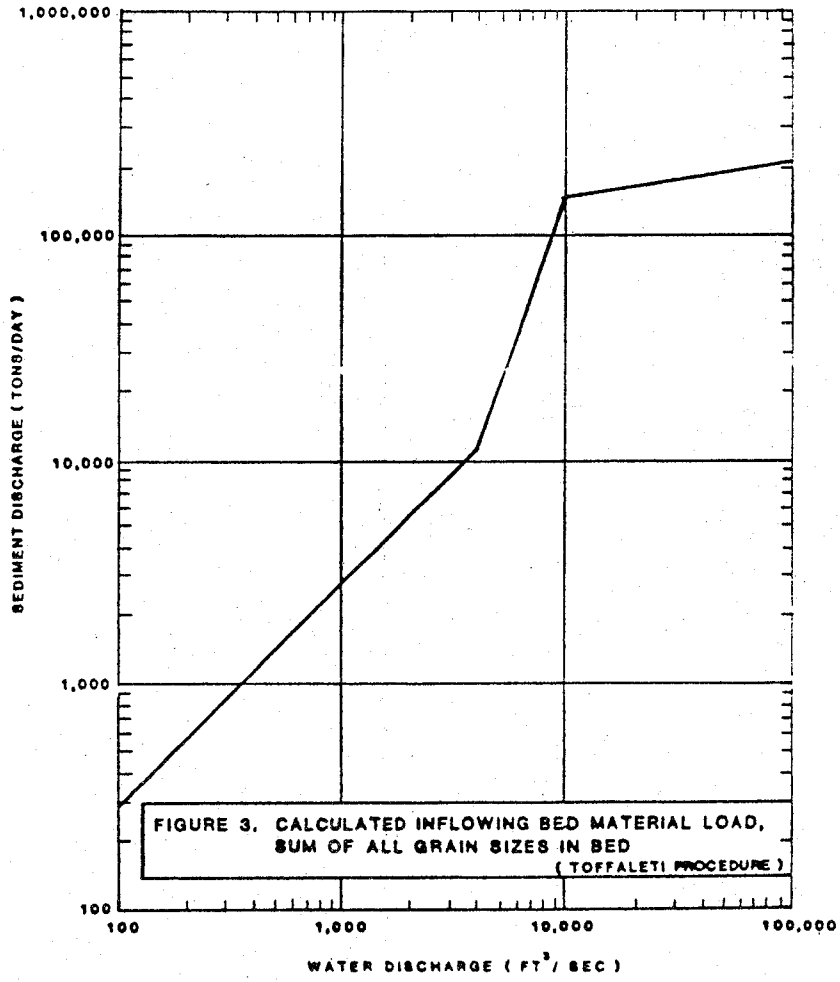

FIGURE 3. CALCULATED INFLOWING BED MATERIAL LOAD, SUM OF ALL GRAIN SIZES IN BED
(TOFFALETI PROCEDURE)

Four major tributaries occur within the study reach: Timpas Creek, Apishapa River, Huerfano River, and Chico Creek. Although instantaneous sediment transport measurements were made on these tributaries in conjunction with early John Martin sedimentation surveys, the original data are no longer available. Monthly and/or yearly averages of those data were kept and were available for use in the study. Those averaged data were used to estimate "instantaneous" relationships between water discharge and sediment load for the tributaries. Monthly averages were used for the Apishapa and Huerfano gages; yearly for the Chico and Timpas gages. These load curves, while yielding correct average volumes of sediment, do not reflect the true relationship between instantaneous water and sediment discharges may require some adjustment during model calibration.

Average grain size distributions for the tributary suspended loads were available (5). These distributions were applied directly to the total-load curves (developed as described above) to yield loads for the individual grain sizes.

The irrigation diversions divert sediment as well as water; although attempts are made to minimize the volume of sediment diverted, particularly of the coarser size fractions. No data were available on the relationship between diverted water and diverted sediment. HEC-6 does not use a load curve to determine quantities of sediment diverted; rather a relation between concentration of sediment in the diverted water and in the main stem is used. For this modeling effort, it was assumed that all the diversions divert silt at a concentration equal to the ambient silt concentration in the main stem. The concentration of all sand fractions diverted was set at 75% of the corresponding main stem concentration based on historical records (5). It was assumed that none of the main stem gravels would be diverted. This capability for realistically simulating diversions with HEC-6 was a key factor in establishing credibility for this model application.

Hydrologic Data

To simulate the behavior of a stream for a 100-year period with a movable boundary model such as HEC-6, one needs a continuous flow record for a 100-year period. Typically, flow data are obtained as mean daily discharges and then aggregated into longer-period, variable time steps to minimize the computational effort. As continuous flow records rarely exist for 100 years or more, the modeler must assemble, construct, or synthesize the record somehow. Development of appropriate long-term flow sequences for sediment routing is an important research topic yet to be addressed. The procedure described below is reasonable and has been used on previous studies. Development of the flow record proved to be the most difficult and time consuming aspect of this study.

Daily stream flow data were obtained for eight gages (Arkansas River and tributaries between the towns of Avondale and Las Animas) from U.S Geological Survey records. Monthly flow volumes for the eleven diversion structures within the study reach were obtained from the State of Colorado.

A base time period of 1941 to 1980 had the most overlapping, continuous, daily data for all the necessary gages. After development of the HEC-6 discharge histogram as described below, that histogram was repeated 2.5 times to produce a 100-year flow record.

Missing tributary records were interpolated on a monthly basis using HEC-4 (7) The interpolated monthly values were then converted to daily flow values. This was accomplished by taking the interpolated missing monthly volume and dividing it by the observed monthly volume of a nearby tributary stream gage. This produced a ratio which was used to multiply the nearby gages' daily flow values. Chico's missing daily flow values were patterned after the Huerfano Gage. Timpas' missing daily flow values were patterned after the Apishapa Gage.

The first adjustment made to the tributary flows was to modify them for ungaged areas and non-contributing areas. This was necessary to provide an estimate of sediment being delivered from adjacent ungaged areas (through the tributary load curve).

A daily flow balance at the mainstem gages was performed which indicated significant errors between flow volumes calculated from the tributary and diversion data and the observed volumes at the gages. These errors were due to a combination of the following:

1. Irrigation return flow and sand sluicing flows that are not gaged
2. Routing effects, attenuation and travel times
3. Interaction of river flows with ground water infiltration and/or exfiltration
4. Use of constant diversion rates for one month periods whereas daily variation probably occurs
5. Random gage errors

It was necessary to remove the error in the water balance; reliable long-term sediment accounting requires accurate water accounting.

To obtain the correct (observed) flow volumes at each of the three intermediate gages, an additional tributary was inserted immediately downstream of each of those gages. This tributary accounted for the ungaged irrigation return flows in the next reach. The tributary flows were calculated as daily flows, constant for a month ,such that a balance was maintained at the intermediate gages. No sediment discharge was associated with these tributaries.

The final adjusted daily flow data were then processed by the HEC-6 data pre-processor to generate a sequence of flows of varying time step to optimize computational efficiency and accuracy. The final computational time steps ranged from one day to one month.

Model Performance and Calibration

Evaluation of the performance of HEC-6 consists of a comparison of trends in scour and/or deposition between model simulations and

historical stream behavior. It is known that the study reach has been aggrading during recent years. According to gage ratings obtained from the U.S. Geological Survey, the rating curve for the Las Animas gage shifted upwards by about 5 feet (1.5 m) between 1955 and 1966. The model simulations adequately reproduce the aggradation trends. The computed trap efficiency for the reach is about 80%. The calculated patterns of deposition also correspond favorably with field observations; deposits appear downstream of tributaries and major irrigation diversions. A more quantitative calibration effort is currently underway. The observed drift in gage ratings will be used to further adjust model parameters if necessary (6).

Simulation Results

A project consisting of a 7.46 mi (12.00 km) long, 175 ft (53.3 m) bottom width channel was analyzed initially. This channel replaces 8.26 mi (13.29 km) of natural river and is, therefore, steeper. The change in bed profile over the 100-year period is shown on Fig. 4 for both existing and project conditions. It is important in interpreting results of model simulations such as these to compare project conditions to a base case condition. The difference between the two results can then be associated with project impacts. For example, in this case, the existing channel exhibited an average of 3.4 ft (1.0 m) deposition in the project subreach while the project channel exhibited only 1.5 ft (0.5m) of deposition for the 100-year period. The reach downstream of La Junta shows somewhat increased deposition under project conditions however.

These results are examples presented for illustrative purposes only and may not reflect the performance of the final project design.

Computational Aspects

This study required utilization of major computational resources. The operation of HEC-6 to simulate a 100-year long period was the primary element. However, developing, manipulating, and storing the 100 years of daily flow records for four main stem gages, four tributary gages, and eleven diversions was a significant data handling effort in its own right. This study utilized software developed at the HEC for hydrologic data storage and manipulation (10), and graphical analysis of data and simulation results (9). The linkage of these various software packages and data files used in this study is shown on Fig. 5. This support software has become an integral and necessary component of any major movable boundary modeling effort at the HEC.

Acknowledgements

This study is being performed for, and sponsored by, the Albuquerque District of the U.S. Army Corps of Engineers. The opinions and conclusions expressed herein are those of the author and not necessarily those of the U.S. Army Corps of Engineers.

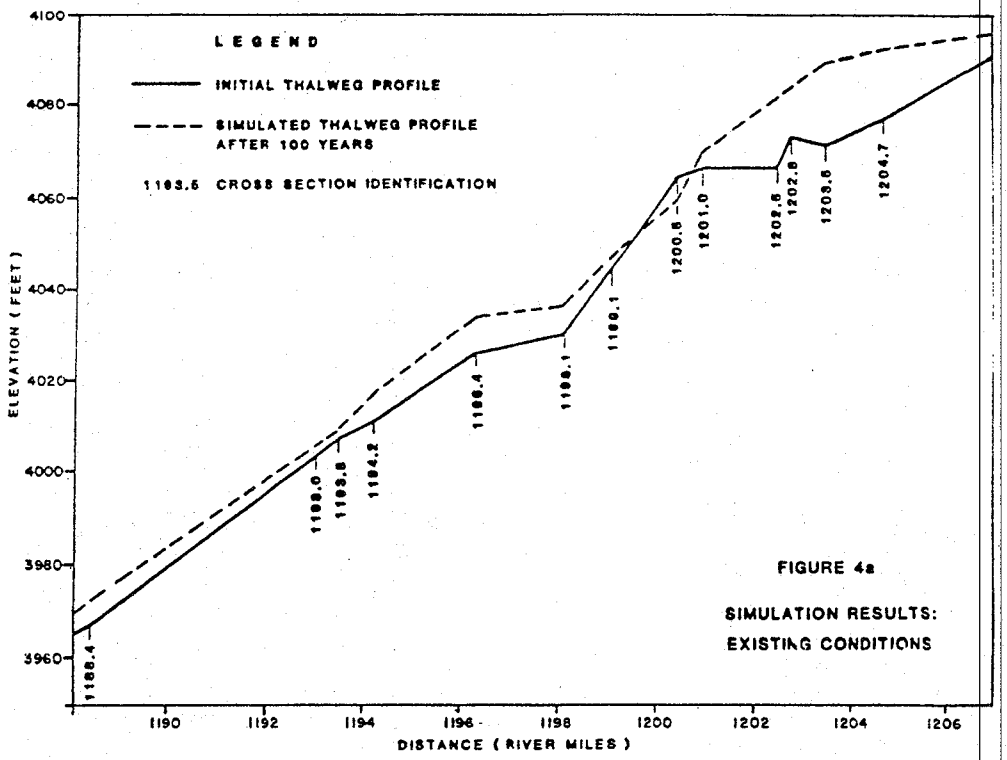

FIGURE 4a

SIMULATION RESULTS: EXISTING CONDITIONS

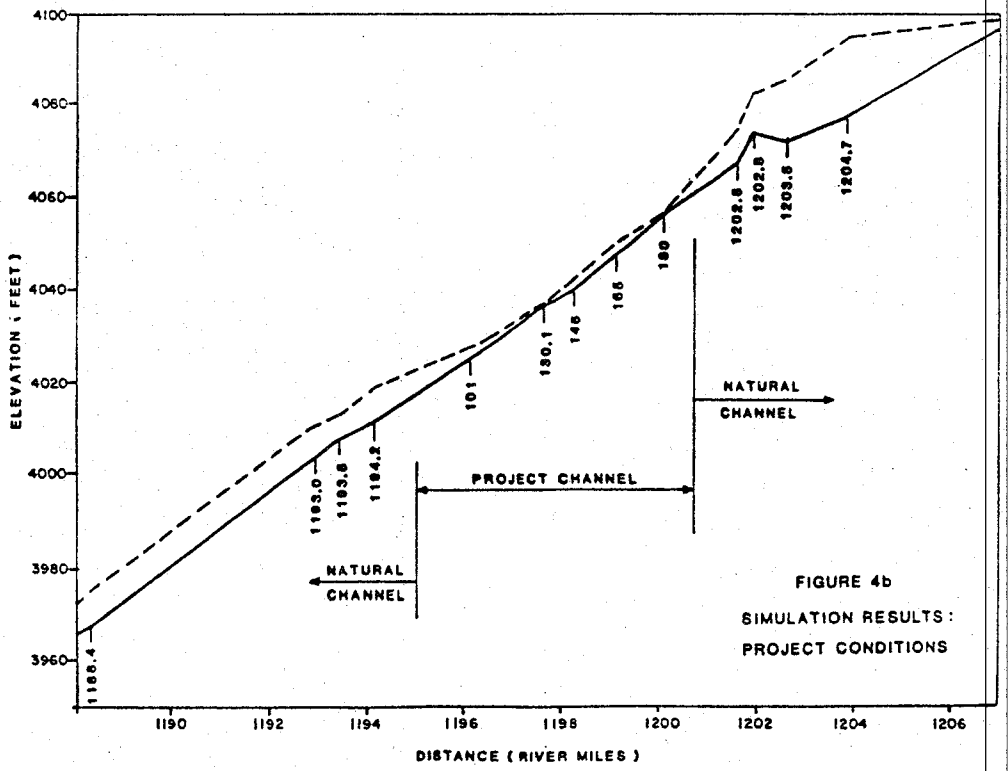

FIGURE 4b

SIMULATION RESULTS: PROJECT CONDITIONS

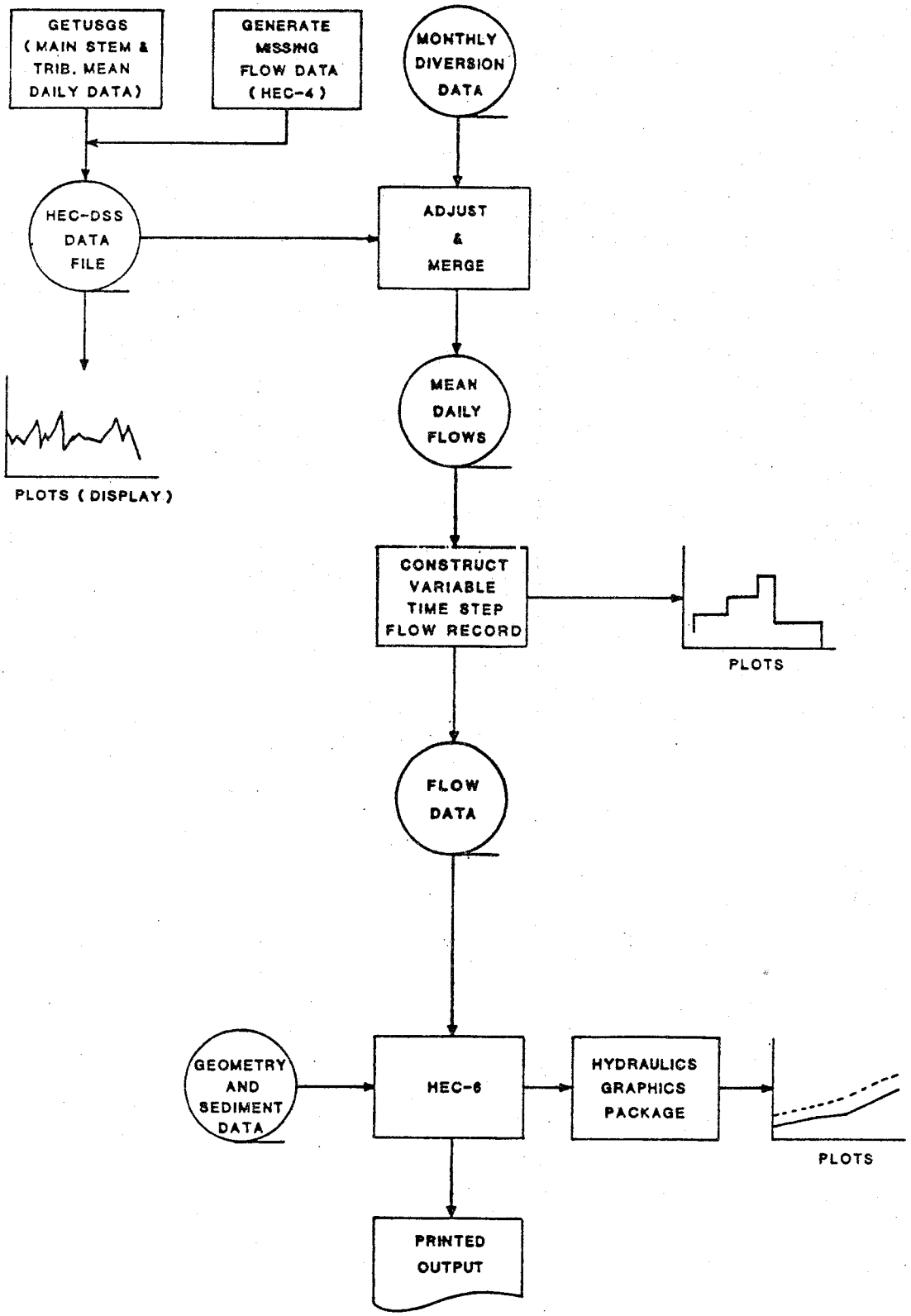

Figure 5 HEC-6 DATA FLOW AND PROGRAM LINKAGE

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A study was undertaken to evaluate the future performance of various flood control alternatives on the Arkansas River near La Junta, CO. The major study component was the application of HEC-6 "Scour and Deposition of Rivers and Reservoirs" to simulate long-term (100-years) changes in the stream profile. A complicating factor was the existence of 11 major irrigation diversions and 4 tributaries in the 100-mile long study reach. This paper describes the development of representative data for the long-term analysis, operation of the model, calibration and simulation strategies employed, (CONTINUED)

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interpretation of model results, and computational aspects of this application.

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