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SEDIMENT TRANSPORT MODEL FOR THE EAST FORK OF THE CARSON RIVER, CARSON VALLEY, NEVADA

by Terry Katzer and James P. Bennett

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Prepared in cooperation with the
Carson Valley Conservation District

Carson City, Nevada
1980

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ILLUSTRATIONS

CONVERSION FACTORS AND ABBREVIATIONS

Only the "inch-pound" system is used in this report. Abbreviations and conversion factors from inch-pound to International (metric) units are listed below.

Multiply inch-pound unit	By	To obtain metric unit
Cubic feet per second (ft^3/s)	0.02832	Cubic meters per second (m^3/s)
Cubic feet per second (ft^3/s)	28.32	Liters per second (L/s)
Feet (ft)	0.3048	Meters (m)
Gallons per minute (gal/min)	0.06309	Liters per second (L/s)
Square miles (mi^2)	2.590	Square kilometers (km^2)
Miles (mi)	1.609	Kilometers (km)
Tons (short)	0.9072	Metric tons

NATIONAL GEODETIC VERTICAL DATUM OF 1929

In this report, the term "National Geodetic Vertical Datum of 1929" (or its abbreviation, "NGVD of 1929") replaces the formerly used term "mean sea level." The datum is detived from a general adjustment of the first-order leveling networks of both the United States and Canada.

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ABSTRACT

A sediment-transport simulation model developed by Bennett and Nordin (1977) was used to predict bedload and suspended-sediment transport and channel-bed scour and fill at selected sites in the East Fork Carson River in Carson Valley, Nevada. The model incorporates an unsteady, nonuniform-flow computation component, a means of simulating bedload and suspended-sediment transport and their interactions, and bed-armoring and elevation-accounting routines. The model was calibrated using 50 days of streamflow and sediment data collected during spring 1978 from a 10.5-mile reach of the East Fork Carson River.

During the 50-day runoff period used for calibration, the total sediment load transported into Carson Valley from the East Fork Carson River was about 60,000 tons. The total load transported out of the study reach was about 14,000 tons. Simulated sediment inflow and outflow were 13 and 8 percent, respectively, lower than measured values. Simulated scour and deposition at selected sites varied up to about 2.0 feet.

Two additional flow periods were simulated; the December 1955 flood which deposited 27,000 tons throughout the study reach and scoured the channel bed up to about 2 feet at selected sites. A 15-year flow period representing long-term average conditions showed a deposition of about 300,000 tons, with a maximum fill of 20 feet in some reaches.

INTRODUCTION

Flooding and high spring flows on the East Fork Carson River in Carson Valley, Nevada have caused channel erosion near bridges and irrigation diversion dams. The Carson Valley Conservation District plans to attempt to stabilize the river channel and minimize the erosional danger to these structures.

To adequately define an erosional problem and to design a corrective stabilization project a knowledge of sediment transport is required. Planning for river management has thus far been seriously hampered by a lack of sediment-transport data.

Purpose and Scope

The purpose of this study is to predict channel-bed elevation changes resulting from scour or fill under varying riverflow regimens. To accomplish this objective, a mathematical sediment-transport model developed by Bennett and Nordin (1977) was used. Calibrating the model for the East Fork Carson River flow and sediment-transport conditions required the collection of sediment-transport data from a 10.5-mile reach of the river as shown in figure 1. Various periods of riverflow have been simulated and the resultant scour-fill effect evaluated. The model is available to water users and managers to simulate the effects of river planning decisions.

This study was conducted by the U.S. Geological Survey in cooperation with the Carson Valley Conservation District who received funding from the Four Corners Regional Commission.

Location and Description of the River

The East Fork Carson River originates in the Sierra Nevada, mostly in California, and is the main tributary of the Carson River, furnishing about 70 percent of the surface-water supply for Carson Valley (Glancy and Katzer, 1976, table 8). The major source of water for the river is the winter snowpack in the Sierra Nevada, but minor amounts of water are contributed locally by rainstorms.

Late summer base flow increases slightly through the fall and winter months until the snowmelt season starts in early spring. High snowmelt flows normally can be expected in May and June and commonly reach 1,000-2,000 ft^3/s as shown by the flood frequency curve in figure 2. Flows that equal or exceed 1,000 ft^3/s occur about 10 percent of the time, as indicated by the flow duration curve in figure 3.

According to Glancy and Katzer (1976), many floods have occurred on the Carson River system since settlement of the area began in the middle of the 19th century. All known floods were caused by heavy rains falling on a heavy snowpack, and flooding resulted from combined effects of rainfall and snowmelt. Major recent floods known to have affected channel morphology occurred 1955 and 1963.

River channel widths and depths vary considerably throughout the study reach; generally the channel is narrower and more incised downstream than upstream from the Highway 88 bridge, shown in figure 1. Channel capacity throughout the study reach is about 4,000 ft^3/s.

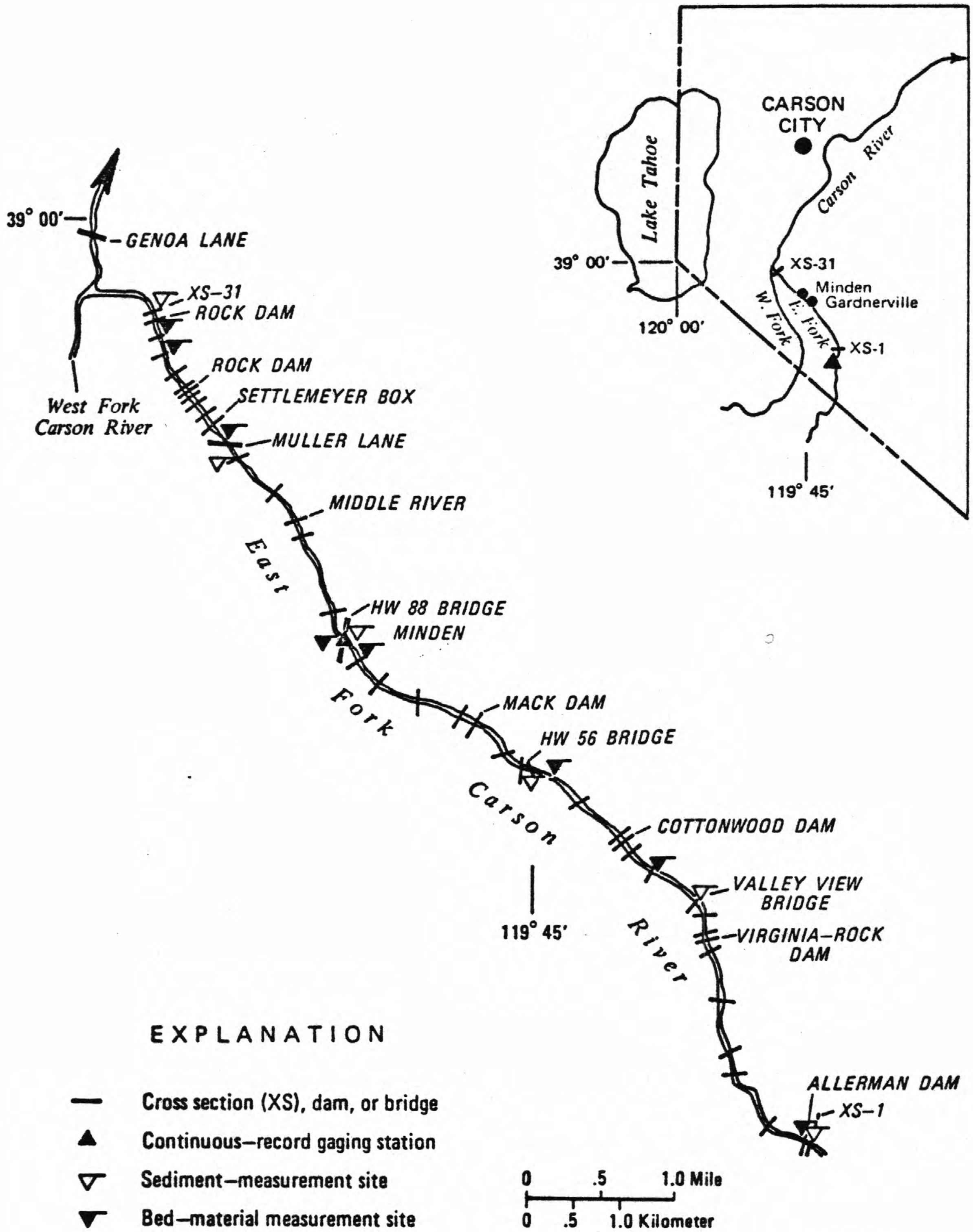

Figure 1. – Sketch map of study reach.

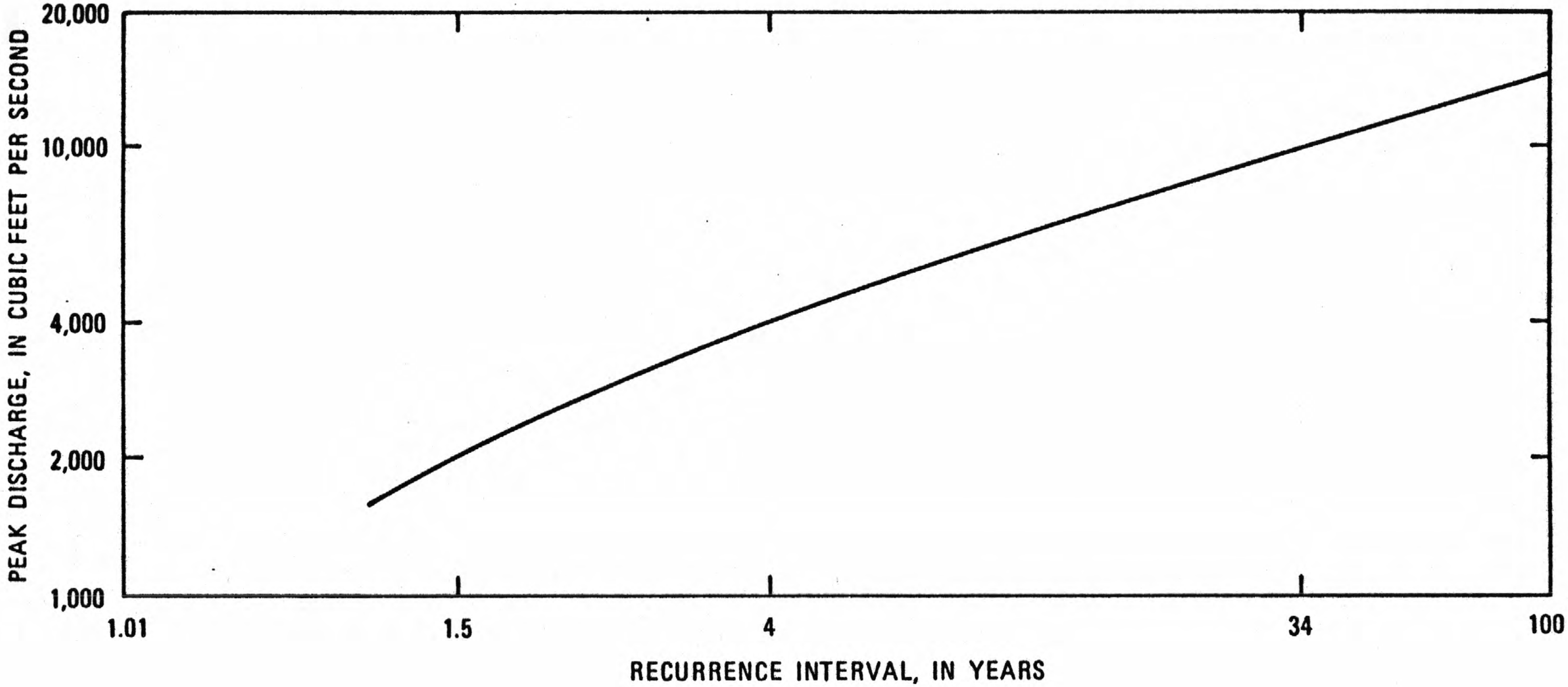

Figure 2. -- Flood-frequency curve for East Fork Carson River near Gardnerville.

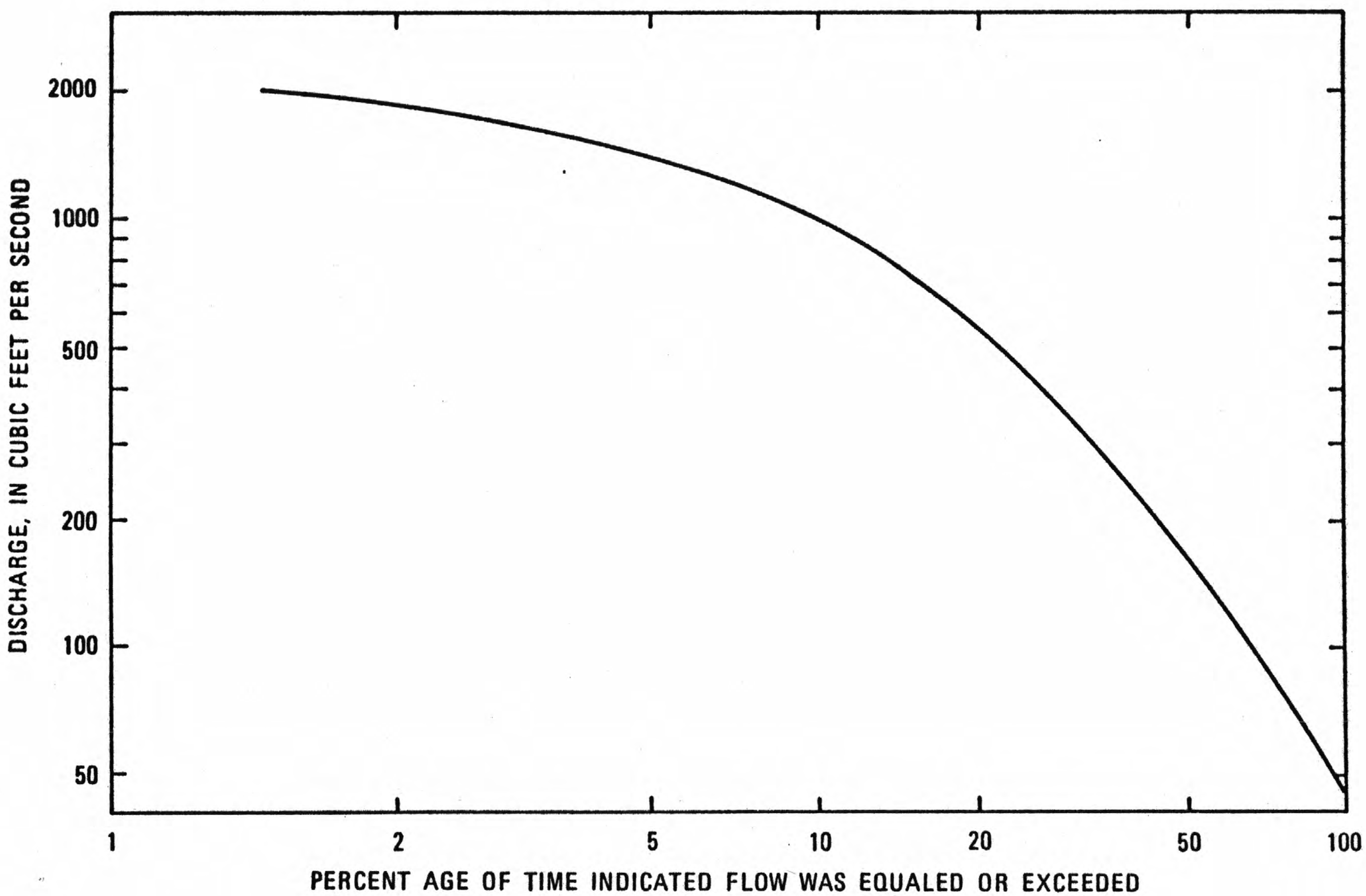

Figure 3. – Flow-duration curve for East Fork Carson River near Gardnerville, water years 1910, 1926-28, 1936-37, 1940-76.

Modifying a natural river system causes the natural sediment transport process to either increase or decrease in varying degrees throughout any given reach. Structural modifications affecting sediment transport within the study reach, shown in figure 1, include four concrete diversion dams, four highway bridges, one footbridge, and about a dozen rock dams. Channel repair after the 1963 flood consisted of channel straightening, placement of riprap, and buildup of banks which increased channel capacity and potential channel erosion. The 1963 flood also destroyed the Middle River Diversion Dam and thereby disrupted the artificial base level of the river upstream from the diversion, allowing several feet of channel downcutting. The dam has not been replaced (1979). Sand and gravel were mined commercially from the channel in at least two sites, and even though this operation was halted about 4 years ago its effect on sediment transport may be felt for some time. Each year, unknown quantities of sand and gravel are removed for private use.

Characterizing the river requires a knowledge of climatic, physiographic, and geologic variables. Climatic variables include precipitation and temperature; physiographic variables are vegetation and slope or elevation change; and geologic variables are the type of rocks (lithology) and the geological structures in the drainage basin. All these variables combine to produce water and sediment yields which form the resultant river.

The East Fork Carson River has evolved to where it is well incised in the mountain block and, by the process of sediment transport, has carried from the mountain block vast amounts of boulders, cobbles, gravel, sand, silt, and clay into Carson Valley. Because more material was transported to the valley than out of the valley, the river channel was continually built up, reducing channel capacity. This caused floods that overtopped the banks and changed the course of the river throughout the valley; by continually changing course, the river filled most of the valley with sediments.

The river elevation profile is continually in motion, not only in the mountain block, but also in the valley. The gradient or slope changes whenever the vertical distance the river travels increases or decreases with respect to a unit of horizontal distance. The vertical change results from a variety of reasons, but all relate to increased or decreased channel erosion, and adjoining channel reaches could easily have markedly different slopes.

Sediment Transport Process

The sediment-transport process referred to above is explained here in general terms; the mathematical equations representing this process and used in this study are found in the section titled "Sediment-Transport Model Description."

Sediment is fragmental material, from boulder to clay-size particles, that originates from the mechanical and chemical breakdown of rocks that comprise the earth's crust. This fragmental material is transported by, suspended in, or deposited by water and air. When water is the principal agent, the sediment is called fluvial sediment and this is the type of sediment of concern in this study.

Fluvial sediment moves by being in suspension in water (suspended discharge), and by sliding and rolling along the riverbed (bedload discharge) and interchangeably by suspended and bedload. Main factors controlling this process are particle size, shape, and specific gravity of the sediment, and water velocity, depth and turbulence. As used in this report, the bedload is assumed to be moving in a zone that extends from the bed to a point 0.3 ft above the bed.

The particle size of the available material and the ability of the water to transport the material govern the erosion or deposition of the material at any location.

For interested readers a detailed description of the sediment-transport processes may be found in Graf (1971), Gregory (1977), and Garde and Ranga Raju (1977).

Modification of the Natural System

On the basis of the foregoing discussion, it can be readily seen that change in any of the many factors controlling river formation and sediment-transport processes may affect the total river regimen. For example, construction of an irrigation diversion dam creates an immediate river response upstream and downstream; with a reduction in upstream slope, water velocity is decreased causing a corresponding deposition of the larger size particles. A plunge pool develops downstream from the dam, water velocity increases, and erosion of certain particle sizes occurs until the sediment-carrying capacity of the water is reached. If river banks are built up and riprapped to reduce flooding, and the system is aggrading, or depositing material, as is the East Fork Carson River, the riverbed elevation will continue to rise. Construction of a major upstream storage dam would reduce the amount of sediment in the larger particle-size classes that are readily available for transport, thus causing the river to have a greater sediment-carrying capacity than it now has when it enters the valley. An aggrading situation would then be turned around to one of degrading or eroding.

General Model Description

The mathematical model developed by Bennett and Nordin (1977) and used in this study is, simply stated, a series of computations that simulate river flows in a channel and compute the resultant scour or fill at any given location.

The model can be divided into three interrelated sections, called routines. The first routine distributes the riverflow in the channel throughout the period of time being investigated. The second routine computes the rate of sediment transport, and the third routine keeps an account of the channel-bed elevation and size composition resulting from the scour or fill.

A detailed explanation of the model has been included in the Sediment Transport Model Description section.

Acknowledgments

The authors express their appreciation to the many people who provided help and information during this investigation. The following persons were particularly helpful: John McLane and Kent Foster, U.S. Soil Conservation Service, Carson Valley residents Leonard Anker, Jim Hussman, Duane Mack, George McAllister, Mrs. Graham Sanford, Arthur Settlemeyer, and Gary Stone.

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A very special debt of gratitude is owed to U.S. Geological Survey Hydrologist Richard LaCamera who participated in all phases of the extremely difficult fieldwork.

Additional thanks go to Keith Katzer who donated his time and canoe to weekend data collection.

DATA COLLECTION

Data collection for various parameters is necessary to define the boundary and initial channel, sediment, and flow conditions that existed prior to and during the calibration period.

Cross-Section Properties

As shown in figure 1, 44 cross sections were surveyed and used to represent the 10.5-mile reach of the river. Standard engineering procedures were followed in surveying all cross sections to National Geodetic Vertical Datum of 1929 and the total error of closure was less than 0.01 ft. The cross-section geometry, width and depth, was put into the model as area and stage tables, which allow the model to distribute the riverflows in space and time.

Bed Material

Data on the character of the channel bed material are necessary inputs to the model in order to determine scour or fill at any given section and to define the interrelationship between the material carried in suspension and material that moves along the channel bottom. The cross-sectional, vertical, and longitudinal variability of the bed-material size distribution need to be defined for the study reach.

To establish the initial condition of the channel bed, samples of the bed materials were taken at many cross sections. Bed-material samples were taken generally at three locations across a cross section by removing a volume of materials from an area of 0.75 m^2 to a depth as great as 80 cm at nine cross sections, for a total of 27 samples. These sites were picked on the basis of an apparent change in surface particle-size distribution. In three of the fine-grained reaches in the lower end of the study area the bed-material sampler, US BMH-53 was used. The removed material was analyzed for particle-size distribution by the U.S. Bureau of Reclamation, Carson City, Nevada, using standard U.S. Geological Survey analytical procedures.

From the particle-size distribution curves prepared from the data, five sizes were selected to represent sediment in the bed and in transport in the study reach. The sizes used were 0.18, 0.71, 2.8, 11.3, and 400 mm (millimeters). The percentage of material associated with each size was determined by assuming that all material finer than 0.25 mm behaves as though it were 0.18 mm; between 0.5 and 1.0 mm as 0.71 mm; between 2.0 and 4.0 mm as 2.8 mm; between 8.0 and 16.0 mm as 11.3 mm; and greater than 16.0 mm as 400 mm. The 400-mm size bed material was considered to be unerodible and to represent the concrete dams in the study reach because the model was not designed to handle concrete dams. The size distribution of the bed material at the individual cross sections is shown in figure 4 and represents a composite of two or more samples.

Suspended-Sediment and Bedload Sampling

Another model requirement is to define the total load (suspended-sediment discharge plus bedload discharge) that is flowing into the study reach. The suspended-sediment discharge was determined from samples taken with the depth-integrating US-DH48 and D-74AL samplers in accordance with procedures described by Guy and Norman (1970). The bedload discharge was determined from samples taken with the standard 3-in Helley-Smith-type sampler (Helley-Smith, 1971). The calibration of the Helley-Smith bedload sampler has not been completed, but preliminary field tests indicate that the sampler's trap efficiency is near 100 percent for particle sizes between 0.5 and 16 mm (Emmett, 1979).

Sediment measurements were made at the upstream station and a sediment-transport curve relating suspended-sediment discharge plus bedload discharge to water discharge was developed. The total sediment-transport curve at cross section 1 is shown in figure 5. Data for the curve were obtained throughout the range in water discharges from 400 to 2,000 ft^3/s.

The curve represents a best "eyeball fit." The "eyeball fit" was used rather than the least-squares method because averaging of the particle-size distribution curves dictated a simplistic approach, and more or less weight was given to some of the sediment samples, depending on sampling conditions and methods prevailing at the time of sampling; thus, for this study the "eyeball fit" is considered to be as accurate as a least-squares fit.

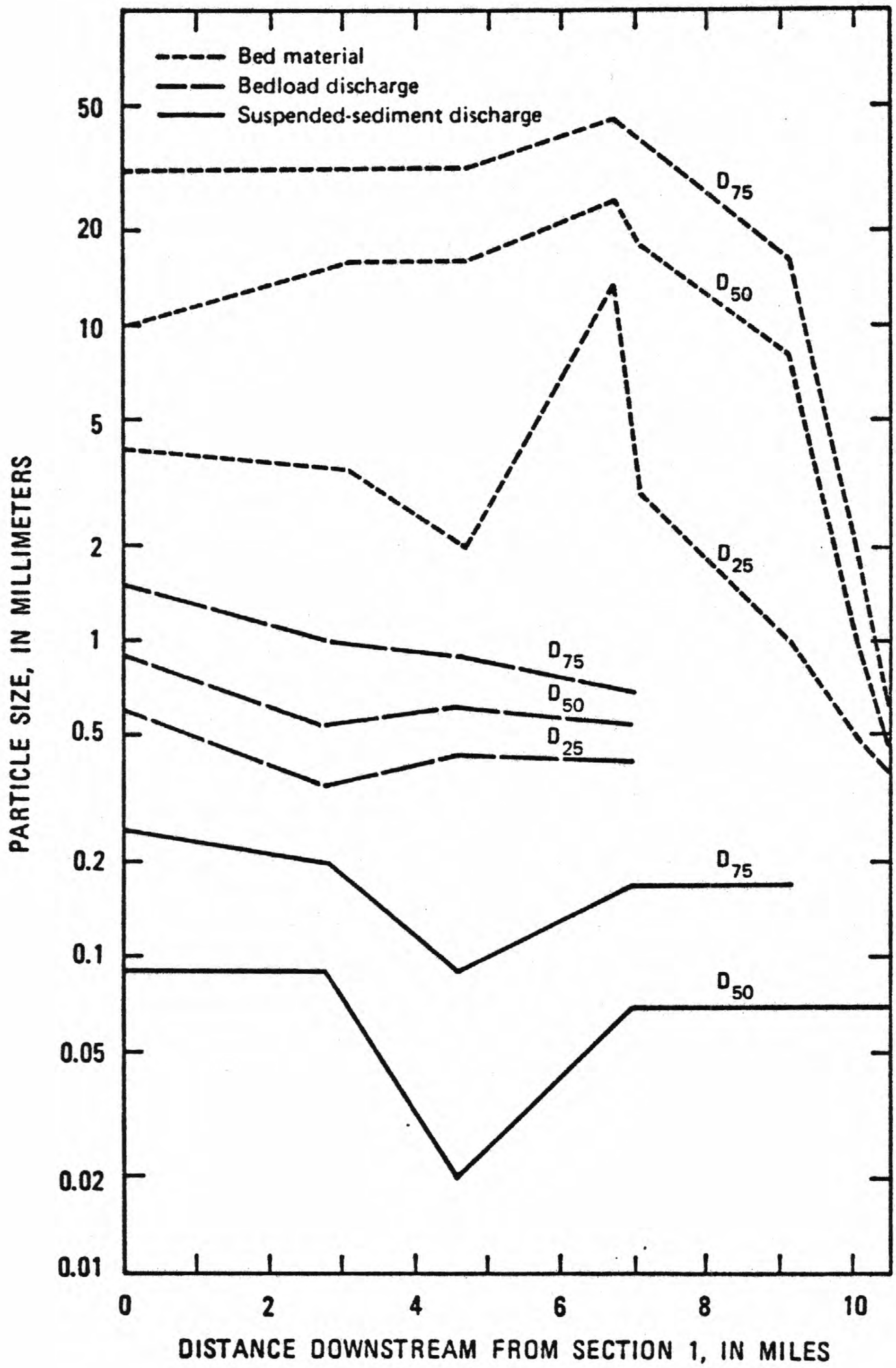

Figure 4. – Generalized particle-size distribution along East Fork Carson River for bed material, bedload, and suspended-sediment discharges during calibration period. D_{75}, D_{50}, and D_{25} indicate that 75, 50, or 25 percent, respectively, of the measured sediment is finer than the stated size. D_{25} for suspended load is not shown because it is equal to or finer than 0.01 mm.

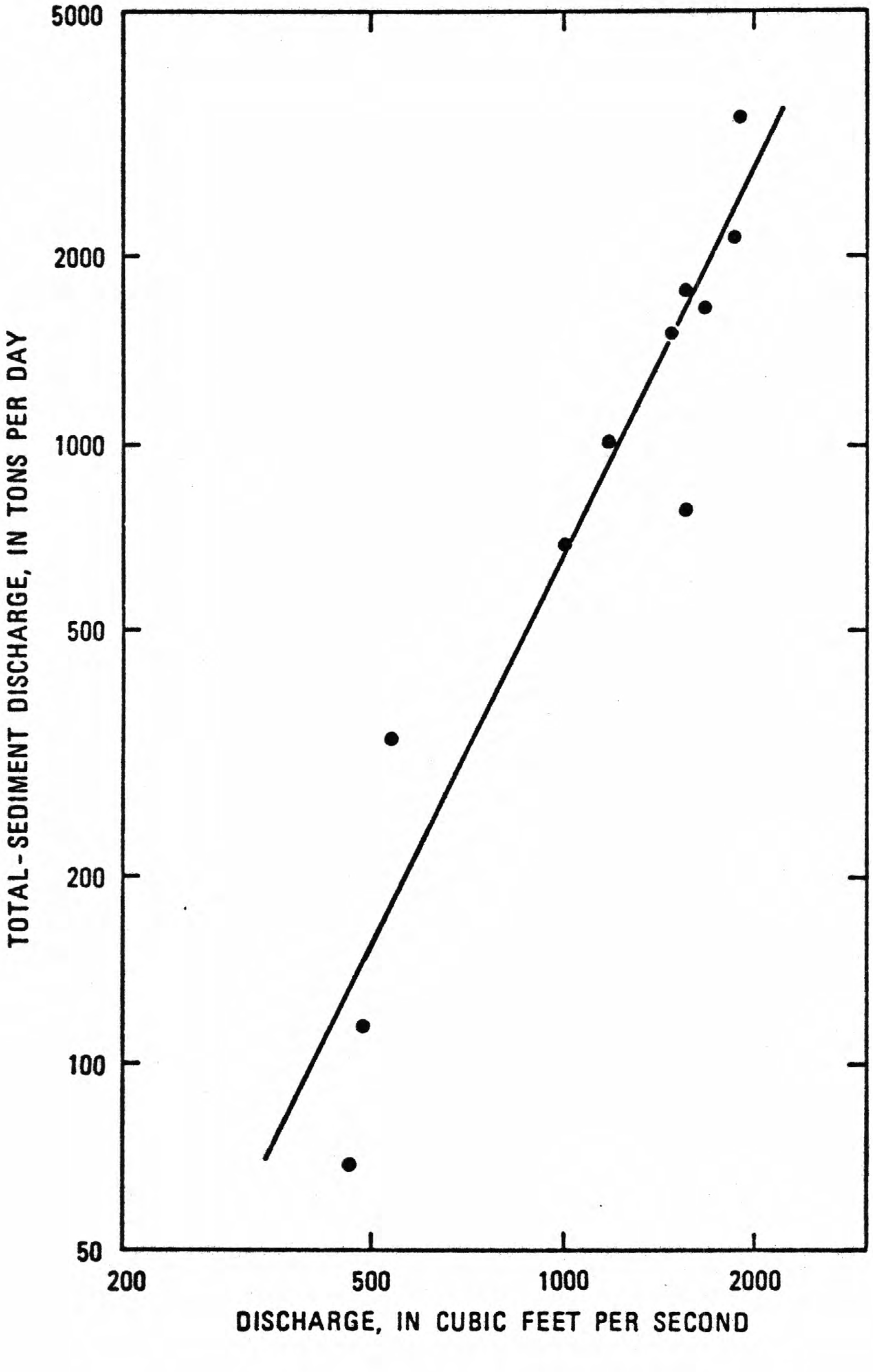

Figure 5. – Total-sediment discharge as a fuction of water discharge, East Fork Carson River near Gardnerville (Section 1), April 27 - June 15, 1978.

The degree of association between sediment and discharge can also be defined and analyzed by a least-squares log-linear regression in terms of a correlation coefficient. A correlation coefficient of 1.0 means the correlation is exact, and when the coefficient equals 0 there is no correlation. The correlation coefficient equals 0.95 for the inflow sediment rating curve as defined by a least-squares plot (not shown). Another important measure of rating curve accuracy is the amount of scatter or variation of data points from the curve. This measure is called the standard error of estimate and equals about ±18 percent based on the least-squares log-linear regression analysis. The larger the standard error of estimate the greater the scatter about the curve and, of course, the poorer the relationship. Eleven total-load sediment samples were used to construct the sediment rating curve; 2 samples exceed the standard error of estimate, 3 samples vary from one-half to one standard error of estimate, and the remaining 6 samples are within one-half of the standard error of estimate.

The accuracy of sediment-discharge values at downstream sites is better than at cross section 1 because of the greater number of samples taken. To exemplify this, the sediment-transport curve for the Highway 88 sampling site is shown in figure 6. The curve representing data collected from May 16 to June 15 shows a large reduction in sediment discharge for a given water discharge after the May 15 peak. This is a common phenomenon and would probably have been defined at cross section 1 if more samples had been taken.

One additional factor affecting the model is the natural process of bank caving. The model was not developed to handle the sediment inflow and channel widening resulting from bank caving; therefore, the model assumed that the banks were erosion resistant. This was generally true throughout the study reach during the simulation period, and it is believed that the localized bank erosion observed would not materially affect overall accuracy.

Figure 4 also shows the generalized average-size distribution of the suspended-sediment discharges and bedload discharges throughout the study reach. The average d_{50} (median particle diameter) for the suspended-sediment discharge was 0.09 mm and for the bedload discharge was 0.9 mm. The ratio of the measured suspended-sediment discharge to bedload discharge at cross section 1 varied from 2 to 22. At other downstream sampling sites the ratio varied from 0.5 to 294.

Approximately 160 additional sediment samples were taken at five other downstream sites to define the daily sediment discharge which was used as calibration data for the model. The two sampling sites farthest downstream were not sampled for bedload discharge because the sampler tended to dig into the fine-grained bed material and overestimate the bedload discharge. The same ratio of suspended-sediment discharge to bedload discharge that was determined at Highway 88 sampling site was used at these two sites.

Some fraction of the total load in the study reach was diverted by irrigation diversions and was not measured. The unmeasured amount was considered to be a minor part of the total load.

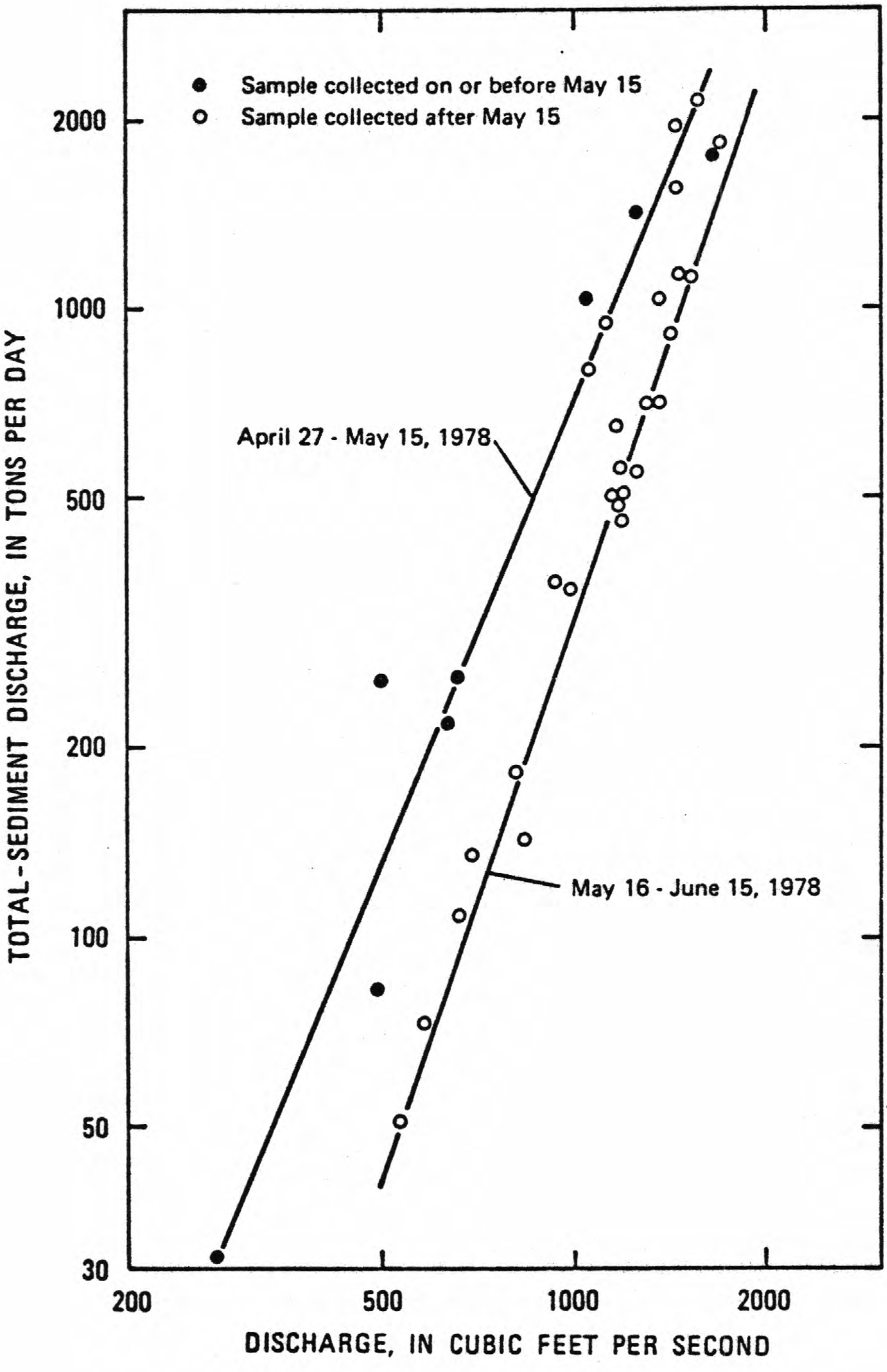

Figure 6. – Total-sediment discharge as a function of water discharge, East Fork Carson River gaging station at Minden, April 27 - June 15, 1978.

Changes in Channel-Bed Elevations

Changes in channel-bed elevations were monitored by periodic soundings at 31 cross sections to define the scour and fill that occurred in the study reach. The first 10 cross sections in the upper reach were sounded once a week because the reach had the largest bed material sizes and changes in bed elevations were less likely to occur. The next seven cross sections were sounded twice a week because the bed materials generally decreased in size in this reach. The last 14 cross sections downstream from Highway 88 bridge were sounded about every other day because the bed materials were mostly coarse to fine sand which are easily moved and cause changes in bed elevations.

Soundings were made by stringing a beaded cable across the channel at previously surveyed points and measuring the water depth with a wading rod from a boat or by wading. By knowing the water-surface elevation, the bed elevation was determined.

The data from the monitoring of bed elevations were also used to determine the active width of the movable bed which is needed for the model. The active width is defined as the lateral distance between the two most widely separated points in the channel cross section at which vertical movement was observed during the calibration period. The soundings of the bed elevations were plotted and compared, the parts of the bed that moved vertically were noted, and the distance between the two most widely separated points was determined. This procedure probably yields too large an estimate of active width, because the channel bed is not always simultaneously in motion at all points between the observed extremes. Initial values obtained in this way were adjusted during model calibration.

Water Discharge

Gaged flows at the Gardnerville gaging station and the Minden gaging station, shown in figure 1, were used as the flow hydrographs for the model (fig. 7). The Gardnerville flows were adjusted for losses from diversions at three sites downstream from section 1. These estimated losses were based on several discharge measurements and comparisons with the recorded values at the Minden station.

Results of the Data-Collection Program

The intensive data-collection program was carried out during the 50-day period of April 27 to June 15, 1978, to document the actual conditions that occurred during this period. Data collection included measurements of sediment discharge, streamflow, and channel cross sections and bed elevations. These data were used as input for the calibration of the sediment-transport model.

The snowmelt-runoff season was selected for the data collection period because the high flows occur at this time of the year and most of the sediment is transported. The length of the data-collection period was dictated by the need to collect data that were representative of a range in flow conditions with time.

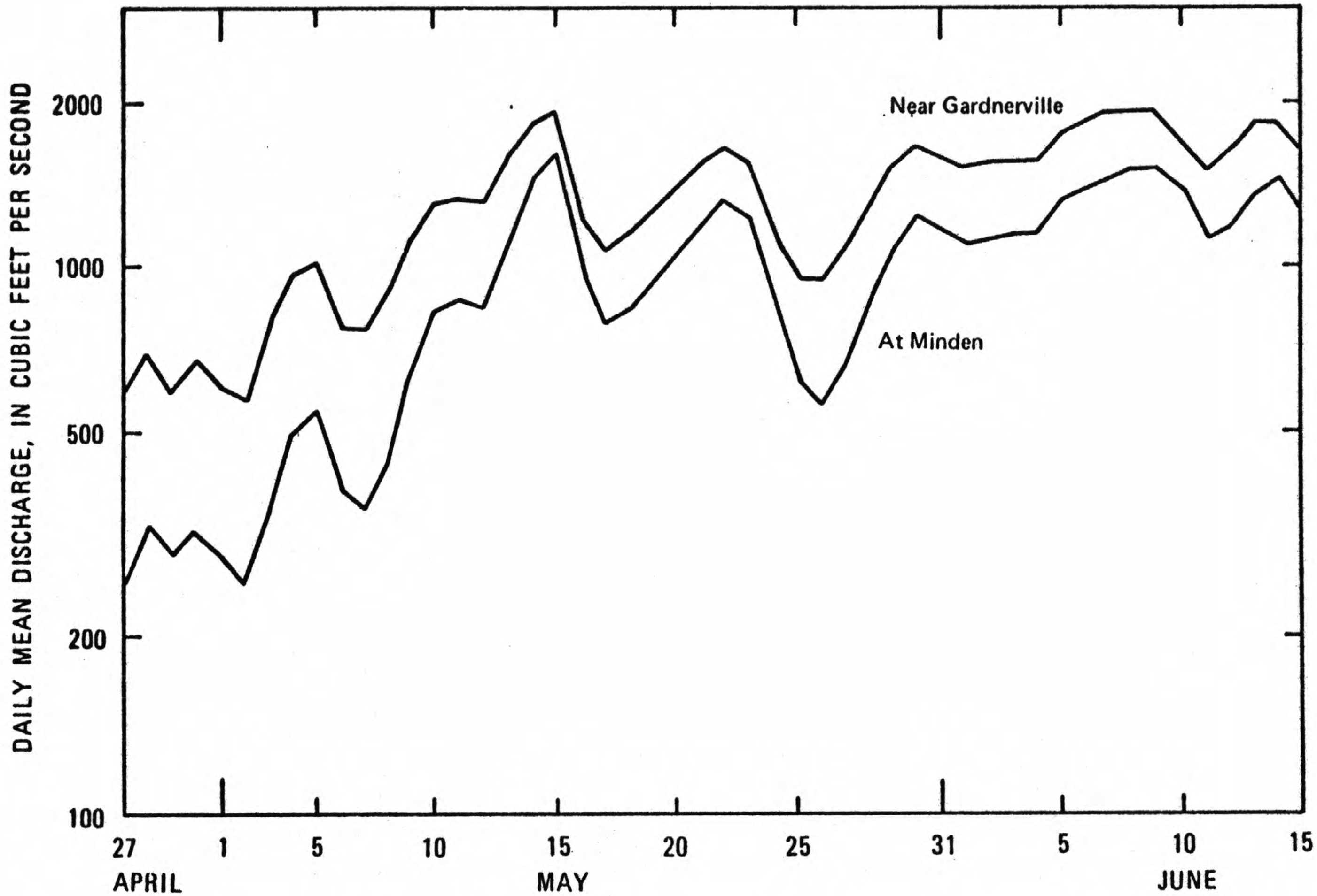

Figure 7. -- Hydrographs for gaging stations on East Fork Carson River during calibration period.

Water discharge during this period at the Gardnerville gage ranged from 562 to 1,940 ft^3/s with an average discharge of 1,330 ft^3/s, which was 117 percent of the average for 47 years of record at the station. Therefore, the water discharge during the calibration period was considered slightly greater than the average.

Analysis of the suspended-sediment and bedload discharge data showed that the sediment load transported into the study reach during the study period was about 60,000 tons and that the load transported out of the reach was about 14,000 tons. About 46,000 tons was estimated to have been deposited in the reach during the period.

Bed elevations changed considerably during the data-collection period. As shown by the solid line in figure 8, the bed increased in elevation, or filled in, about 2.5 ft at the Stodieck Dam and decreased in elevation, or scoured, about 1.9 ft immediately upstream from the Highway 88 bridge. Most of the changes in bed elevation at all other sites were less than 1 ft. Increases in bed elevation occurred in the upper reach where the bed materials are up to 1 ft in diameter and less likely to be eroded. In most of the lower reach, the bed elevations decreased, indicating scour. The bed materials in the lower reach were mostly coarse to fine sands that are more easily eroded.

The measured changes in bed elevation (fig. 8) indicate only changes that occurred at each measuring section and do not reflect the net volume of sediment deposited or scoured within the study reach. The reach was aggrading; however, the figure shows that the increases and decreases in bed elevations are about in balance. This is probably the result of nonuniformity of the channel geometry.

Total sediment discharge records showed a net deposit of 36,000 tons between Allerman Dam and Virginia-Rocky Dam. In further support of aggrading are the numerous gravel bars and islands that were observed throughout the reach. About the same amount of material was transported into the reach between Virginia-Rocky Dam and Highway 56 as was transported out, even though scour and fill occurred in localized areas. A net deposition of about 6,000 tons occurred in the reach between Highways 56 and 88. From Highway 88 to the end of the study reach, the net deposition was estimated to be 4,000 tons. This value is an approximation because of the lack of accurate bedload discharge data at the downstream reach in the study area. At first inspection it seems obvious that if a reach is aggrading the cross section, soundings should reflect this by showing an increase in bed elevation, however, the amount of channel represented by the measured cross sections is very small compared to the total channel area available for deposition.

Accuracy Summary

In lieu of a mathematical data error analysis, the following qualitative evaluation is presented:

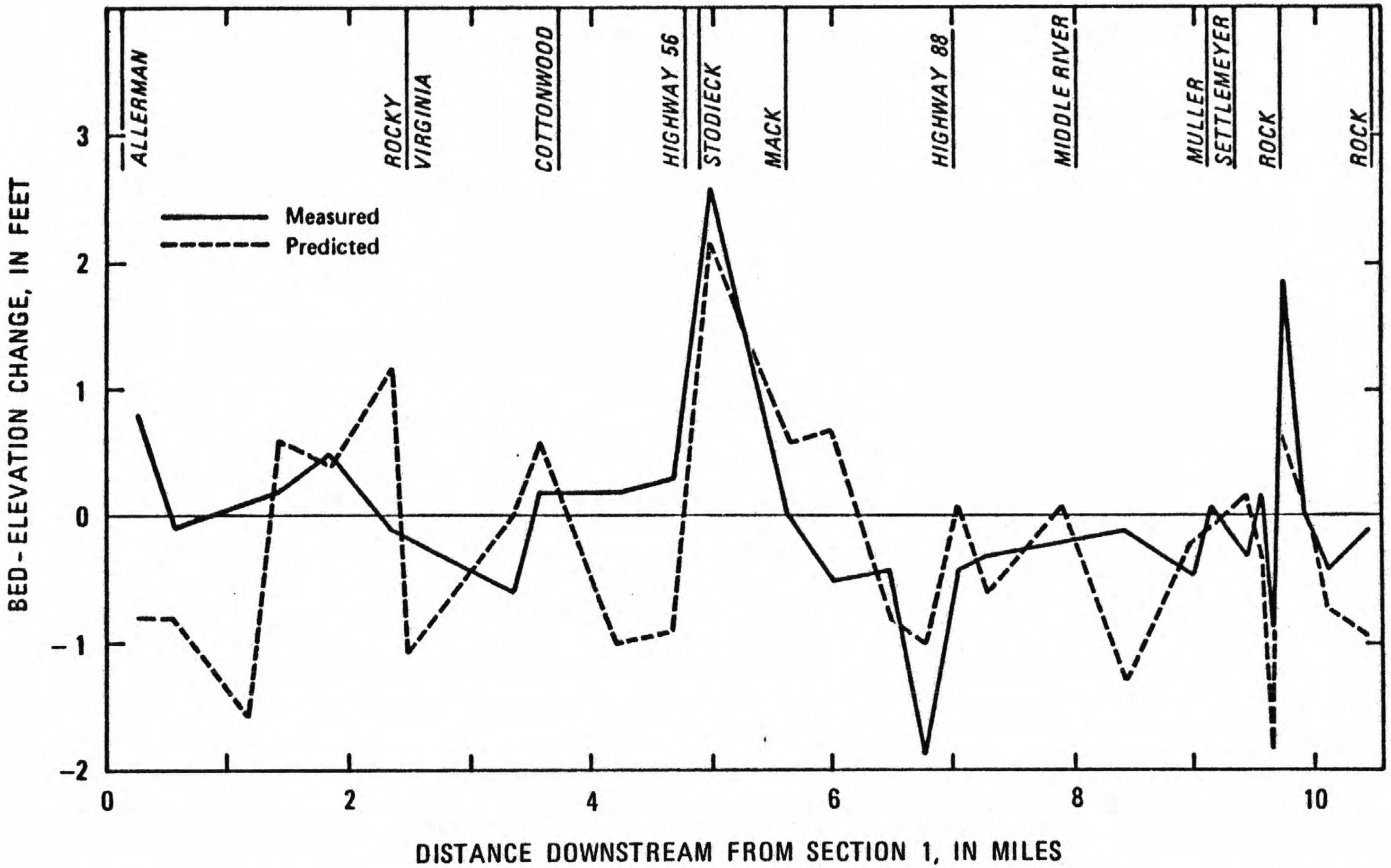

Figure 8. – Difference between measured and predicted changes in riverbed elevation at end of 1978 calibration period. Zero line indicates initial riverbed elevation. Location of dams and bridges shown at top. Boundary sections 1 and 31 not shown.

Item	Rating	
	Good	Fair
Datum survey	X	—
Sampling		
Bed material	—	X
Suspended-sediment discharge	X	X
Bedload discharge	—	X
Bed-elevation changes	—	X
Water discharge	X	—

Thus, an overall data rating of good to fair is probably appropriate.

MODEL CALIBRATION

Calibration is the process of adjusting model parameters to obtain best fit of model predictions to measurements. The adjustment should always be performed while keeping in mind that these parameters represent some physical process and there are, therefore, reasonable physical bounds beyond which they should not be adjusted. The criterion of best fit is variable, depending upon the intended use of the model. It may be root mean square error, absolute value of error, peaks, total volumes, or best "eyeball fit." In the present case, best "eyeball fit" and total volumes were used.

There are one flow parameter and five sediment-transport parameters available for judicious adjustment in calibration. The flow parameter is the Chezy discharge coefficient. The sediment-transport parameters are: M, the bedload layer thickness; N, thickness of the active layer; , the duBoys transport coefficient for a particular sediment size; W, active bed widths; and τ_c, duBoys critical shear stress as given by Graf (1971, p. 126).

Flow Parameter

A mathematical model of a movable-boundary stream is more difficult to calibrate than one of a rigid-boundary channel because of the effect of shifting bed forms on observed water-surface elevations. Thus, the Chezy discharge coefficients for the study reach (based on an estimate of Mannings roughness) were adjusted to provide best fit to observed water-surface elevations at control sections. The entire study reach was divided into eight separate reaches due to the location of the diversion dams. The final Chezy coefficients used in downstream order were: 30.00, 30.00, 30.00, 37.25, 42.57, 47.00, 60.00, and 49.60. These values were constant within the eight separate reaches.

Sediment-Transport Parameters

The first of the five sediment-transport parameters available for adjustment during calibration in the study is M, the bedload-layer thickness parameter. For long uniform reaches, this parameter determines the average value of suspended-sediment concentration through its role in determining the concentration at the lower edge of the suspended-load layer. M was varied from an initial value of 100 to a value of 20 (dimensionless) and the simulated suspended discharge to bedload discharge ratio generally tripled, as shown in figure 9, which is a sensitivity test for M; however, the actual values were several magnitudes higher, and thus the model is not sensitive to M for East Fork Carson River conditions. Further research is required in this area.

The parameters important in determining bed-load discharge are N (dimensionless), which determines the thickness of the active layer, and χ, the duBoys transport coefficient for a particular sediment size. Ideally, it would be best to determine these parameters by calibration where their effects can be separated. The parameter χ should be determined in an aggrading reach, where transport capacity is the limiting factor, whereas N should be determined in a degrading reach (where availability limits transport) where the most useful information would be the rate of degradation. Unfortunately, the two widely different situations are not often available, and χ and N must usually be determined under more adverse conditions.

In the simulation model, χ is determined from Graf's (1971) equation 7.12 along with the multiplicative factor, R,

$$\chi = R \frac{0.173}{(d_{50})^{3/4}}$$

where d_{50} is in millimeters.

The parameter, N, by determining the thickness of the active layer, determines the availability of bed material for scour and transport in a given time step. The East Fork Carson River is very heavily armored in the upper reaches, which required N to be set to its minimum value of 1. In combination with N, the third parameter adjusted was R, the multiplicative factor shown above. In combination with the value of N, the best overall value of R was found to be 0.0095. These values compare with N = 8 and R = 0.05 used by Bennett and Nordin (1977) on the East Fork River in Wyoming, which has much finer and more uniform bed material and has less tendency to armor than the study reach of the East Fork Carson River.

A primary factor in matching predicted to measured values of total-sediment discharge and of scour or fill at localized sections is the active bed width, W, of the individual cross sections. These widths were adjusted as closely as possible to the observed active widths. A change in active bed width at any section causes an immediate response in sediment discharge at adjoining sections.

Figure 8 shows the bed elevation difference between measured and predicted values as functions of downstream distance. An examination of figure 8 shows a rather poor comparison in the upper reaches, which is reasonable because this reach has the lowest sounding accuracy due to the larger size bed material. The fairly good comparison shown in the lower reach is probably because the materials are finer grained and the distance between the cross sections was relatively short.

The general agreement between the measured and predicted changes in bed elevations is shown by the scatter diagram in figure 10. The measured changes were plotted against the predicted changes at the 29 measured cross sections. If all

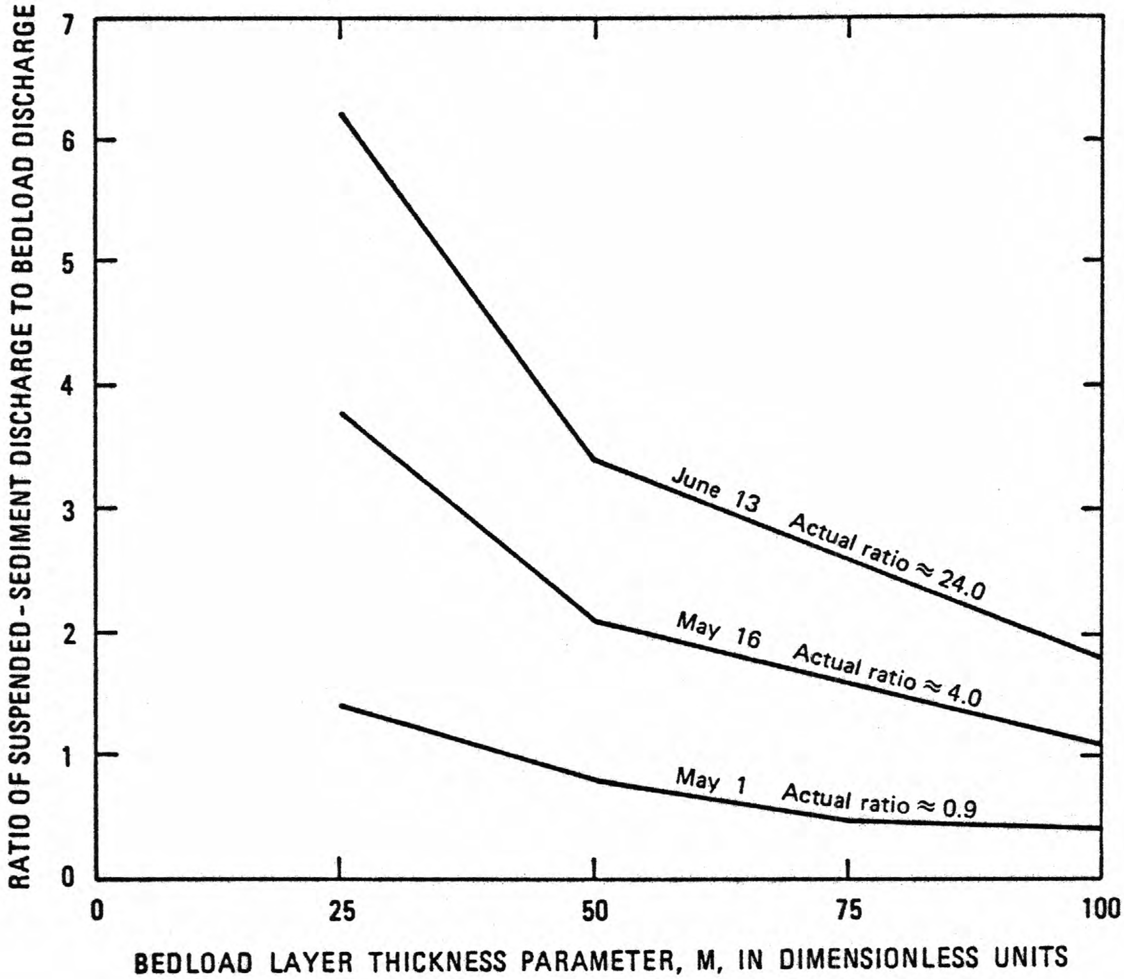

Figure 9. – Sensitivity test for the bedload layer thickness calibration parameter.

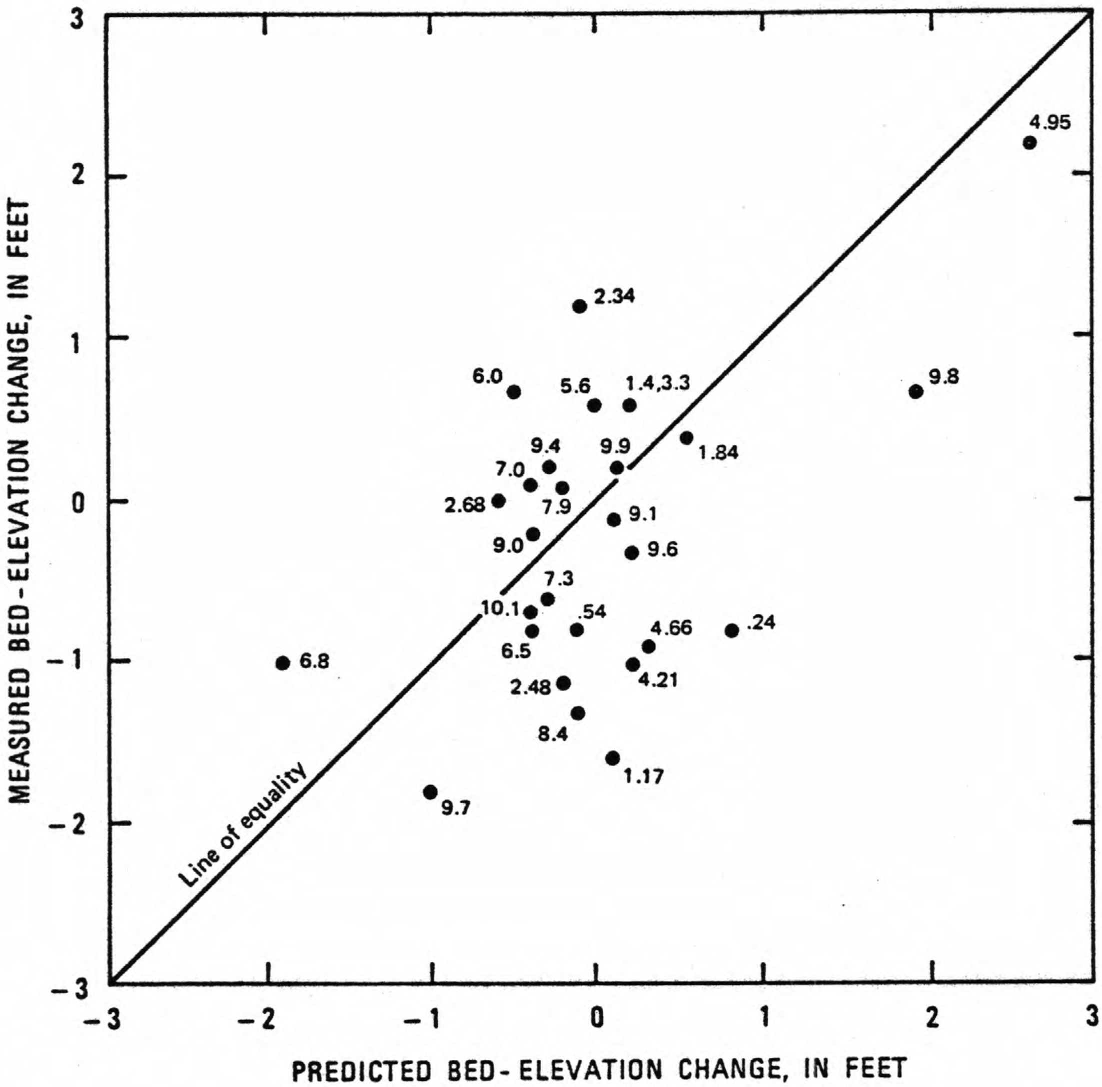

Figure 10. – Predicted versus measured riverbed elevation changes. Distance from diagonal line reflects degree of disagreement. Numbers give distance downstream from cross section 1, in miles.

the predicted changes agreed exactly with the measured changes, all the points would fall on the 45-degree line passing through the intersection of the zero coordinates. The plot shows considerable scatter; however, the model did predict the reaches where fill and scour are most likely to occur.

Additional information that the figure shows are (1) at 11 cross sections the model predicted changes in the wrong direction; (2) at 17 sections the predicted change was underestimated in comparison to the actual change; and (3) at 12 sections the predicted change was over-estimated. Most of the predicted changes were within 1 foot of the measured change.

A fortunate characteristic of sediment-transport models is that the longitudinal variation of the transport rate decreases with time as improperly posed initial conditions are healed by simulated erosion and deposition.

A comparison of the resulting predicted and measured total-sediment discharge passing sections 1 and 31 is listed below for the 50-day calibration period.

Location	Predicted (Tons)	Measured (Tons)
Inflow-Section 1	52,000	60,000
Outflow-Section 31	13,000	14,000

At the end of the simulation period the model indicated that of the 31 control sections one was availability limited in four sizes, six in three sizes, four in two sizes, and one in one size.

The parameter not adjusted was the duBoys critical shear stress, τ_c, as given by Graf (1971, p. 126). τ_c is the critical bed shear stress below which there is no particle motion. In this study, the bed shear stresses were so high as to preclude physically reasonable adjustments in τ_c having an influence on the predictions. That is, in this case the results are not sensitive to τ_c.

Calibration is a process of compromise. Matching predicted sediment discharge to measured would be simple if that were the only goal, and likewise it would be easy to match only predicted bed elevations to measured. One function is dependent on the other; scour or fill will not take place without sediment movement. The test of reasonableness, a judgment factor, is applied to determine if the predicted sediment-discharge values and bed-elevation changes seem reasonable in view of the limits of accuracy in measuring these values, and if the active bed widths, which also govern scour-fill and sediment transport rates, are in line with measured values. When these values are reasonable, the model is said to be calibrated.

The East Fork Carson River sediment-transport model is calibrated to the conditions that existed during the calibration period.

PREDICTIONS FROM THE MODEL

A mathematical model has been satisfactorily calibrated to simulate sediment transport rates for the East Fork Carson River. Two additional flow hydrographs from the Gardnerville gage were simulated to assess sediment discharge and the corresponding scour and fill, and to test the model's ability to extrapolate the 1978 conditions for several years.

The first period simulated was the December 1955 flood, which covered 7 days of rise, peak, recession, and return to base flow. The maximum flow simulated was 4,000 ft^3/s which is about equal to channel capacity throughout the reach. No attempt was made to include sediment inflow resulting from return flows to the river from the valley flood plain, because there were no data. River diversions were also ignored because of the short flow duration and the probable minimal effect. The listing at the end of this section compares total inflow-outflow sediment loads in the study reach with other simulated periods. Figure 11 shows the bed-elevation change at the end of the simulation period. The sections immediately downstream from the Allerman, Rocky-Virginia, and Cottonwood Dams all show scour. The river reach immediately upstream from the Highway 56 and 88 bridges also show scour, while the reaches immediately downstream from the bridges show fill. The reaches immediately upstream from the next to last rock dam in the study reach show about 1.7 ft of scour. This may indicate that through the years the crest elevation of the dam has not been maintained.

The second flow period simulated was the historical record from the Gardnerville gage for water years 1926-28, 1936-37, and 1940-49. This multiple period was used because it is representative of long-term average flow values.

The predicted total sediment load inflow to and outflow from the study reach for the 15-year period was 756,000 and 357,000 tons, respectively; thus, a net deposition of about 300,000 tons was predicted.

Figure 11 shows the river bed-elevation change at the end of the simulation period. The area showing the greatest deposition is the 1.5-mile reach immediately downstream from the Cottonwood Dam where fill values exceed 20 ft. Is this a realistic situation and can this be explained? This particular reach is one of the areas where sand and gravel were mined for years, and Dallas Byington (oral commun., 1979), a local rancher, recalls excavated depths of nearly 20 ft. The banks have been built up several feet in height since the 1963 flood, and the slope through the reach is less than that of river reaches immediately upstream and downstream. Thus, the natural river progression in an aggrading situation is to raise the channel-bed elevation to a point where high flows can overtop the bank and cut a new channel.

There are areas of local scour, such as those immediately downstream from the Allerman and Virginia-Rocky Dams and the Highway 88 dam; however, as long as all the present dams are maintained the vertical riverbed scour between them can probably be controlled.

Period of record	Sediment Load in Tons Inflow	Sediment Load in Tons Outflow	Ratio inflow/outflow (rounded)
1978 calibration (50 days)	60,000	14,000	4/1
Historical record 1/ (15 yrs)	756,000	351,000	2/1
December 1955 flood (7 days)	34,000	7,000	5/1

1. Water years 1926-28, 1936-37, 1940-49.

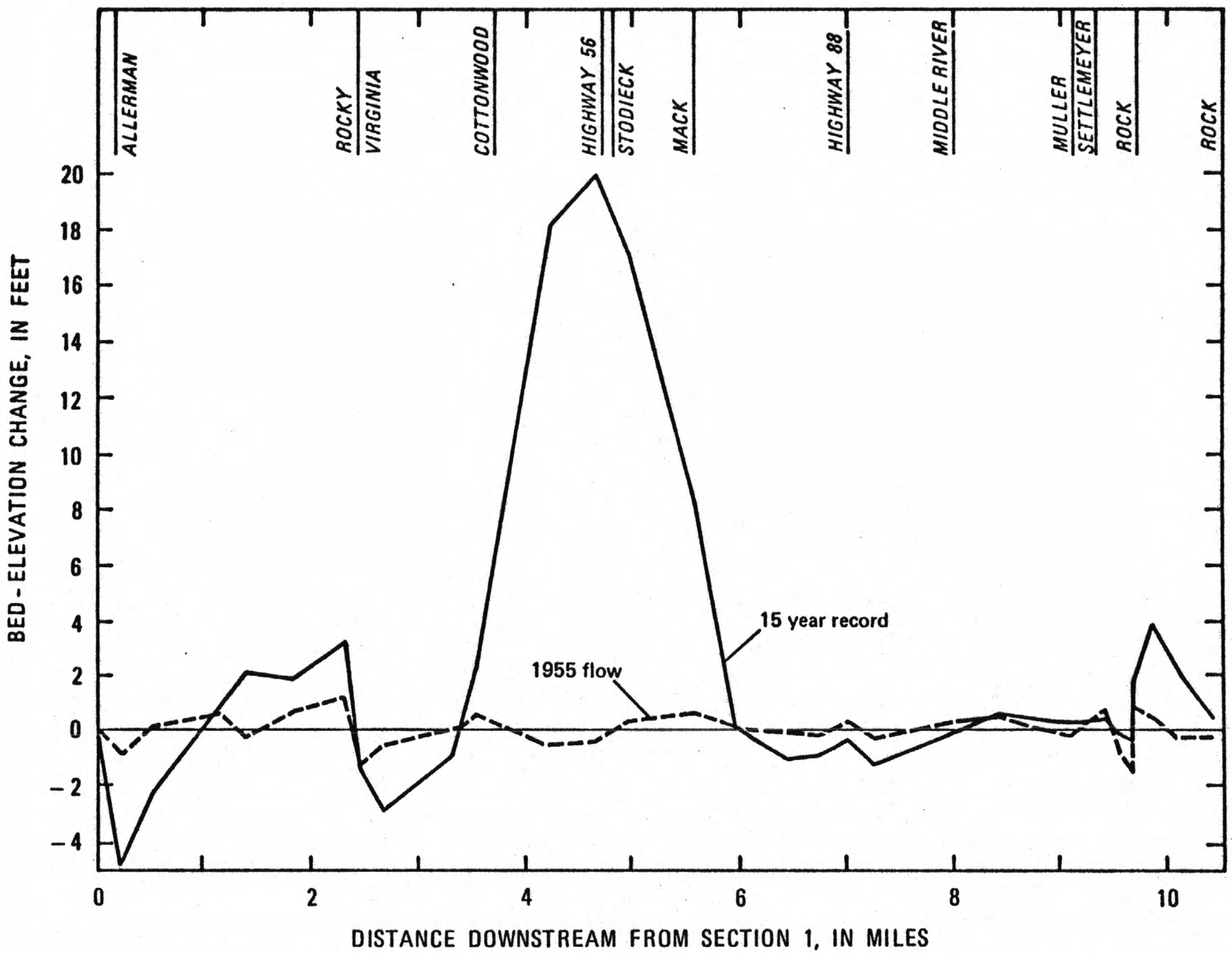

Figure 11. – Predicted changes in riverbed elevations for two simulation periods.

SUMMARY AND CONCLUSIONS

The intensive data-collection program during the 50-day period of April 27 to June 15, 1978, showed that the study reach was aggrading during the period. About 60,000 tons of sediment were transported into the study reach and only 14,000 tons were transported out; 46,000 tons of sediment were deposited in the reach. The streamflow at the Gardnerville gage was slightly greater than the 46-year period of record for this period, and without evidence to the contrary it was assumed that the sediment discharge was slightly greater than average for the period.

The bed elevations changed considerably during the period, with most of the changes being less than 1 ft. The bed showed a fill of as much as 2.5 ft at Stodieck Dam and a scour of 1.9 ft at Highway 88 bridge.

The data collected during the 50-day period were used in the calibration of the sediment-transport model. The model reproduced values of sediment discharge and bed-elevation changes that were considered reasonable for the calibration period. The total-sediment discharge into the study reach was predicted to be 52,000 tons in comparison to the 60,000 tons measured. The sediment discharge out of the study reach was to be 13,000 tons and measured sediment discharge was 14,000 tons. Although the predicted bed-elevation changes were not in very close agreement with the measured changes, the model was able to show the general reaches where fill or scour are most likely to occur. The model should be useful in predicting general changes that might occur in the study reach resulting from channel improvements or changes.

The model was used to predict volumes of sediment discharges and bed-elevation changes that might have occurred for two historical flow periods. A 7-day period in December 1955 was used to predict what might have happened during a flood-event of 4,000 ft^3/s which is about equal to the channel capacity. The sediment discharge into the study reach was computed to be 34,000 tons and the sediment discharge out of the reach to be 7,000 tons during the 7-day period. An estimated 27,000 tons of sediment were deposited. The bed-elevation changes were less than 1.7 ft, which is the scour at the most downstream rock dam in the study reach.

An aggregated 15-year period comprising the periods 1926-28, 1936-37, and 1940-49 was used to represent a long-term average flow period for the model. The model predicted that the sediment load into and out of the study reach was 756,000 tons and 357,000 tons, respectively. A net deposition of 300,000 tons was predicted for the 15-year period. The annual average sediment load was 50,000 tons into the study reach and 24,000 tons out of the reach. The bed-elevation changes showed about 20 ft of sediment deposition downstream from Cottonwood Dam, for an annual average of 1.4 ft. The predicted deposition appears to be realistic because sand and gravel have been mined in this reach for years with mining depths to 20 ft below the riverbed.

A sediment-transport model was calibrated during this study and is available for water users and managers to assess the effects of channel improvement or construction. Some situations for which the model might be used to make predictions are:

1. Failure of existing dam.
2. Construction of a dam.
3. Change in operation of dams.
4. Addition to upstream storage.
5. Mining of sand and gravel.

SEDIMENT TRANSPORT MODEL DESCRIPTION

Bennett and Nordin (1977) have previously described this model essentially as follows. A successful sediment-transport model must contain three basic components. The first computes the space and time distribution of flow in a channel segment or segments, given information concerning channel geometry and roughness, a time history of inflowing water discharge, and the stage or a rating curve at a downstream section. The second component computes the rate of sediment transport, given information concerning bed composition, hydraulic variables, and suspended-sediment and bedload inflows. This component must compute suspended-sediment and bedload outflows and channel fill or scour. The final component keeps an account of local channel-bed elevation and size composition.

Flow Computations

Because of the long time step necessary for simulating the lengthy calibration data-collection period, and because of stability and expense considerations, a sequential backwater-curve computation method was substituted for the unsteady-flow computation technique presented by Bennett (1975). In this method, the unsteady-inflow hydrograph is represented as step-wise variable, with the discharge for each 12-hour increment equal to the average value for that period. The water-surface profile is computed using the standard step method given by, among others, Chow (1959, p. 265). The usual boundary condition for flow across the weir is assumed to be critical depth. However, if at a particular weir, the backwater curve projected from downstream gives a greater water-surface elevation than the critical depth condition, then the critical flow section is assumed to be drowned out and the backwater curve is extended upstream through the weir.

Sediment-Transport Computation

In the bedload zone the conservation of mass equation for bedload transport is

$$nW\frac{\partial z_b}{\partial t} + \frac{\partial Q_b}{\partial x} = S \qquad (1)$$

where n is one minus the porosity, W is the active width of bed—that part of channel width in which erosion or deposition can take place, z_b is the local bed elevation, t is time, Q_b is the bedload volume flux, x is the distance along the channel, and S is a source term for transfer from the suspended-load zone across B-B', as shown in figure 12, into the bedload zone. In the model, a finite-difference version of equation 1 is solved.

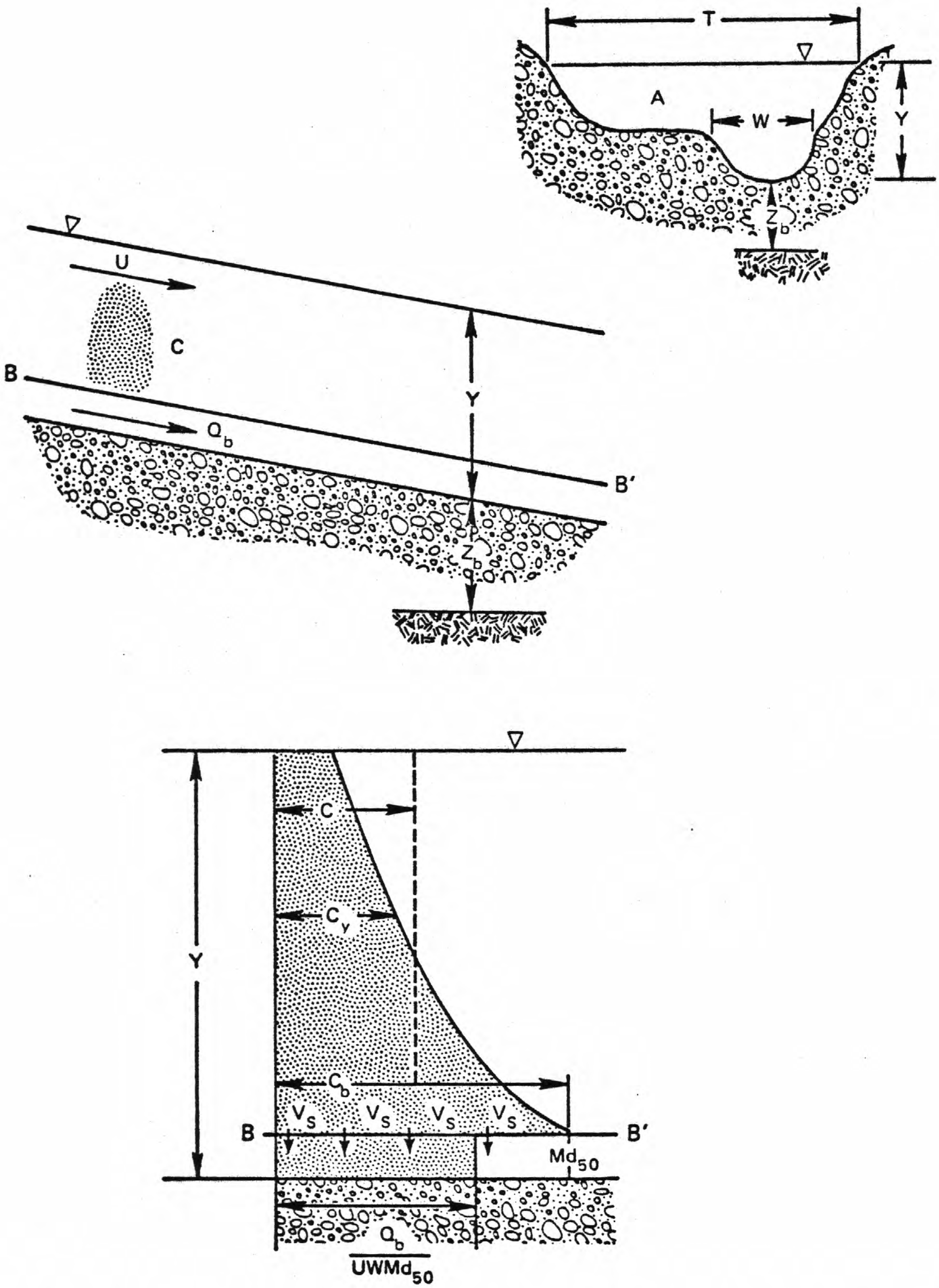

Figure 12. – Definition sketches of vertical transport processes. See text for definition of symbols used.

A form of the duBoys equation (Graf, 1971) is used to relate bedload transport to local hydraulic conditions by the relation

$$Q_b = W \chi \tau (\tau - \tau_c) \qquad (2)$$

where χ is the transport coefficient, τ is the bed shear stress, and τ_c is the critical bed shear stress below which there is no particle motion.

The bed shear stress

$$\tau = \gamma y s_o = \gamma \frac{U^2}{C'} \qquad (3)$$

is approximated in the model by the terms to the far right in equation 3 wherein C' is Chezy's hydraulic-conductivity parameter γ is the unit weight of water and U is the cross-sectional average velocity. This is done because it is difficult to define the local bed slope, s_o, in a nonuniform unsteady flow.

χ is an experimentally determined transport coefficient. Its variation with sediment diameter has been established for a small range of sediment sizes in flume studies of flow over uniform beds (Graf, 1971). As used here, χ is a transport coefficient for a particular size of material among other sizes present in a nonuniform bed. It is doubtful that the value of χ will be the same in both situations, and in this study it is treated as a parameter subject to adjustment in calibration.

The conservation of mass equation for sediment in the suspended-load zone is

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} - \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) = S' \qquad (4)$$

wherein C is the volume concentration of suspended sediment in a particular size class, D is the longitudinal dispersion coefficient, U is velocity, and S' is a source term for transfer across B-B' (fig. 12) from the bedload zone. In equation 4, S' differs only in sign and by a multiplicative factor from S in equation 1.

Longitudinal dispersion in the suspended-load zone is negligible with respect to dispersion due to the storage of particles in the stream bed. Therefore, the third term on the left in equation 4 may be omitted. When this is done, equation 4 reduces to a plug-flow approximation. In plug flow, for a time increment Δt is about equal to the flow time for a channel segment of length Δx, equation 4 may be written

$$U \frac{dC}{dx} = S' \qquad (5)$$

if the inflow concentration to the segment is always taken as the value at the start of the time increment, time t. This is because in plug flow for Δt equal to the flow time, the inflow concentration is translated without dispersion a distance $U.\ t = \Delta x$ in the time increment Δt. As a result, the concentration value input at time t arrives at the end of the segment at time $t + \Delta t$, subject to modification only by the source term S'. The best estimate for U to use in simulation modeling is the four-point average comprised of the individual values at both ends of the segment at times t and $t + \Delta t$.

To define the source terms S and S', postulate that an instantaneous change in sediment transport capacity induces a concentration difference between the bedload zone and the suspended-load zone across the line B-B' of figure 12. Further postulate that this concentration difference causes a flux from the higher to the lower concentration and that this flux is proportional to the magnitude of this difference, that is, postulate a linear transfer of flux across B-B' proportional to the concentration deficit.

Referring to figure 12, and assuming that $Q_b = 0$ and that a logarithmic velocity profile with origin at elevation Md_{50} (a vertical eddy diffusivity of zero at elevation Md_{50}, see below), considerations of particle mechanics show the downward flux in equation 1 at B-B' to be $W.v_s.C_b$. If Q_b is nonzero, then the concentration in the bedload layer is $Q_b/(W.M.d_{50})$., and postulating the flux proportional to the concentration deficit, the term S in equation 1 becomes

$$S = Wv_s\left(\frac{Q_b}{WMd_{50}U} - C_b\right) \qquad (6)$$

where v_s is the sediment settling velocity and C_b is the sediment concentration at the lower edge of the suspended-load zone.

Knowledge of the mechanics of equilibrium sediment concentration profiles can be used to approximate the concentration C_b at the lower edge of the suspended-load zone. In terms of the depth averaged suspended-sediment concentration C (the concentration used in the simulation model), C_b is

$$C_b = C\frac{yv_s}{\varepsilon s}\left(1-\exp\left(\frac{\varepsilon s}{yv_s}\right)\right) \qquad (7)$$

where y is flow depth and ε_s is the eddy diffusivity for sediment, here assumed to be a depth-averaged value based on a logarithmic velocity profile, and again assuming the local bed slope to equal the friction slope,

$$s = \frac{K\sqrt{g}}{6}\frac{U}{C'}\, y \qquad (8)$$

where K is von Karman's coefficient, which is approximately equal to 0.4. Those interested in more detail concerning vertical concentration profiles should consult Graf (1971) or Bennett and Nordin (1973).

Considering the above, equation 5 becomes

$$U\frac{dc}{dx} = v_s\frac{W}{A}\left(\frac{Q_b}{WMd_{50}} - C_b\right) \qquad (9)$$

where Q_b and W/A, as well as, the parameters used in determining C_b are four-point averages over the time increment Δt and the distance increment Δx, and A is channel cross-sectional area. As compared to the source term of equation 6, the sign change in equation 9 is to account for a change in direction of the flux at B-B' and the term W/A arises from a consideration of the flux balance for the suspended-load layer. Substitution of equation 7 into equation 9 provides an expression which can be evaluated in closed form for each Δx increment over each Δt time step. This analytical expression was used in calculating suspended-sediment discharge in the simulation model.

As will be seen subsequently, occasions arise when the transport is governed not directly by equation 1, equation 2, and equation 9, but by the amount of material available to be scoured from the bed during a particular time increment. In this situation, $\partial z_b/\partial t$ is known and the downstream values of Q_b and C are obtained from finite difference versions of equation 1 and equation 9.

Bed-Composition Accounting

The bed-composition accounting component keeps track of the size composition and elevation of the bed at each of the discrete cross sections chosen to represent the stream or streams being simulated. The accounting is accomplished conceptually using two or three layers depending on whether net erosion or net deposition has occurred at the cross section during the simulation time. Each layer is assumed to be homogeneous within itself and to have the same porosity as that of the original bed.

The upper layer of the bed is called the active layer. Its thickness is specified by a parameter, N, times the d_{50} of the largest size used in simulation. The active layer is always present and its thickness is constant over the simulation time. The composition of the active layer at each cross section is a function of time and it incorporates the cumulative effects of selective scour and deposition.

Bed armoring is simulated by limiting erosion of a particular size of material in a time step to the amount of that size available in the active layer. If bed shear stress at a cross section is too low to transport any size present in the active layer, then the bed is armored and no erosion can occur until the bed shear stress exceeds the critical value for the smallest size present in the active layer. If for a particular size, the transport capacity as given by equation 2 is such that equation 1 postulates erosion of more material of that size than is present in the active layer, only the amount present is eroded, and the transport is availability-limited in that size. If there is enough present in the active layer to allow the erosion postulated by equation 1, transport is capacity-limited for that size at that cross section. In the first situation above, the cross section is static, in the latter two it is degrading. Capacity limited transport also occurs when there is deposition of a particular size at a cross section. If there is net deposition at the cross section, it is aggrading.

Conceptually, the active layer represents the bed-material layer that can be worked or "sorted through" by the action of the flowing water in the time step, Δt, to supply the volume of material necessary for erosion. The thickness of the layer must have some relation to the height of bed forms in the channel, and to their rate of movement. The parameter N is related to Δt; the larger Δt; the smaller N must be to yield the same predictions. From consideration of bed-form mechanics, this inverse relationship is reasonable because in a stream a greater depth of bed can be sorted in a greater time.

At a cross section when simulation starts, the bed composition and bed elevation are specified. The composition is assumed to be homogeneous over the active width of channel and to extend downward indefinitely. In the present model, only one original bed-material layer is specified; however, if clearcut individual layers are present, their compositions and elevations could be specified and considered in the scheme discussed below with little modification.

When the deposition of a certain thickness of a particular size fraction occurs during simulation, this material is added to the active layer. An equal thickness of the active layer is added to a second layer, the inactive deposition layer shown in figure 13. The size composition of the inactive-deposition layer is recomputed assuming it to be homogeneous and considering the size composition of the active layer. The thickness of the inactive-deposition layer is also updated. The size composition of the active layer is then recomputed, considering the size fraction and thickness of the layer of material deposited. The local elevation of the channel bottom is then updated by adding to it the thickness of the material deposited divided by bed porosity (volume of solids deposited divided by active width and by porosity). This process is repeated for each size fraction.

If equation 1 predicts erosion of a particular size class of material from the bed, the reverse of the above procedure is followed. The required thickness is removed from the active layer, if available. The same thickness of material is added to the active layer from the one below it. The composition of the active layer and the bed elevation are updated, considering the size class of material removed and the composition of the layer below. If the layer below the active layer is inactive deposition, its thickness must also be updated. Provision is also made for destroying the inactive-deposition layer and adding material to the active layer from original bed material, if necessary.

If there is erosion, and transport is availability-limited, only the available amount of material is removed from the active layer. The updating process is the same as described above. Following updating, new values of Q_b and the downstream suspended-sediment concentration are computed as described at the end of the previous section.

Simulation Model

For use in the simulation model, the components just discussed are implemented as shown in the simplified logic diagram of figure 14. In the figure, Δz_b is equal to the thickness of erosion or deposition for a particular size class. C_{DS} is equal to the computed downstream suspended-sediment concentration and $T_{1,k}$ is equal to the thickness of the layer of material of a size fraction k in the active layer. Figure 14 indicates in graphic form the decision processes discussed in the previous section.

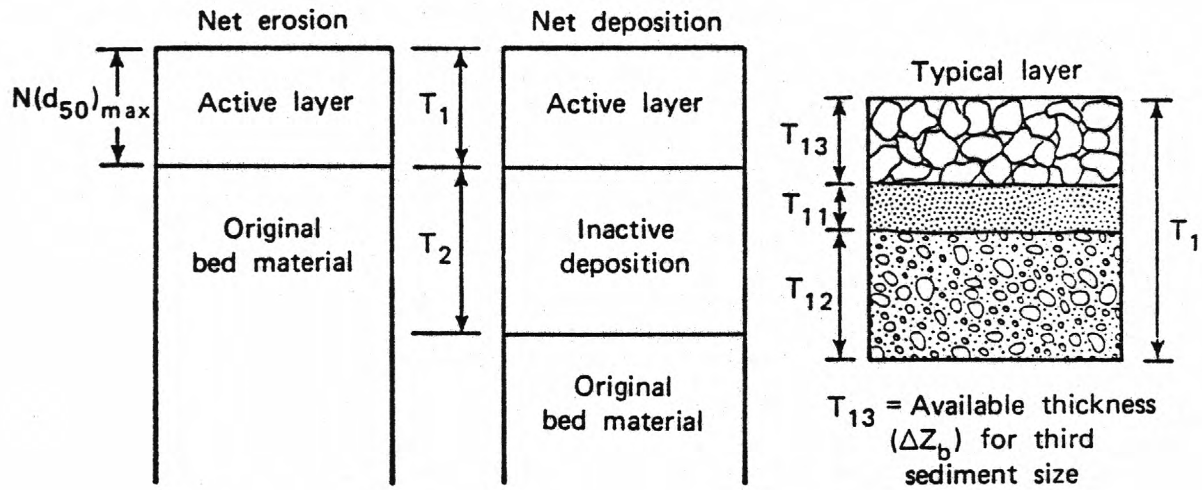

Figure 13. – Bed composition accounting procedures. See text for definition of symbols used.

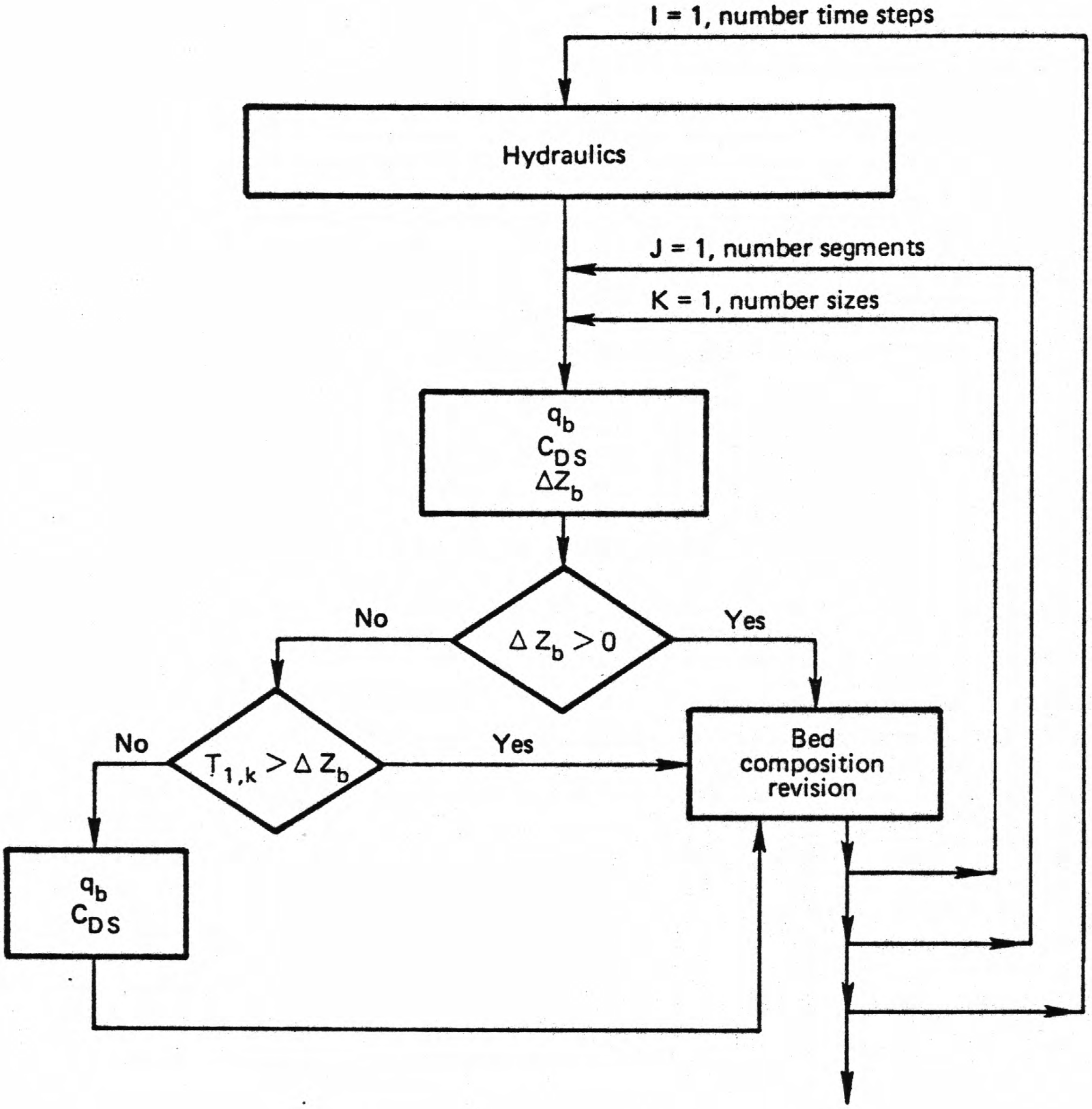

Figure 14. – Simplified logic diagram. See text for definition of symbols used.

To recapitulate briefly, to run the simulation model initial-condition requirements for flow computation are cross-section geometry and absolute elevation, velocity, and depth. For sediment transport, initial-condition requirements are active width and bed-size composition. Boundary-condition requirements for flow computation are time histories of inflow water discharge, and downstream stage or a downstream stage-discharge rating curve. For sediment transport, the requirements are time histories of inflowing suspended-sediment discharge and bedload discharge by size class.

For the flow component, the parameter available to fit the model to particular field situations is the Chezy discharge coefficient, C'. For the transport component, the parameters are the duBoys characteristic sediment coefficient, X, the critical shear stress; τ_c, and, M, which governs the thickness of the bedload zone. The parameter M indirectly governs the ratio of suspended-sediment discharge to bedload discharge. The armoring parameter is N, which governs the thickness of the active layer and thus determines the amount of material available for erosion during a particular time step. Until sufficient experience has been gained concerning the variability of these parameters in field situations, it is extremely important that any model be carefully calibrated before prediction is attempted.

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