SEDIMENT TRANSPORT AND RIVER SIMULATION MODEL

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SEDIMENT TRANSPORT AND RIVER SIMULATION MODEL

by

By Curtis J. Orvis and Timothy J. Randle, Hydraulic Engineers

Bureau of Reclamation, Denver, Colorado

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This study summarizes the development and application of the Sediment Transport and River Simmulation (STARS) Model to sediment studies in the Grand Canyon. The methods used to compute water surface profiles, determine streamtube hydraulic properties, and calculate sediment transport capacity are discussed, along with the routines to mix transported and in-place sediment and update cross section geometries. The sensitivity of the input variables were tested (bed material grain size distribution and areal extent of the different bed material types, active layer mixing zone thickness, Manning's roughness coefficient, and cross-section geometry). Each of the four parameters was varied and the resulting volume change in stream bed analyzed to determine its sensitivity. Results show the STARS model to be most sensitive to the bed material size gradations and least sensitive to the number of cross sections. The model is not oversensitive to variations in input data. For every variable tested, the percent change in the volume of material removed was less than the percent change in the input data. The accuracy of the model is within the range of accuracy of the data collection program.

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SEDIMENT TRANSPORT AND RIVER SIMULATION MODEL

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ABSTRACT

The STARS model was developed to mathematically simulate the movement of water and sediment through alluvial river channels. The unique feature of this one-dimensional, steady-state model is the use of streamtubes to vary the hydraulic and sediment transport characteristics across a cross section. This will allow a more realistic representation of sediment movement. For example, scour can be modeled at one portion of a cross section while concurrent deposition occurs at another portion. The user can choose from a variety of sediment transport equations. A special routine is included in the model to reduce, if necessary, the computed transport rate to the supply limited rate.

Data requirements for operation of the STARS model include initial conditions such as cross section geometries and bed material size gradations. Also needed are reach boundary conditions such as water discharges, stages, sediment supply, and temperatures.

This report describes the STARS model input, output, and design. The methods used to compute water surface profiles, determine streamtube hydraulic properties, calculate sediment transport, update cross section geometries, and mix transported and streambed sediment are explained. Example applications for the East Fork River, in Wyoming and the Colorado River between Glen Canyon Dam and Lees Ferry are discussed. Sensitivity analyses for the STARS model applied to the Colorado River in the Grand Canyon are also provided.

INTRODUCTION

Background

A number of unique features were added to the STARS model to support the modeling efforts on the Colorado River in the Grand Canyon. With the closure of Glen Canyon Dam all of the incoming sediment to the study reach of the Grand Canyon is supplied from tributary inflow. Therefore, routines were included to increment water and sediment discharge at any location in the study reach. Additional routines were developed to vary initial bed material in three dimensions (longitudinal, lateral, and vertical). Bed material size gradations can be different at each cross section, varied laterally across a given section by streamtube, and varied vertically by layers within a streamtube. Additional features were developed for routing water and sediment in channels where rapids or bedrock outcrops occur. The Colorado River in the Grand Canyon has provided a difficult testing ground for the STARS model with flow conditions ranging from rapids at critical flow to slower velocity pools and bed material ranging from bedrock to fine sand.

Origin of the STARS Model

Rivers in the semiarid western United States often carry high concentrations of sediment which create problems for designers of bridges, dams, and other hydraulic structures. Aggrading and degrading rivers have been under study by hydraulic engineers, geomorphologists, and others for a number of years. With the advent of present day microcomputers and the ability to store and manipulate large quantities of data, mathematical models have gained wider acceptance and use. The STARS model has been developed by the Bureau of Reclamation using the basic concepts described in a report submitted by Albert Molinas to Ted Yang (Molinas, 1983). The model developed by Dr. Molinas, at Colorado State University, demonstrated the feasibility of simulating the movement and distribution of water and sediment in rivers using streamline theory. The STARS model is an outgrowth of the original and has different treatments of the active layer thickness, mixing properties, time steps, critical velocity constraints, and incremental water and sediment discharge. Additional features were included to make the STARS model efficient, flexible, and user oriented; such as simplified data file preparation, detailed error messages, tailored report generation, and personal computer and mainframe compatability. Further testing and refinement of the STARS model will continue as an ongoing process at the Bureau of Reclamation. The STARS model holds promise for the short, intermediate, and long term evaluation of rivers and river response to human intervention.

Purpose of the STARS Model

The main functions of the model are to calculate water surface profiles and simulate streambed response to varying water and sediment discharges. The Bureau of Reclamation STARS (Sediment Transport and River Simulation) model was developed to mathematically simulate the movement of water and sediment through alluvial river channels. A unique feature of this one-dimensional, steady-state model is the use of streamtubes to vary the hydraulic and sediment transport characteristics across a cross section. This will allow a more defined representation of sediment movement. For example, scour can be modeled at one portion of a cross section while concurrent deposition occurs at another portion. Other features include routines developed to route water and sediment in channels where rapids or bedrock outcrops occur, to increment main channel discharge with tributary inflow, and to simulate transport through varying layers of bed material having different size distributions.

Operational Concept

The STARS model may be used to perform either a fixed or moveable bed hydraulic analysis. When STARS is used as a fixed bed model, no sediment data are required and water surface profiles are computed assuming an unchanging bed.

When a moveable bed analysis is desired, the user must provide a discharge hydrograph (described by a series of discharges and corresponding time steps). A steady-state water surface profile is computed for the initial discharge of this hydrograph. Using these water surface elevations, each cross section is divided into streamtubes of equal discharge and hydraulic properties are determined. The incoming sediment load to the study reach can be entered as a sediment load hydrograph, sediment-discharge rating curve, or (as a default) the model will compute a sediment transport rate in each streamtube based on initial hydraulics and bed material size gradations at the upstream most section. Sediment transport rates are then computed for each streamtube at each cross section and the amount of scour or fill is determined. Finally a new size gradation of the bed is computed and the cross section coordinates are adjusted. Then the model proceeds through the rest of the discharge hydrograph in a similar manner.

The STARS model is one-dimensional, meaning no attempt is made to simulate secondary currents in the hydraulic calculations and compute sediment transport between streamtubes. Sediment transport routines are developed for sand or gravel bed channels and applications at present are limited to non-cohesive, coarse-grained materials.

Potential Applications

The fixed bed portion of the model is designed to calculate water surface profiles for any reach of river. Potential applications for the Bureau of Reclamation include tailwater studies downstream of a dam, backwater effects from a reservoir, and profiles in canals. The moveable bed portion has been designed to apply to degradation studies downstream from a dam, armoring analysis of a reach of river, scour due to channel constrictions, and scour and deposition patterns in general for such problems as locating intakes to pumping plants or diversion headworks.

DATA COLLECTION AND STARS INPUT

Specific field data needed to execute the fixed bed or hydraulic portion of the STARS model are similar to the data required for any of the available water surface profile computer programs. Geometric data to define the channel shape include cross section profiles, channel reach lengths between sections and roughness coefficients. Channel roughness values across a section are segmented with corresponding lateral coordinate endpoints and longitudinal reach lengths. The upstream boundary is specified as a discharge hydrograph and the downstream boundary is specified as either a stage or slope hydrograph. The only additional input is the number of streamtubes which gives the user the ability to further define the channel velocities and associated sediment transport rates across the section. Input of geometric data can be in English or metric units.

In order to run the moveable bed portion of the model in conjunction with the hydraulic computations, additional sediment data are required. Basic input includes representative sediment size gradations of the streambed material at each cross section. The gradations are presently input only in metric units. The user can vary the initial bed material size gradations both laterally and vertically at each cross section. An incoming sediment load hydrograph or sediment-discharge rating curve, corresponding to the water discharge hydrograph, is required along with the water temperature hydrograph to provide the upstream boundary conditions. A sediment transport method or algorithm must be selected which best fits the river conditions or available data in the study reach. Limits on the depth of degradation can be supplied by the user for the case where there is a known grade control or bedrock elevation below the streambed.

STARS OUTPUT AND REPORT GENERATOR

The output from the model can vary significantly from a fixed bed to moveable bed analysis and with the intent of the user. Therefore, a separate report generator was developed to summarize large quantities of computational output. Output tables are designed by the user to meet specific needs. Example output would be information for a given cross section on a page with a user defined choice of hydraulic or sediment transport parameters for column headings and time incrementing in rows. Table 1 is a list of column headings presently available.

TABLE 1

Report Generator Output Parameters

1. Cross Section Name
2. River Station
3. Water Surface Elevation
4. Thalweg Elevation
5. Elapsed Time Simulated
6. Major Time Step
7. Accumulated Minor Time Steps
8. Total Discharge
9. Critical Discharge
10. Average Velocity
11. Velocity Distribution Coefficient
12. Total Flow Area
13. Total Wetted Perimeter
18. Average Hydraulic Radius
19. Average Hydraulic Depth
20. Total Bed Material Transport
21. Accumulated Sediment Flux
22. Accumulated Scour or Fill
23. Streamtube Boundary Stations
24. Streamtube Area
25. Streamtube Perimeter
26. Streamtube Width
27. Streamtube Velocity
28. Streamtube Bed Material Transport
29. Streamtube Accumulated Flux
30. Streamtube Scour (-) or Fill (+)

14. Total Top Width

15. Total Conveyance

16. Hydraulic Slope

17. Temperature

31. Streamtube D_{35}

32. Streamtube D_{50}

33. Streamtube D_{65}

34. Streamtube D_{90}

STARS MODEL DESIGN

Water Surface Profile Computation

Open Channel Flow. - Water surface elevations are computed assuming steady-state conditions using the standard step method. An upstream boundary discharge hydrograph and a downstream boundary elevation are required by the model. The downstream elevation may be expressed as a stage-discharge rating curve, an elevation hydrograph, normal depth (slope-discharge relationship), or critical depth. Unsteady open channel flow analysis is not used because of prohibitive computational time and cost.

From the water surface elevation at downstream most section, calculations proceed upstream satisfying the conditions of conservation of energy unless critical discharge occurs. The energy equation used in the model to compute water surface profiles takes the form:

$$Y_1 + \alpha_1 \frac{V_1^2}{2g} = Y_2 + \frac{\alpha_2 V_2^2}{2g} + H_f + H_e$$

where: Y_1 = water surface elevation at the upstream section,
Y_2 = water surface elevation at the downstream section,
α_1 = energy coefficient at the upstream section,
α_2 = energy coefficient at the downstream section,
V_1 = velocity at the upstream section,
V_2 = velocity at the downstream section,
g = acceleration due to gravity,
H_f = energy loss due to boundary friction, and
H_e = energy loss due to eddys which includes expansion and contraction losses.

The friction slope is computed using the Manning's equation. A Newton algorithm with special checks for convergence problems is used to solve the energy balance, normal depth, and critical depth equations. Convergence is usually obtained in two or three iterations, but for sections with large changes in width for small changes in elevation, these functions can have discontinuities in slope and a step search is temporarily employed until the trial water surface is past the point of discontinuity. Convergence is always obtained to a minimum tolerance of 0.01 feet.

The energy balance is voided when the computed water surface elevation has an adverse water slope or is below the critical elevation. When an adverse water slope is computed, the upstream water surface elevation is set equal to the downstream water surface elevation. When the computed water surface elevation is below critical depth, the model brings the water surface up to the critical depth. This is reasonable because supercritical flow rarely occurs in natural channels as an average condition across the entire section and because the sediment transport equations were developed with subcritical discharges. Also, supercritical elevations cannot be computed from a downstream water surface elevation.

Incremental Discharge. - The main channel flow may be increased in the case of tributary inflow or decreased in the case of a diversion. The change in discharge is considered to occur at a point between cross sections. The user provides the main stem discharge hydrograph at the upstream most cross section and incremental flow hydrographs (positive for inflow and negative for outflow) are added to the main stem flow.

Streamtube Concept

The mathematical basis for routing water and sediment in streamtubes begins with two definitions from Chow (1964):

1. "A streamline is an imaginary line within the flow for which the tangent at any point is the time average of the direction of motion at that point," and

2. "A streamtube is a tube of fluid bounded by a group of streamlines which enclose the flow."

The streamtube, in the case of river modeling, is not circular in shape but is an irregular area bounded by the channel geometry, the water surface, and the vertical streamtube divisions. Figure 1 shows a typical cross section divided into five streamtubes. This mathematical approach divides the flow into segments of equal conveyance and discharge. By calculating sediment transport in streamtubes, the distribution of the sediment transport across the section can be obtained. In this manner, transport rates calculated in overbank areas are lower than those for the main channel, as would be expected.

Streamtube boundaries are determined after the water surface elevation is computed for a given time step and discharge for the cross section as a whole. The total conveyance, summed from increments between individual coordinate points, is divided by a user supplied number of streamtubes (maximum of 10). The lateral locations of the streamtube boundaries are interpolated between cross section coordinate points. The area, wetted perimeter, and top width can then be calculated for the individual streamtubes. These parameters together with slope, velocity and bed material gradations are essential to computing sediment transport.

Sediment Transport Computations

Sediment Transport Equations. - A number of sediment transport equations have been developed from flume and river data based on bed material ranging from medium gravel to very fine sand. The predictive equations programmed into the STARS model are:

Meyer-Peter and Muller (1948) based on USBR investigations (1960, 1984). (This will be a future addition.)

Einstein Bed-Load Function (1950) based on the Velocity-Xi Adjusted Einstein Equations (Pemberton, 1972 and USBR, 1963).

Engelund and Hansen (1967). (This will be a future addition.)

Toffaleti (1968, 1969) adaptation of the Einstein Bed-Load Function.

Yang (1973) with the updated gravel bed equation from Yang (1984).

Ackers and White (1973).

Supply Limited Transport. - A distinction is made in the model between the sediment transport capability of a given river flow for a certain sediment mixture and actual availability of sediment supply. The transport equation predicts total bed material load for each of the size ranges in the bed based upon hydraulics for a certain discharge and time step. The sediment transport is considered to be supply limited when there is insufficient material available from upstream and also in the bed to supply this calculated transport capacity. The supply routine checks the availability of sediment and when the transport is supply limited, the model automatically reduces the transport rate, based upon capacity, to the supply limited rate.

Incremental Sediment Supply and Temperature. - The ability to add sediment from tributary inflows was included with the moveable bed portion of the model. Input of the incremental sediment can be in the form of a sediment discharge rating curve, or a sediment load or concentration hydrograph. The model weights the sediment supply in each streamtube by velocity. Higher velocities in the main channel would thereby contain larger portions of the incoming sediment load. Water temperature data can also be included with the incremental sediment supply since water temperature can have an effect on viscosity and, in turn, sediment transport. Temperature data from tributary inflows are discharge weighted with the main channel.

Cross Section Updating Routine

The critical link to making the STARS model accurately simulate a moveable bed is the ability to apply the predictive sediment transport calculations to the cross section coordinates. Sediment transport calculations proceed in the downstream direction matching the physical movement of water and sediment. For each of the streamtubes, sediment transport rates are compared between the upstream and downstream sections and a net sediment flux is computed for the subreach between the two sections by streamtube. Using the bulk density for sand, a volumetric change can be computed from the net sediment flux. Dividing the volumetric difference by the distance between sections gives a net change in cross sectional area to be applied to the coordinate points in the streamtube. After a net change in elevation is computed for each streamtube, the cross section coordinates are adjusted across the entire cross section. The elevation adjustment is the same for all coordinates within a streamtube but the adjustment is different for each streamtube.

Active Layer and Time Step

The sediment transport process is a gradual sorting and mixing of the incoming sediment load with the existing bed material. A certain thickness of bed material, or active layer, is considered to be in a state of flux at any cross section and time step. The thickness of the active layer must have some relationship to the height of bed forms in the channel (Bennett and Nordin, 1977).

In the STARS model the active layer, is a function of the hydraulic depth, which is considered to be a first approximation to the height of bed-forms in the channel. To date, active layer thickness in the model has ranged from 10-30 percent of hydraulic depth. While this relationship may underestimate some bed-form heights and overestimate others, it is practical for modeling because too small an active layer would severely reduce computational efficiency (increase modeling cost) and too large an active layer would introduce too much error. Once the active layer is computed, then an appropriate time step is determined.

A time step is the period for which the model will apply transport rates to scour and fill computations before the cross section geometries and bed materials are updated. The model's time steps are limited by either the user-specified time step or the minimum time in which any one streamtube scours or fills to a depth equal to its active layer thickness. The user provides a hydrograph of water discharges and corresponding time steps (major time steps). When this time step results in a scour or fill depth greater than the active layer, it is automatically divided into smaller (minor) time steps. The minor time step for all cross sections is computed so that the limiting tube and cross section will have a scour or fill depth equal to the active layer thickness.

When fill occurs, an inactive layer is established and maintained in a manner similar to the method used by Bennett and Nordin (1977). The inactive layer is used to keep track of the gradation and thickness of the fill material between the active layer and the original bed. If scour occurs after fill and the inactive layer is removed, the model then uses the gradation of the original bed material (see figure 2). This feature of the model may also be used to represent a river with two initial bed material layers of different gradations. In this case, the surface bed material gradation and its thickness are assigned to the active and inactive layer while the underlying bed material gradation is assigned to the original bed. Once the surface bed material has been scoured, the model will begin using the underlying bed material gradation (see figure 3).

Geometric Input Data

In order to route water and/or sediment through a study reach, the boundary of the channel bed and banks is approximated by a one-dimensional system. Cross sections give the channel definition in the vertical plane. They are generally located at even intervals along the reach and perpendicular to the flow. Survey data for channel cross sections are paired horizontal (X) and vertical (Y) measurements. Field work required to determine the hydraulic dimensions of a cross section involves setting up some type of distance measuring equipment such as a level, transit, or EDM system and taking intermittent soundings and distance measurements across the section. When selecting locations for cross sections in a particular reach, care should be exercised to provide the proper definition of channel features.

Reach lengths are defined by measuring horizontal distances between the centroids of area for roughness segments in the cross sections. Figure 4 shows three roughness segments denoted by n1, n2, and n3 corresponding to reach lengths $\Delta x1$, $\Delta x2$, $\Delta x3$.

Selecting Manning's n values requires considerable judgement. If water surface profile data are available a slope-area method may be used to arrive at the appropriate n value. The process involves adjusting n values to match observed water surface elevations with computed values. A number of publications are available to use as guides in choosing an n value:

1. "Design of Small Dams," U.S. Bureau of Reclamation, Second Edition, 1974, U.S. Government Printing Office, Washington, DC, 816 pages.

2. "Hydraulic and Excavation Tables," U.S. Bureau of Reclamation, eleventh edition, 1957, U.S. Government Printing Office, Washington, DC, 350 pages.

3. "Handbook of Hydraulics," King, H. W. and, Brater E. F., sixth edition, 1976, McGraw Hill, New York, NY, 584 pages.

4. "Open-Channel Hydraulics," Chow, Ven Te, 1959, McGraw-Hill, New York, NY, 680 pages.

5. "Open Channel Flow," Henderson, F. M., 1966, MacMillan Publishing Company, New York, NY, 522 pages.

6. "Roughness Characteristics of Natural Channels," Barnes H. H., Water Supply paper 1849, U.S. Department of the Interior, Geological Survey, 1967, U.S. Government Printing Office, Washington, DC, 213 pages.

Hydraulic Input Data

Hydraulic data are necessary input to define the upstream and downstream boundary conditions throughout the period of analysis. Since the reach is considered to be steady-state, a discharge hydrograph is applied to the upstream boundaries (main stem and tributaries). The hydrograph includes paired data for discharge and major time step durations and is blocked in the manner shown on Figure 5.

An initial water surface elevation is required for each time step at the downstream most section in order to compute water surface profiles. The stage hydrograph can be specified as either a stage-discharge rating curve, elevation hydrograph, or initial water surface slope hydrograph. The stage-discharge rating curve can be input as an equation or series of points to define the curve. Figure 6 gives an example rating curve with both options plotted together to show the difference in approximating the curve. Locating the downstream most section at a known control is useful to avoid shifts in the rating curve. Elevation or slope hydrographs are paired data sets which give the water surface elevation for a major time step duration generally corresponding to the water discharge hydrograph. Slope data are used to compute a normal water surface elevation. In the case where the downstream most section is in the delta area of a reservoir the water surface elevation hydrograph may vary based on reservoir operational schemes and not upstream discharge.

In general, the number of streamtubes should not exceed the amount of known variation of bed material across a section. The upper limit for practicality in moveable bed computations seems to be around five streamtubes. For a simulation with one streamtube the hydraulic and sediment transport parameters are computed only once at each section. Separate hydraulic and sediment transport computations are made for each streamtube. The time, and in effect cost of making runs, increases with more streamtubes.

Sediment Input Data

The river channel bed material is defined by sediment gradations at the boundary of the channel bed and banks. The bed material can vary laterally across the section and vertically by layers as given on figure 7. A gradation can be used to define each of the segments on figure 7 as reemphasized in the following table:

Table 2

Variation in Bed Material Size Gradations at a Cross Section

Vertical Type	Depth (ft)	Horizontal Type	Representative Bed Material Size, D_{50} (mm)
Upper Zone	0-12	Left	0.6
Upper Zone	0-18	Middle	0.4
Upper Zone	0-14	Right	1.2
Underlying Zone	12-∞	Left	2.1
Underlying Zone	18-∞	Middle	1.9
Underlying Zone	14-∞	Right	8.2

In many cases, the availability of bed material size gradation data may be very limited and it will be necessary to represent a study reach with only one size gradation. If sufficient data exist to vary the initial bed material size gradation throughout the study reach, then care should be taken. In general, cross sections with high velocities will have a coarser streambed than sections with lower velocities. If the initial bed material gradation is too fine at a high velocity section, the model may compute an excessive amount of scour. An inordinate amount of fill could be computed at low velocity sections if the initial bed gradation is too coarse. In simulating channels with a wide range of velocities, for a given discharge, it will be beneficial to match the higher velocity sections with coarse bed material gradations and the lower velocity sections with the finer bed material gradations.

The incoming sediment load to the study reach is applied to the upstream end and can be entered as a sediment load hydrograph, sediment discharge rating curve, or as a default the model will compute a sediment transport rate in each streamtube based on the initial hydraulics and bed material size gradations. The sediment load hydrograph is a blocked data set with paired points of sediment discharge and major time step durations. The durations cannot be more defined or have more blocked data pairs than the water discharge hydrograph. An example sediment discharge hydrograph is included as figure 8. The sediment discharge rating curve relates the sediment load to the discharge hydrograph. For example, a sediment discharge is computed for each water discharge in the hydrograph. Corresponding major time step durations would therefore be equal. Figure 9 is an example of a sediment discharge rating curve.

The water temperature of a river often varies with seasons and in the case of discharges from a dam, temperatures could vary with the level of outlet from the intake tower to the outlet works. Temperature has a direct effect on viscosity of the water, and in turn, sediment transport. The temperature hydrograph is input in paired data points and again cannot be broken into a greater number of parts than given on the water discharge hydrograph. An example temperature hydrograph is given on figure 10.

Selection of a Sediment Transport Equation

A number of sediment transport equations have been developed from flume and river data based on bed material ranging from coarse to fine sand. The predictive equations programmed into the STARS model in chronological order are: Meyer-Peter and Muller (1948), Einstein Bed-Load Function (1950) based on Velocity-Xi Adjusted Einstein (1963), Engelund and Hansen (1967), Toffaleti (1968, 1969), Yang (1973), and Ackers and White (1973). The user decides which predictive equation to use.

The Meyer-Peter and Muller routine is based on the USBR investigations (1960, 1984) converting the equations for use in natural channels. The original formulas were developed from coarse bedload in rectangular flumes and are applicable to streams carrying mostly coarse sand and gravel.

The Einstein Bed-Load Function generally computes sediment transport values that are greater than measured or observed. Einstein (1950) suggested that improvements could be made in the empirical curves for figures 5, 6, 7, and 8. Therefore, the Velocity-Xi Adjusted Einstein equation (Pemberton, 1972) was developed by USBR personnel (1963) to improve on the Einstein Bed-load Function and calculate the total bed material discharge for streams with sand and coarser size bed material. Adjustments were made to the Einstein Bed-Load Function for mean velocity and the Xi correction factor. The equations should apply to rivers and channels having a predominant sand bed.

The Engelund and Hansen (1967) method for calculating bed material transport is based on the similarity principle, dimensionless ratios for total shear stress, and empirical constants from flume data taken at Colorado State University. The authors have reservations for applying the equations to material smaller than 0.15 mm suggesting that the principle of similarity becomes impossible for large concentrations of suspended material. Sediment transport calculations for existing river data were completed by size fraction and showed unrealistically high transport rates for size ranges smaller than .15 mm. Therefore, calculations in the model are limited to bed material sizes greater than .15 mm.

F. B. Toffaleti (1968, 1969) developed another adaptation of the Einstein Bed-Load Function to compute total river sand discharge with a detailed distribution from the bed to surface. Total bed material load can be calculated by size fraction and transport rates in the lower, middle, and upper zones of flow can be determined. A large variety of experimental and field data were applied to the empirical equations ranging from the 8-foot Colorado State University flume to the Mississippi River. The author limits sediment transport calculations to sand size material greater than 0.0625 mm or 0.000205 feet and a similar limitation is applied in the STARS model.

The STARS model version of the Yang (1973) method to calculate sediment transport is a modification which includes sediment transport by size fraction. The theory calculates a sediment concentration based on dimensionless parameters. A limitation to the mathematics of the theory was included in the STARS model calculating sediment transport for size ranges with shear velocity Reynolds numbers greater than 1.2. The updated gravel bed equation was also included in the STARS model making the routine applicable to bed materials from fine sand to gravel up to 10 mm in diameter.

At about the same time as C. T. Yang was developing his equation for sediment transport in the United States, P. Ackers and W. R. White (1973) developed their equations in England to calculate sediment transport based on dimensionless parameters describing sediment mobility. The STARS model version includes a modification to calculate sediment transport by size fraction. The calculations are limited to partical sizes in excess of .04 mm as suggested by the authors. Independent flume data, and data from small and very large sand bed rivers were collected and used in the analysis giving the theory a wide range of applicability.

Mixing of Bed Material Sediment

Accounting steps and checks are undertaken in the mixing routine to mix incoming sediment with the streambed and maintain proper gradations across the section and through the vertical by streamtube. A new size gradation of the streambed is determined from a mass balance (by size fraction) of the incoming sediment, sediment in the active layer, and sediment passing the cross section.

The first step in determining a new bed material size gradation is to determine the proper bed material for each streamtube by selecting the dominate size gradation within the streamtube. Size gradations in dry overbank areas are kept the same. The fraction of material in the active layer is computed for each streamtube using the initial or old bed material size gradation and the initial active layer thickness (based on a percentage of the hydraulic depth). The total supply or source of sediment is computed for each size fraction for a given streamtube by adding the incoming sediment to the material in the active layer. If the bed material is bedrock or the material is too coarse to transport, the supply is set equal to the transport of the upstream cross section. New active and inactive layer depths are determined, based upon the amount of scour or fill, and used to compute a thickness-weighted gradation to be applied at the end of the time step.

The active layer thickness, at the beginning of the minor time step, will increase or decrease depending upon whether the streambed is filling or scouring. The change in the active layer thickness is limited to plus or minus 100 percent of its original size. The exact change in thickness is determined from the mass balance. At this point, new bed material size gradations are determined with separate procedures for scour and fill. New active and inactive layer depths are computed and the new size gradations for each layer are determined by a thickness-weighted average of the initial and ending active and inactive layers (see figure 11).

A base gradation is used to keep track of the gradation below the inactive layer. When the bed has scoured through the upper bed material zone or inactive layer the underlying bed material is used. The base gradation is updated whenever the bed has scoured to a new minimum elevation and subsequently fills. If the initial active layer is completely removed, the bed material size gradation is adopted from the inactive layer. When there is no inactive layer, then the bed material size gradation is set equal to the base or underlying size gradation.

The boundaries or station limits corresponding to the bed material size gradations are allowed to expand as discharge increases and overbank areas become wet. The bed material station limits remain constant as discharge decreases and the water's edge recedes. The bed material station limits for the interior streamtubes are set equal to the streamtube boundaries at the end of each time step. Streamtube boundaries change with time as a function of both discharge and new cross section geometry. If the change in streamtube boundaries from one minor time step to the next is small, then the bed material size gradation of the streamtube will be continuous with time. However, if the streamtube boundaries do change considerably, e.g., due to a large change in discharge for a given cross section geometry, then the bed material size gradation of the streamtube will reflect the new position of the tube in the cross section.

The model allows fill to occur on bedrock only if the Froude number and velocity, at a given section, are less than 95 percent of those computed for the next upstream section. Also, a maximum threshold velocity above which material will be carried over the bedrock is determined in the model by allowing sediment deposit on bedrock and then applying the sediment transport equation during the next minor time step to see if the material will be either removed or continue to fill. In the interest of computational efficiency, the user may provide the model a predetermined threshold velocity for which there is certainty throughout the simulation that any material deposited upon bedrock would be immediately removed during the next time step.

Once the cross section geometry and size gradation are updated, the minor time step is finished and the next time step begins with the computation of a new water surface profile. New velocities and size gradations will be used in the next computation of sediment transport. Thus for a given discharge, rates of scour or fill will decrease with time.

Model Limitations

The greatest limitations to effectively using the STARS model is level of experience of the user, time, and money. The model also has other limitations concerning deficiencies of input data, bank erosion, and application to fine-grained streambeds (silts and clays). Lack of good input data is frequently a limiting factor in modeling. Adequate input data describing the initial channel geometry, initial bed material size gradation, and upstream boundary water and sediment supply (including tributaries) for the study reach are requisite for proper application to the STARS model.

Rivers are dynamic systems and channel geometry may dramatically change with time. Thus, it is important to have cross section data collected as close in time as possible to the beginning time of simulation. For example if cross sections were collected after a large flood, the measured channel geometry and bed material size distribution may reflect conditions that are not typical of pre-flood conditions.

Initial bed material size gradations are important in several ways. First, the computed transport rates are very dependent upon bed material size gradations. Second, the initial bed material conditions define the thickness of material which may limit maximum scour depths. Lastly, the knowledge of lateral variation of bed material will in part determine how many streamtubes are used. In general, the number of streamtubes should be related to the amount of known variation of the bed material across a section.

Sediment supply at the boundary conditions influences channel aggradation and degradation. Thus, accurate sediment supply data at these locations are important elements in river simulation. The supply of sand to a river immediately below a dam is often assumed to be zero.

Data are also useful, if not required, to calibrate or verify various aspects of the model. Observed water surface elevations for a known discharge are needed to calibrate the Manning's n roughness coefficient. Ideally, Manning's n should be calibrated for the range of discharge used in the river simulation. Also, suspended sediment, bed material size gradations, and hydraulic data (at the upstream boundary) influence the choice of a sediment transport equation. Finally, field measurements of actual river conditions are necessary to verify or calibrate the input data used in predictive river simulations. These data might include: sediment outflow from the study reach, initial and ending conditions of channel geometry and/or bed material size gradations, and/or observed water surface elevations.

The STARS model can predict different rates of scour and fill for each streamtube but it does not specifically address bank erosion. For rivers where bank erosion or river meandering is of extreme importance, use of the STARS model is not recommended.

The STARS model is not applicable to a cohesive or fine-grained streambed because the sediment transport equations presently in the model apply only to sand size or larger sediments. The ability to model the armoring process is also limited by the chosen sediment transport equation. The Einstein-based sediment transport equations (Velocity-Xi Adjusted Einstein and Toffaleti) predict transport by size fraction and have hiding factors that limit the transport of smaller size sediments when mixed with larger particles. The other sediment transport equations were designed to predict the total bed material load only; the transport is not first determined for individual size ranges. These equations can be made to estimate the transport by size range but any hiding factor would have to be external. The STARS model presently has no external hiding factor.

In general, the STARS model predicts that as the streambed fills the bed material will become finer and velocities will increase, and as scour occurs the streambed will coarsen and velocities decrease. Thus, for a given discharge, rates of scour or fill as computed by the STARS model will decrease with time. However, no provision is made to change the Manning's roughness coefficient with changes in bed material.

Model Abilities

With the critical depth constraint, the STARS model has the ability to model steep channels with continuous water surface profiles. Rapids in natural rivers are comprised of a series of hydraulic jumps distributed in a seemingly random pattern across the channel and it is not realistic to simulate this system as one hydraulic jump as average conditions across a channel. All of the energy dissipation in a natural river does not occur in one hydraulic jump and it is reasonable to approximate the water surface profile through a rapid by limiting the elevation to the critical depth.

As few as one or as many as ten streamtubes can be used to vary hydraulic and sediment parameters across the channel. The user should be aware that modeling costs can drastically increase with the number of streamtubes and the number of streamtubes should be related to the amount of input data.

The STARS model can be used to perform river simulation with either a fixed or moveable streambed.

Initial bed material size gradations can be varied in the longitudinal, lateral, and vertical dimensions.

For the moveable bed portion of the model, instantaneous rates of scour or fill are applied to discrete increments of time.

The STARS model seeks to balance the sediment transport rate at each cross section for a given streamtube and discharge. This is done by adjusting both the channel geometry and bed material through the scour and fill process. Therefore, the model compensates for small errors in the input data by automatically adjusting the channel geometry. For example, if a computed velocity at a given streamtube were higher than the actual velocity, scour would occur and the velocity would decrease. The user should note that river simulations must be long enough so that one can be sure that channel adjustments are not continuing to be made to account for errors in the input data.

Data preparation is designed to be simple and easy with any redundancies kept to a minimum. For example, any number of cross sections can be input and in the upstream or downstream order. Up to 200 pairs of X and Y coordinate points can be input per cross section.

EXAMPLE APPLICATIONS

Results Using The East Fork River Data

A comprehensive data set to describe water and sediment movement was gathered by the U.S. Geological Survey on the East Fork River near Boulder, Wyoming (Emmett, et. al., 1980, and Meade, et. al., 1980). The reach of river simulated with the STARS model is 3213 meters long and has an average slope of 0.0007. At the bankfull stage the river is about 18 meters wide and 1.2 meters deep. Bed material consists of sand and gravel with a median diameter of about 1 mm. A more detailed description of the study reach is given by Leopold and Emmett (1976).

The reach was modeled for a 30-day period from May 22 to June 20, 1979 covering the majority of the spring runoff. The water discharge hydrograph included as figure 12 shows three distinct peaks. Input data included 39 surveyed cross sections with corresponding bed material size gradations, the upstream boundary discharge and sediment hydrographs, and a downstream boundary stage hydrograph.

Initial bed material size gradations varied only in the longitudinal direction with median diameters ranging from 0.39 mm to 14.3 mm. The initial bed material for a given section did not vary laterally and was assumed to have an infinite thickness. Simulation was performed using three streamtubes and the Velocity-Xi Adjusted Einstein sediment transport equation was chosen. The supply of sediment at the upstream boundary was determined from Helley-Smith bedload samples and suspended sediment concentrations.

Figure 13 shows successive thalweg profiles plotted with time (into the page). This plot summarizes the entire simulation period and qualitatively shows which cross sections experienced the most fill or scour and at which times. This sand and gravel bed river did not experience large changes with time but it tests of the ability of the STARS model to simulate rivers that are in equilibrium. Figure 14 compares the initial thalweg profile with both the measured thalweg profile and the one predicted by the STARS model. The majority of predicted points followed the trends in scour and fill over the 30-day period. The root mean squared error between the observed and computed thalwegs, after 30 days, was 0.17 meters. Bed material samples were not collected at the end of the 30-day period so a comparison of computed and measured size gradations was not possible.

Hydraulic and sediment transport routing schemes have been coupled in the STARS model to reasonably predict changes in the bed profile on the East Fork River. Success in the application was partly due to the representation of lateral variation in water and sediment movement through the use of streamtubes. Since the STARS model performed well in the highly variable sand and gravel beds of the East Fork River, it is expected to apply to a variety of other sand and gravel bed rivers.

Results Using Glen Canyon Data

The reach of the Colorado River between Glen Canyon Dam and Lees Ferry was chosen for verification and sensitivity testing of the STARS model. River simulations would later be made on Colorado River below Lees Ferry. Cross section data were available for the reach prior to closure of the cofferdam and during the degradation monitoring (Pemberton, 1976). The upstream sand sediment supply was considered to be cut off (zero) with the closure of the cofferdam causing the flow to degrade the streambed.

A 6.6-year period was simulated from February 11, 1959 to September 30, 1965 following the closure of the construction cofferdam. The hydraulic geometry was obtained from 23 cross sections, collected in 1956. It was assumed that these cross sections did not change until closure of the cofferdam. However, there were two floods during the period from cross section measurements to closure of the cofferdam. Both of these floods had peak discharges exceeding 100,000 ft^3/s. Half of these cross sections were resurveyed 10 months after closure of the cofferdam and all were resurveyed in 1965.

The initial bed material size gradations were varied only in the vertical direction. Bed material size gradations for both the upper and underlying zones were averaged for the upper 22 cross sections and bedrock was used at the downstream most cross section (Paria Riffle). The thickness of the upper bed material zone was measured by a jet probe at 10 cross sections. Thickness for the remaining sections was interpolated. The input hydrograph is included as figure 15. Discharges ranged from a low of about 1,000 ft^3/s to about 80,000 ft^3/s.

For simulations of the Colorado River below Glen Canyon Dam transport equations using a hiding factor were found necessary to properly model the armoring processes occurring in the reach. Both the Velocity-Xi adjusted Einstein equations and Toffaleti adaptation of the Einstein Bed-Load Function were programmed into the STARS model and tested. It was evident in simulation runs for the 10-month period on the reach from Glen Canyon Dam to Lees Ferry that the Toffaleti version would provide similar and reliable results at about half the cost. The Toffaleti formulation was therefore used for the longer 6.6-year period.

Results are summarized on a plot of accumulated volume of material removed versus channel length given as figure 16. The plot shows that the model overpredicted the volume removed in the upper portion of the reach from cross section S-0 to S-9 and underpredicted the material removed in the lower portion of the reach from S-9 to the Paria Riffle. The overall prediction of volume removed was within 11 percent of the measured volume. Figure 17 gives another perspective on the measured versus computed volume removed as accumulated with time. The steps in the curve correspond to peaks in the discharge hydrograph. Both plots show the STARS model successfully predicted the degradation below Glen Canyon Dam.

SENSITIVITY ANALYSIS OF THE STARS MODEL

Background

Parameter sensitivity analysis can be a useful tool in identification of data needs, error analysis, and model calibration. A sensitivity analysis can determine which input parameters are most sensitive to model results and identify areas where data collection programs will be the most effective. The following sensitivity analysis applies to the Colorado River below Glen Canyon Dam. Sensitivity analysis for other studies should be tailored to the needs of the specific modeling effort.

The Glen Canyon Environmental Studies were initiated by the Department of the Interior to evaluate the relationships between Glen Canyon Dam and the natural resources of the Grand Canyon. The STARS model was chosen as a tool to determine the relative impacts of the Glen Canyon Dam Powerplant operation scenarios on the Colorado River in the Grand Canyon. To accomplish this task over 700 cross sections were needed to model 225 miles of river. This would be one of the largest river modeling efforts conducted by the Bureau of Reclamation.

The 225 miles of river would be modeled with both measured and interpolated cross sections, an assumed Manning's roughness coefficient of 0.035, and three-dimensional variation in the initial bed material size gradations. The sensitivity of the following input variables were tested:

1. Bed material grain size distribution and areal extent of the different bed material types,

2. active layer mixing zone thickness,

3. Manning's roughness coefficient n, and

4. cross section geometry pertaining to the number and shape of interpolated sections.

Purpose

The purpose of the sensitivity analysis is to determine the relative importance of the STARS model input data in the prediction of sediment transport. This was accomplished by developing a base river simulation and comparing changes in modeled results when input data were varied.

Base River Simulation

The sensitivity testing was performed on the reach of the Colorado River between Glen Canyon Dam and Lees Ferry simulating a 6.6-year period (2424 days from February 11, 1959 to September 30, 1965) following the closure of the construction cofferdam. The STARS model was used to simulate the degradation of the river in order to verify the applicability of the model downstream from Lees Ferry.

The hydraulic geometry was obtained from 1956 cross section surveys. It was assumed that these cross sections did not change until closure of the construction cofferdam three years later. Half of these cross sections were resurveyed 10 months after closure of the cofferdam and all were resurveyed in 1965. This provided two checks on the predictions of the STARS model. Bed material samples of the surface layer, underlying layers of sand, and subsequent layers of gravel were taken at the same time (Pemberton, 1976).

The STARS model successfully predicted the volume of degradation, below Glen Canyon Dam, to within 11 percent of the measured volume for the 6.6-year period. Input data to the STARS model for this river simulation are summarized below:

- Streambed geometry defined by 23 cross sections, measured in 1956,
- Measured flows for the discharge hydrograph of 6.6 years,
- Toffaleti sediment transport equation,
- Three streamtubes,
- Vertical variation only of initial bed material size gradations,
- The same upper zone bed material size gradation (D_{50} equal to 0.32 mm) for the upper 22 cross sections,
- The same underlying zone bed material size gradation (D_{50} equal to 20. mm) for the upper 22 cross sections,
- Bedrock at the 23d cross section (Paria Riffle),
- Measured thickness of the upper bed material zone where known,
- Active layer thickness computed as 20 percent of the local hydraulic depth,
- Interpolated thickness of the upper bed material zone where unmeasured.

This verification run serves as the base run for determining the sensitivity of the various parameters, except for the distribution of bed material types in the channel. Each of the five parameters was varied and the resulting volume change in streambed analyzed to determine its sensitivity.

Bed Material

To test the sensitivity of the bed material grain size distribution, represented by the D_{50}, four river simulations were performed using a D_{50} of 0.32 mm, 0.55 mm, 0.90 mm, and 2.00 mm, respectively. The volume of streambed degradation for each of the simulations was compared for both the 10-month and 6.6-year periods (see table 3). Figure 18 shows a plot of D_{50} versus the volume of degradation for the two periods. This plot illustrates that for

TABLE 3

GLEN CANYON ENVIRONMENTAL STUDIES:
SENSITIVITY TESTING OF THE STARS MODEL
FEBRUARY 11, 1959 TO SEPTEMBER 30, 1965

SENSITIVITY OF BED MATERIAL SIZE GRADATION

D_{50}	Percent Change in D_{50}	10-Month Volume Removed Acre-ft	Percent Change in Volume	6.6-Year Volume Removed Acre-ft	Percent Change in Volume
0.32	---	1316	---	7066	---
0.55	+72	552	-58	3218	-54
0.90	+181	239	-82	1380	-80
2.00	+525	66	-95	407	-94

SENSITIVITY OF AREAL COVERAGE OF BED MATERIAL TYPE

Area of Sediment Wave Pattern square feet	Percent Change in Area	167-Day Volume Past RM 61 Acre-ft	Percent Change in Volume
14,759,982	---	480	-----
45,360,105	+307	987	+205

SENSITIVITY OF ACTIVE LAYER THICKNESS

Active Layer Thickness % of depth	Percent Change in Thickness	10-Month Volume Removed Acre-ft	Percent Change in Volume	6.6-Year Volume Removed Acre-ft	Percent Change in Volume
20	---	1341	-----	10350	-----
10	-50	1286	-4.1	9799	-5.3

Active Layer Thickness % of depth	Percent Change in Thickness	170-Day Volume Removed Acre-ft	Percent Change in Volume
20	---	1382	-----
30	+50	1500	+8.5

coarse size gradations (D_{50} larger than 1.5 mm) the sensitivity is minimal, however, for finer size gradations (D_{50} less than 1.0 mm) the sensitivity of grain size to degradation is at its greatest. For larger bed material sizes there is less sediment transport at the flows simulated and, in turn, less volume of material removed. The finer the size gradation, the larger the volume of material removed. Of the variables tested, initial bed material size gradation was found to have the greatest impact on the model's results.

In the reach of the Colorado River below Lees Ferry, maps of bed material were provided by the U.S. Geological Survey (Wilson, 1986). These maps show areas of moveable and immoveable material. The moveable material is further divided by bed form into areas of "sediment waves" and "smooth bottom" patterns. Interpretation of these maps is based upon bed material samples which indicates that in general the "sediment wave" areas are mostly sand (D_{50} equal to 0.30 mm), the "smooth bottom" areas are a sand and gravel mixture (D_{50} equal to 2.0 mm), and the immoveable areas are mostly "boulders and bedrock". The same size gradation was used everywhere in the reach for a given bed material category.

To test the sensitivity of the distribution of the three bed material types, the 61-mile reach of the Colorado River below Lees Ferry was modeled with three streamtubes. Only the areas of "sediment wave" and "smooth bottom" patterns were varied in sensitivity testing, since there is more confidence in knowing which portions of the Colorado River channel bottom are "boulders and bedrock" but less confidence in knowing the areal extent of sand or gravel. The base simulation was made using the bed material maps provided by the U.S. Geological Survey with the above mentioned interpretation. In the second simulation, the size gradation for all of the "smooth bottom" areas was replaced with the grain size distribution of the "sediment wave" areas. This would represent an extreme condition of the streambed having only areas of bedrock and mostly sand. Comparing these two simulations shows that varying the areal distribution of initial bed material patterns can be sensitive to sediment transport in the same way that directly varying the size gradation can be sensitive. Increasing the area of sands by a factor of 3.0 increases the sediment transport at the downstream end by a factor of 2.1 (see table 3).

A third simulation where the size gradation for the "sediment wave" areas is replaced with that of the "smooth bottom" pattern was not performed because this testing is so similar to directly varying the D_{50}.

Active Layer Thickness

During STARS model development, sensitivity testing of the active layer thickness was performed. River simulations were made on the Colorado River, between Glen Canyon Dam and Lees Ferry, with active layer depths varying from 10 to 20 percent of the local hydraulic depth.

The results of these tests showed that the volume of degradation decreased by 4.1 and 5.3 percent, for the 10-month and 6.6-year periods, by decreasing the active layer thickness from 20 to 10 percent (50 percent reduction) of the hydraulic depth (see table 3). Since only slight decreases in scour or fill depths were noted with large decreases in active layer thicknesses the model is not considered very sensitive to changes in active layer thickness. When the active layer thickness is increased, both the time steps and scour or fill depths increase. While the rates of fill or scour, for a given time step, do not change, an increase in the time step will increase the amount of fill or scour proportional to the increase in active layer thickness.

Modeling costs were found to be significant in the testing of the active layer thickness. Computer costs are directly proportional to the number of minor time steps which are in turn related to active layer thickness. The smaller the thickness used in the mixing layer, the smaller the minor time step becomes and the longer or more costly the simulation. Computer costs can be cut almost in half by doubling the active layer thickness. Since only small differences in bed material size gradations, volumes removed, and scour or fill depths were observed with increasing active layer thicknesses, the active layer thickness was increased to 30 percent to determine whether additional cost savings could be made without sacrificing accuracy. Two river simulations were performed using active layer thickness of 20 and 30 percent of the hydraulic depth on the reach of the Colorado River extending 61 miles downstream from Lees Ferry. By increasing the active layer thickness from 20 to 30 percent (50 percent increase) of the hydraulic depth, the volume of degradation increased by 8.5 percent but with a 32 percent cost savings. This savings was significant enough to merit using an active layer thickness based on 30 percent of the hydraulic depth for simulation of the Colorado River in the Grand Canyon.

Manning's Roughness Coefficient n

To test the sensitivity of the Manning's roughness coefficient (n value), river simulations were made using n values of 0.025, 0.035, and 0.045. The n value of 0.035 is considered to be the average over the test reach and is supported by observed water surface elevations from the 1956, 1959, and 1965 surveys below Glen Canyon Dam. An average n value of 0.025 is considered to be the lower limit applicable to straight natural river channels of regular section with no boulders or brush. An average n value of 0.045 is considered to be the upper limit applicable to very winding and overgrown natural river channels of irregular section.

Changing the Manning's n value in the range of 0.025 to 0.045 showed little change in volume of sediment removed as presented on figure 19. A lower n value will result in lower water surface elevations with the greatest difference in elevation occurring at the upstream most section (assuming that downstream water surface is the same). These lower water surface elevations in turn result in higher velocities with a corresponding higher capacity to transport sediment. In the Glen Canyon reach of river, lower n values resulted in higher sediment transport rates and greater volumes of degradation at the upper end of the reach. With the increased sediment supply from the upper cross sections, the lower sections did not degrade as much. The total volume of material removed was nearly the same as the simulation with a higher n value (see table 3). Figures 20 and 21 show the volume of degradation plotted with channel distance for the three different roughness coefficients.

Figure 22 shows the volume of degradation, for the entire 15-mile reach, plotted with time.

Higher n values result in higher water surface elevations, lower velocities, and lower sediment transport rates. Sensitivity analysis showed that a higher n value resulted in a slight decrease in the volume of material degraded. For steep channels with rapids, any error in the water surface profile caused by inaccurate n values will be wiped out at cross sections with critical depths. In general, the steeper the channel the less effect Manning's n will have on the computed water surface profile because high velocity heads and expansion and contraction losses will become larger relative to friction heads.

Cross Section Interpolation

In order to model the Colorado River below Lees Ferry, interpolated cross sections at rapids were required to properly define the channel geometry. Each interpolated section was assumed to be trapezoidal. Top widths were measured from aerial photography, depths were measured with sonar equipment, and side slopes were estimated from measured cross sections. Since a large number of interpolated cross sections would be used, the sensitivity of both the number of interpolated sections and their cross sectional geometry was tested.

To test the sensitivity of cross section geometry, the cross sections that were surveyed in 1956 were converted to trapezoidal sections. The bottom elevation was set equal to the thalweg elevation of the surveyed sections, side slopes were equated to the average side slopes of all the surveyed sections, and the top width and corresponding elevation were equated to the top width and elevation of the surveyed sections. Using only the trapezoidal cross sections resulted in a 36 and 13.5 percent decrease in volume of material removed, for the 10-month and 6.6-year periods.

In the reach of the Colorado below Lees Ferry, interpolated cross sections were used in addition to the measured cross sections. Therefore, another simulation was performed using all 23 measured cross sections and 22 interpolated sections (one interpolated between each measured cross section). This resulted in a 23 and 5.2 percent decrease in volume of material removed, for the 10-month and 6.6-year periods (see table 3). Figures 23 and 24 show the volume of degradation plotted with channel distance for the three cases. Figure 25 shows the volume of degradation plotted with time. Comparing the changes in volume of material removed to the base run indicated that the trapezoidal shape of interpolated cross sections introduces some error which decreases with time. By calibrating the cross section geometry, using computed and observed water surface elevations, this error can be minimized.

To test the sensitivity of the number of sections used to define the river profile, surveyed or interpolated, a model run was made using only those 1956 cross sections that were resurveyed in 1965. This constituted a 48 percent reduction in number of cross sections. Reducing the number of cross section from 23 to 12 resulted in a 5.5 and 1.3 percent increase in the volume of material removed which is minimal (see table 3). Figures 26 and 27 show the effect of reducing the number of sections on accumulated volume removed versus channel length for short and long-term simulations, respectively. The plot of accumulated volume removed versus time (figure 28) shows the model is not sensitive to the number of interpolated sections. Engineering judgement is still considered necessary in the placement of interpolated cross sections.

Summary of Sensitivity Analysis

Sensitivity analysis was performed on the bed material, active layer thickness, channel roughness, and cross section geometry. Results from the analysis show the STARS model to be most sensitive to the bed material size gradations and least sensitive to the number of cross sections.

Results verify that the STARS model is not oversensitive to variations in input data. For every variable tested, the percentage change in the volume of material removed was less than the percentage change in the input data. The accuracy of the model is within the range of accuracy of the data collection program.

SUMMARY AND CONCLUSIONS

The STARS model was developed to mathematically simulate the movement of water and sediment through alluvial river channels. The methods incorporated in the model to compute water surface profiles, determine hydraulic properties by streamtube, calculate sediment transport capacity and supply, route and mix sediment by size fraction, and update cross sections were reviewed in this report. Specific routines added to route water and sediment where rapids, bedrock outcrops, or side canyon tributaries occur were also discussed. Data collection and required input to the STARS model were summarized, along with the operational concept and the output from the report generator. Results from simulations of the East Fork River and Colorado River from Glen Canyon Dam to Lees Ferry showed the model performed well in the highly variable sand and gravel channel beds. The STARS model was found applicable to the study reaches in the Grand Canyon as well as other alluvial channels.

REFERENCES

Ackers, P., and R. W. White, 1973, Sediment Transport: New Approach and Analysis, Journal of the Hydraulics Division, ASCE, Vol. 99, No. HYII, Proc. Paper 10167, pp. 2041-2060.

Bennett, James P. and Nordin, Carl F., 1977, Simulation of Sediment Transport and Armouring, Hydrological Sciences Bulletin, Vol. 22, No. 4, pp. 555-569.

Chow, V. T., 1964, Handbook of Applied Hydrology, McGraw-Hill Book Company, 29 chapters, p. 7-9.

Einstein, H. A., 1950, The Bed-Load Function for Sediment Transportation in Open Channel Flows, USDA Soil Conservation Service, Technical Bulletin No. 1026, pp. 1-71.

Emmett, William W., Myrick, Robert M., and Meade, Robert H., 1980, Field Data Describing the Movement and Storage of Sediment in the East Fork River, Wyoming PART I. River Hydraulics and Sediment Transport, U.S. Geological Survey Open - File Report 80-1189, pp. 1-171.

Engelund, Frank and Hansen, Eggert, 1967, A Monograph on Sediment Transport in Alluvial Streams, Teknisk Forlag, Copenhagen, Denmark, pp. 1-62.

Leopold, L. B. and Emmett, W. W., 1976, Bed-Load Measurements, East Fork River, Wyoming Proc. Nat. Acad. Sci. Wash. 73, No. 4, p.100-1004.

Meade, Robert H., Myrick, Robert M., and Emmett, William W., 1980, Field Data Describing the Movement and Storage of Sediment in the East Fork River, Wyoming PART II. Bed Elevations, U.S. Geological Survey Open-File Report 80-1190, pp. 1-242.

Meyer-Peter, E. and Muller, R., 1948, Formulas for Bed-Load Transport, The Second Meeting of the International Association for Hydraulic Structures Research, Appendix 2, pp. 39-64.

Molinas, Albert, 1983, Mathematical Simulation of Rivers Based on Stream Line Theory: User's Manual, submitted to C. T. Yang, U.S. Bureau of Reclamation, pp. 1-259.

Pemberton, Ernest L., 1972, Einstein's Bed-Load Function Applied to Channel Design and Degradation, Sedimentation Symposium to Honor Professor H. A. Einstein, CSU, Fort Collins, Colorado, pp. 16-1 to 16-28.

Pemberton, Ernest L., 1976, Channel Changes in the Colorado River Below Glen Canyon Dam, Proceedings of the Third Federal Interagency Sedimentation Conference, Denver, Colorado, Sedimentation Committee, Water Resources Council, pp. 5-61 to 5-73.

Randle, T. J., 1984, Meyer-Peter and Muller Bed-Load Formulas Applied to Natural Channels, U.S. Bureau of Reclamation, pp. 1-23.

Sedimentation Section, U.S. Bureau of Reclamation, 1960, Investigation of Meyer-Peter, Muller Bed-Load Formulas, Denver, Colorado, pp. 1-26.

Sedimentation Section, U.S. Bureau of Reclamation, 1963, PSANDS: Computer Program for Computing Total Sediment Load by the Original Einstein, Modified Einstein, and Velocity-Xi Methods, pp. 1-9.

Toffaleti, F. B., 1968, Technical Report Number 5: A Procedure for Computation of the Total River Sand Discharge and Detailed Distribution, Bed to Surface, Committee on Channel Stabilization, U.S. Army Corps of Engineers, pp. 1-29, appendices A, B, and C.

Toffaleti, F. B., 1969, Definitive Computations of Sand Discharge in Rivers, Journal of the Hydraulics Division, ASCE., Vol. 95, No. HY1, pp. 225-248.

Wilson, Richard P., 1986, Sonar Patterns of Colorado River Bed, Grand Canyon, Proceedings of the Fourth Federal Interagency Sedimentaion Conference, Las Vegas, Nevada, Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data, Vol. 2, pp. 5-133 to 5-142.

Yang, Chih Ted, 1973, Incipient Motion and Sediment Transport, Journal of the Hydraulics Division, ASCE, Vol. 99, No. HY10, pp. 1679-1704.

Yang, Chih Ted, 1984, Unit Stream Power Equation for Gravel, Journal of the Hydraulics Division, ASCE, Vol. 110, No. HY12, pp. 1783-1797.

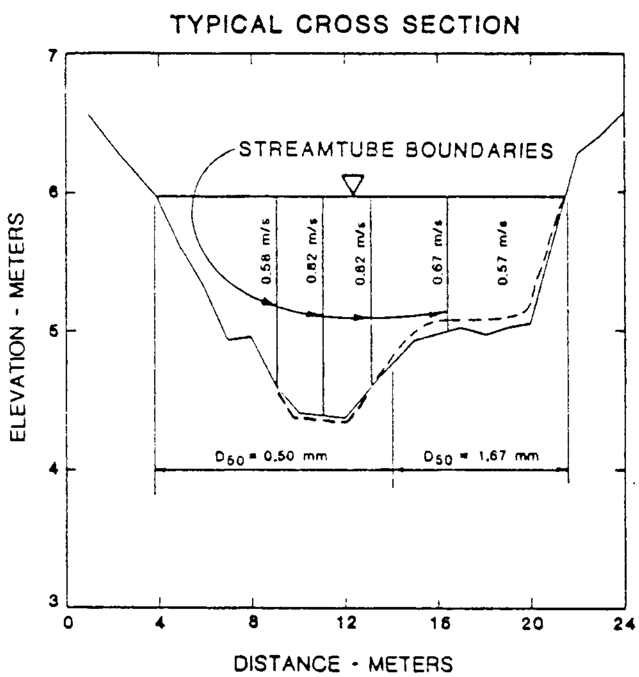


Figure 1. Typical Cross Section With Five Streamtubes

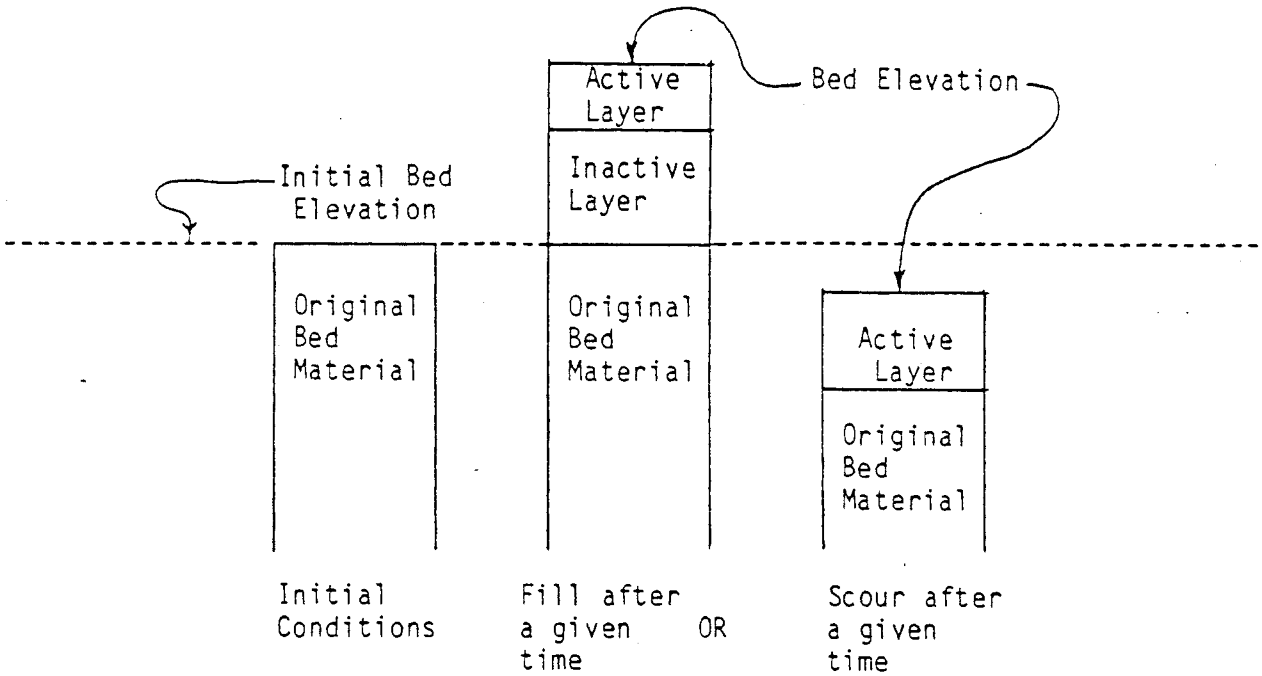


Figure 2. Active and Inactive Layer Definition Sketch (One Initial Gradation)

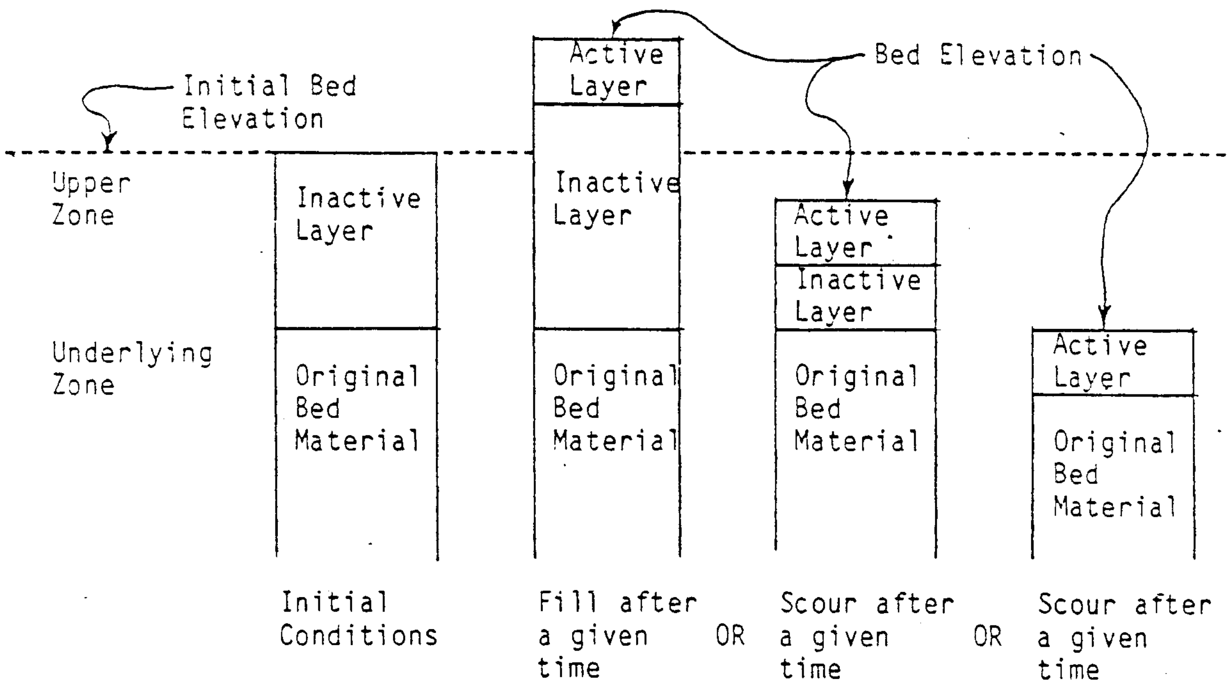


Figure 3. Active and Inactive Layer Definition Sketch (Two Initial Gradations)

A. GEOMETRIC DATA

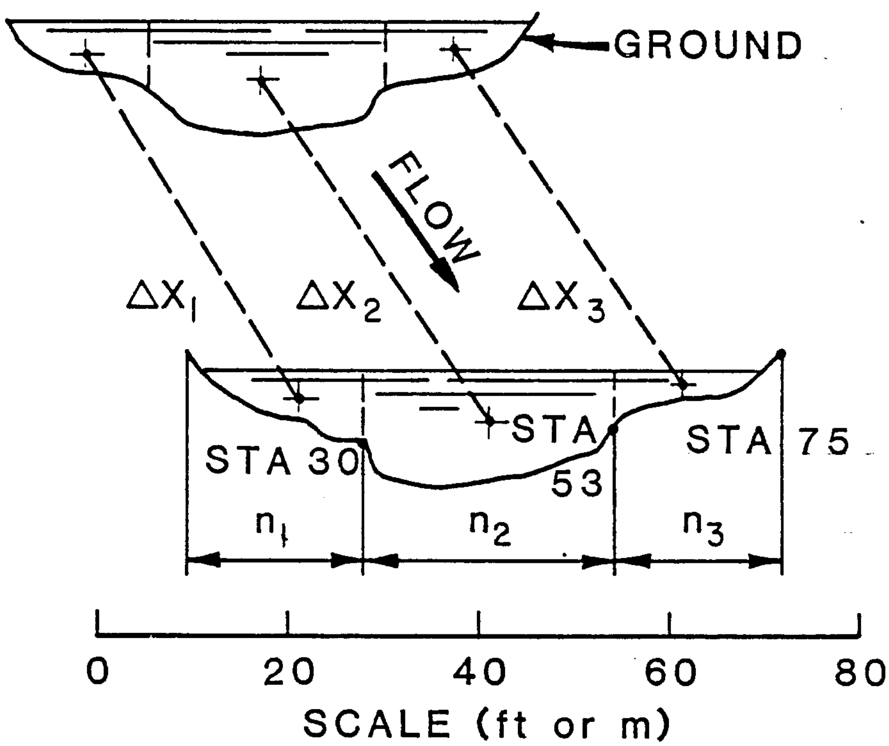
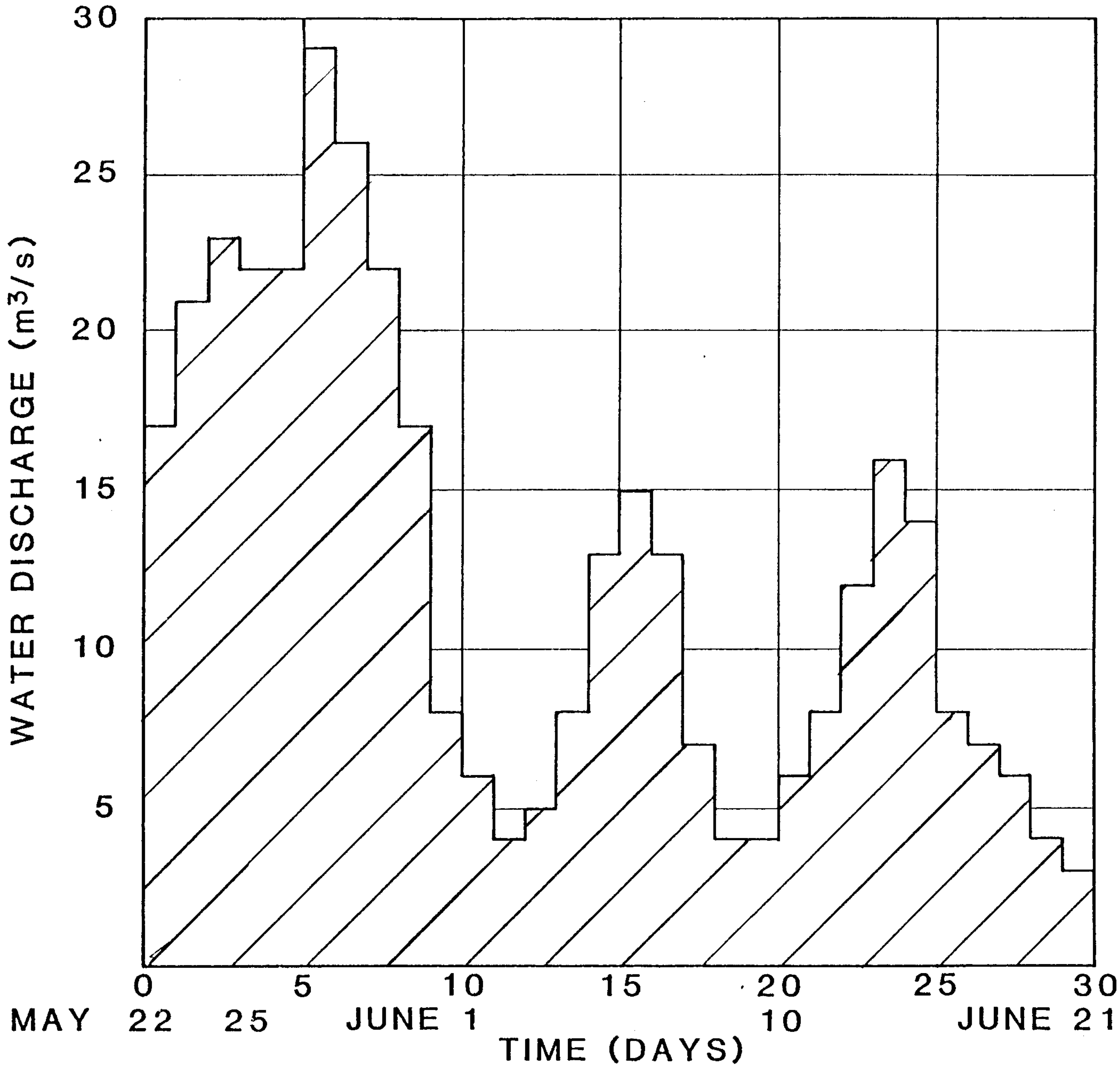


Figure 4



INPUT HYDROGRAPH
EAST FORK RIVER, WYOMING
MAY 22, 1979 TO JUNE 22, 1979

Figure 5

STAGE VERSUS DISCHARGE RATING CURVE
EAST FORK RIVER, WYOMING
MAY 22, 1979 TO JUNE 22, 1979

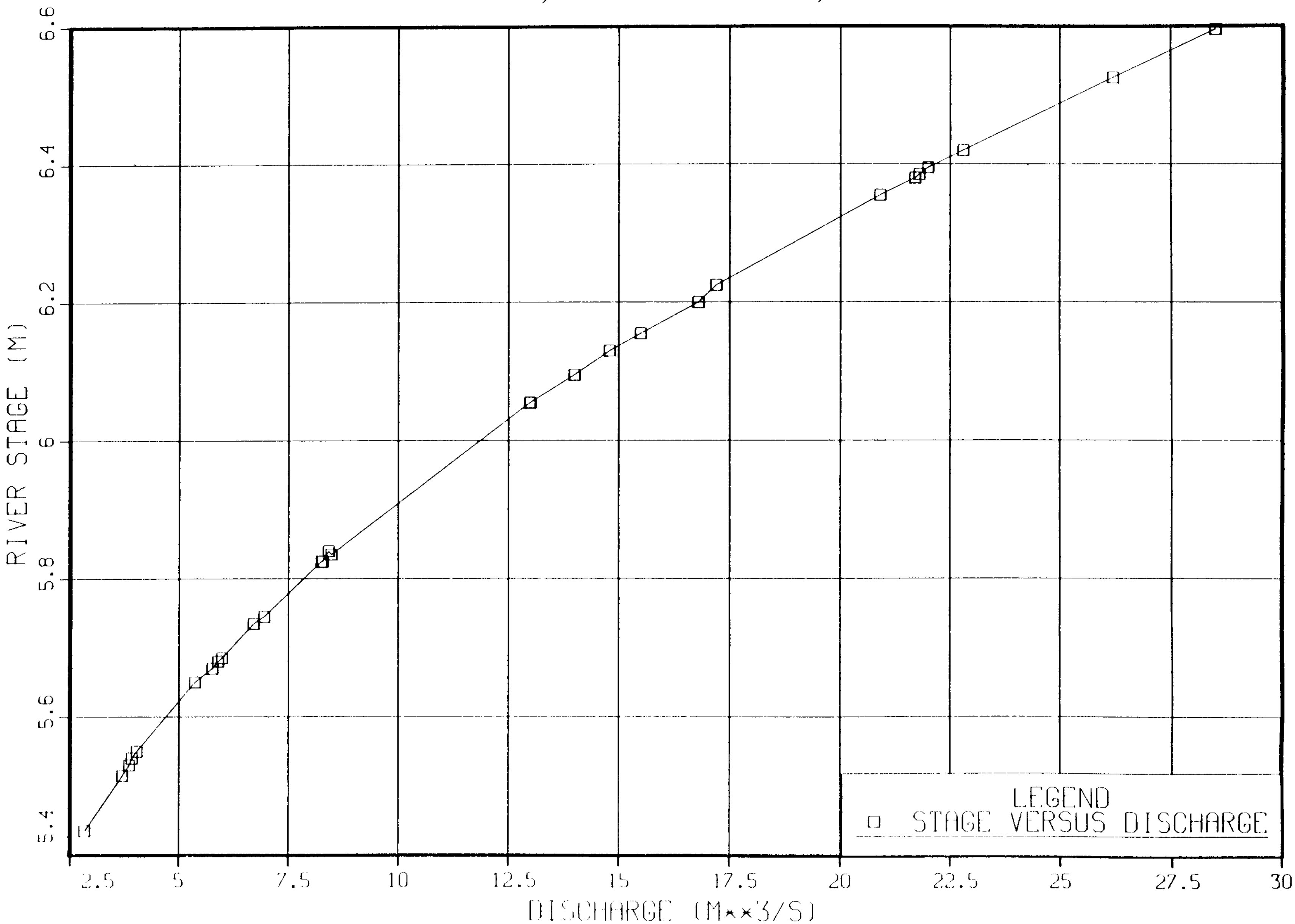


Figure 6

C. SEDIMENT DATA

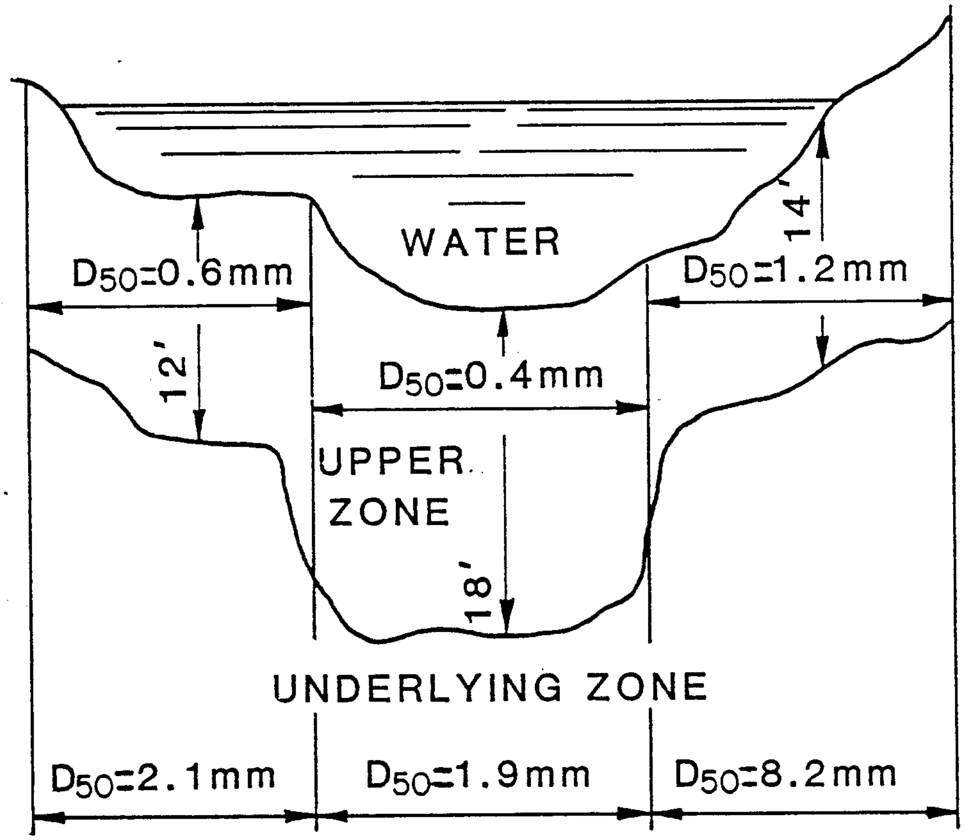


Figure 7

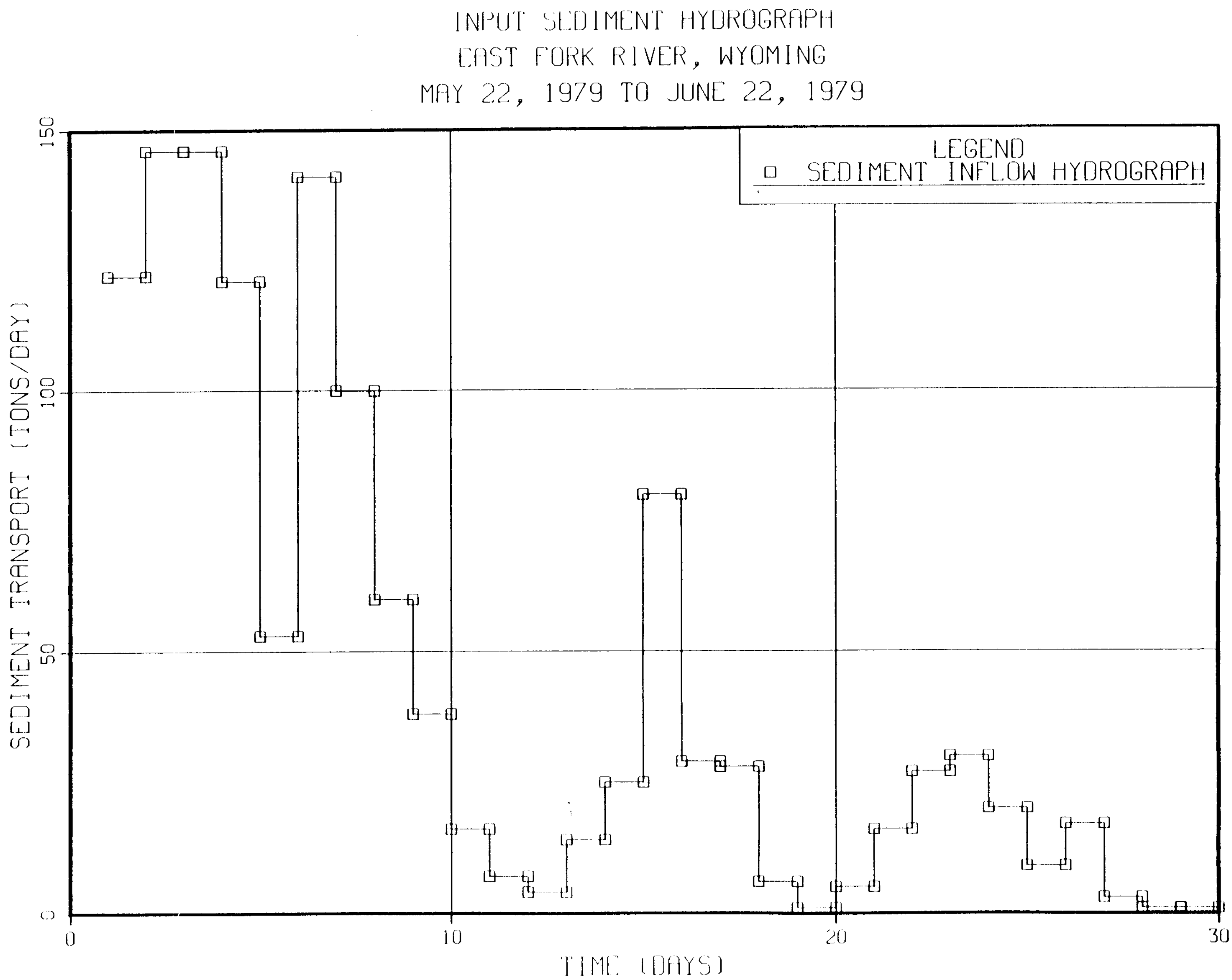

INPUT SEDIMENT HYDROGRAPH
EAST FORK RIVER, WYOMING
MAY 22, 1979 TO JUNE 22, 1979
LEGEND
SEDIMENT INFLOW HYDROGRAPH
SEDIMENT TRANSPORT (TONS/DAY)
TIME (DAYS)
0
50
100
150
0
10
20
30

Figure 8

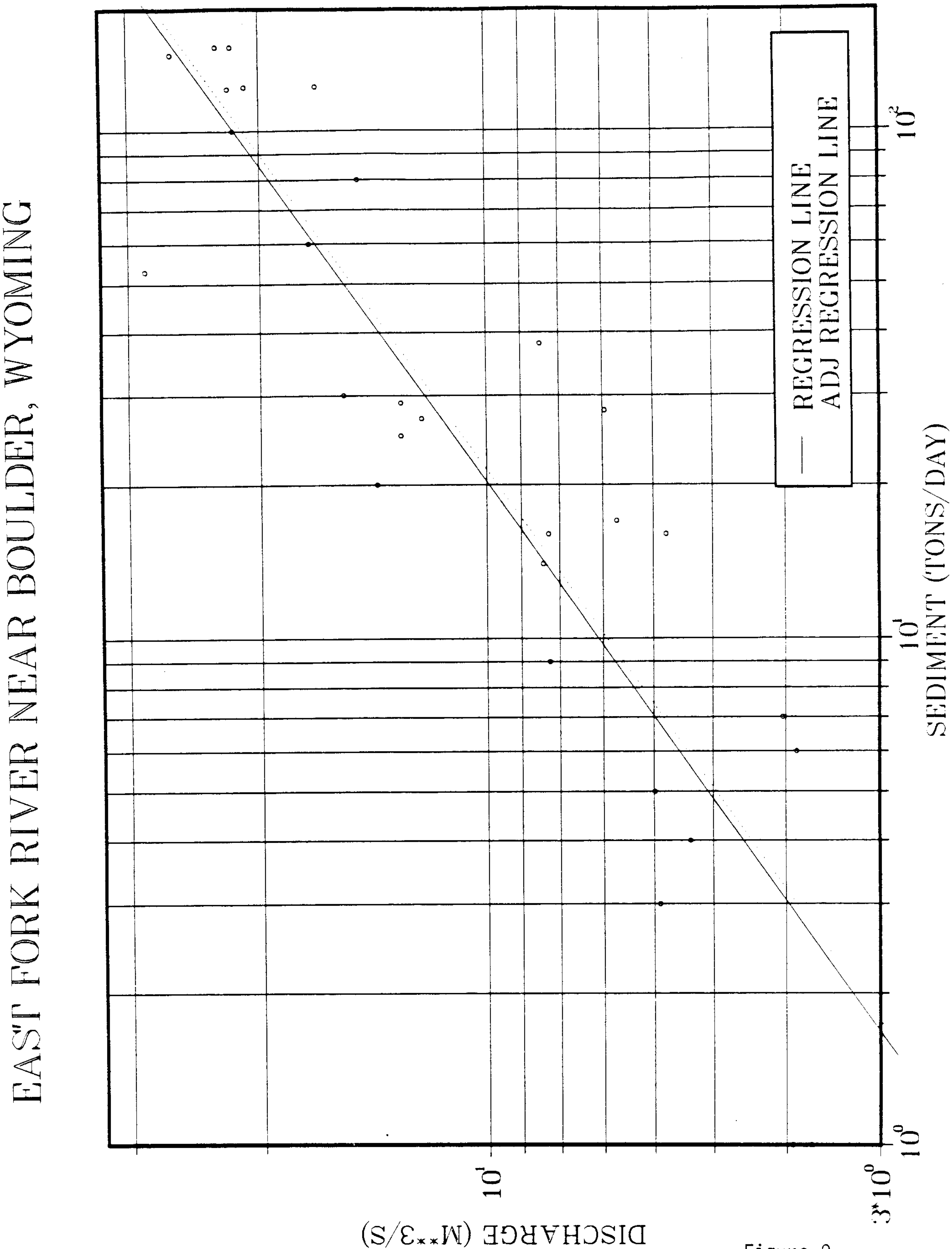
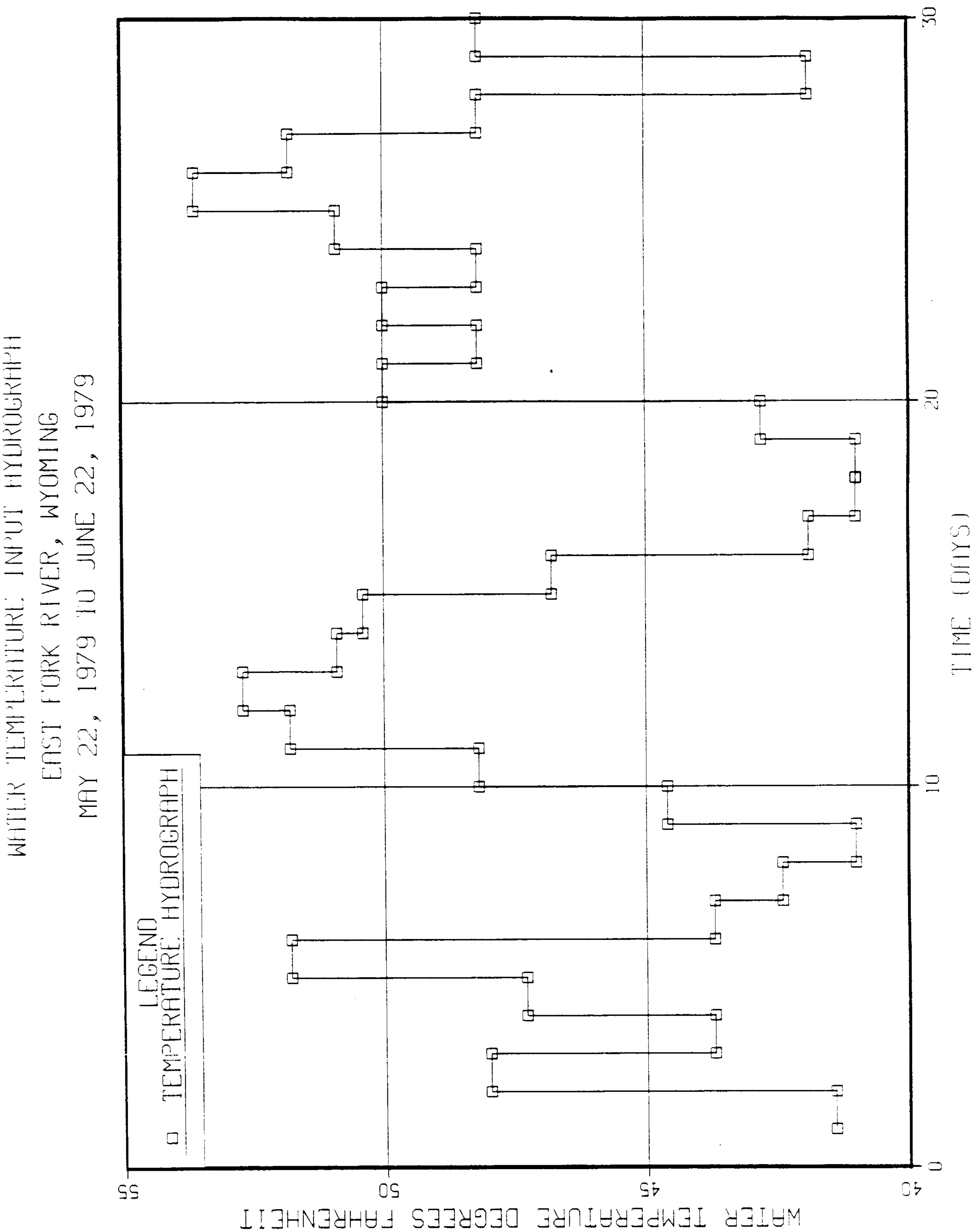

EAST FORK RIVER NEAR BOULDER, WYOMING
REGRESSION LINE
ADJ REGRESSION LINE
SEDIMENT (TONS/DAY)
DISCHARGE (M**3/S)
10^0
10^1
10^2
$3*10^0$
10^1

Figure 9

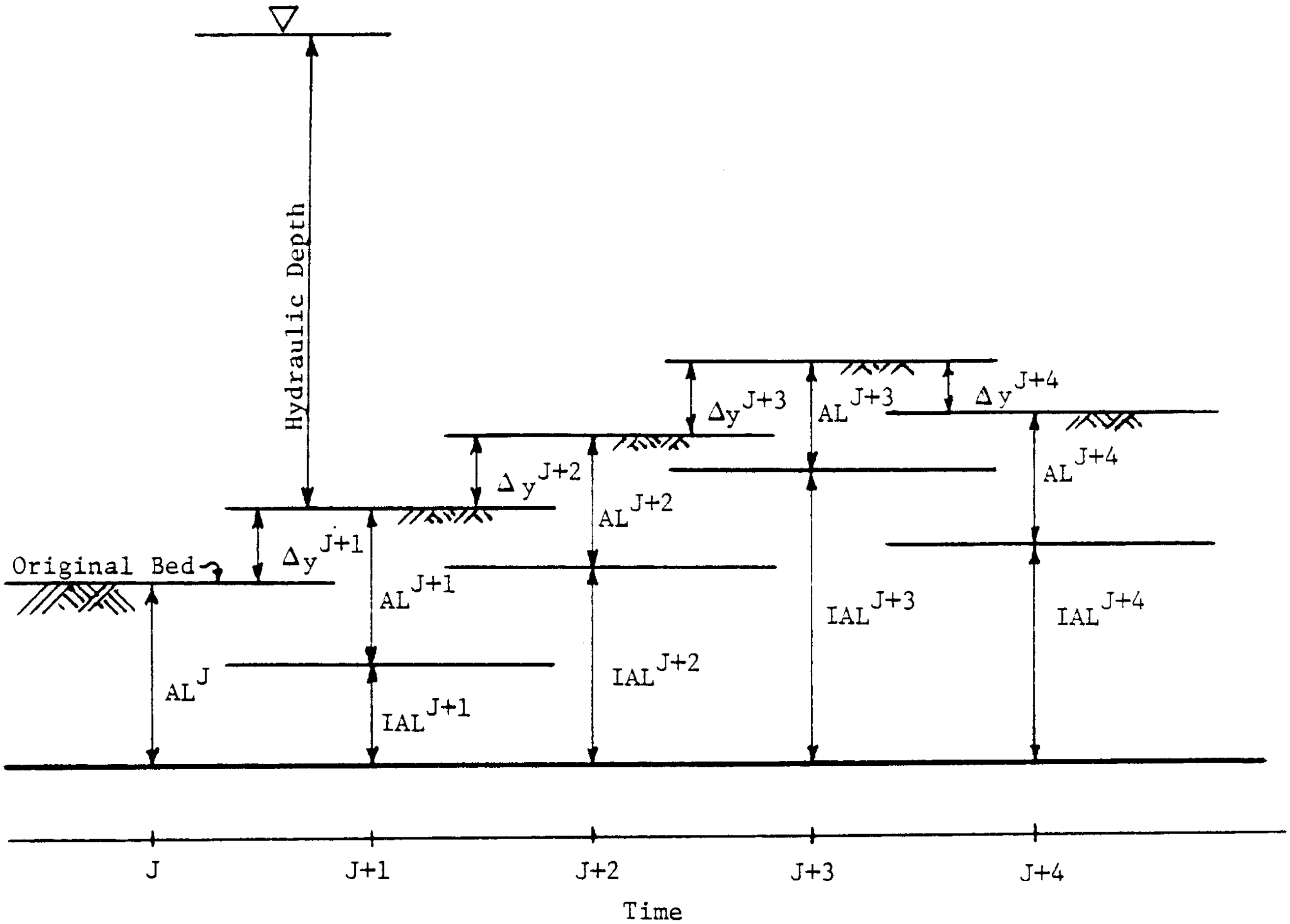


WATER TEMPERATURE INPUT HYDROGRAPH
EAST FORK RIVER, WYOMING
MAY 22, 1979 TO JUNE 22, 1979
LEGEND
TEMPERATURE HYDROGRAPH
TIME (DAYS)
WATER TEMPERATURE DEGREES FAHRENHEIT
0
10
20
30
40
45
50
55

Figure 10

SEDIMENT TRANSPORT AND RIVER SIMULATION MODEL

Active and Inactive Layer Thickness



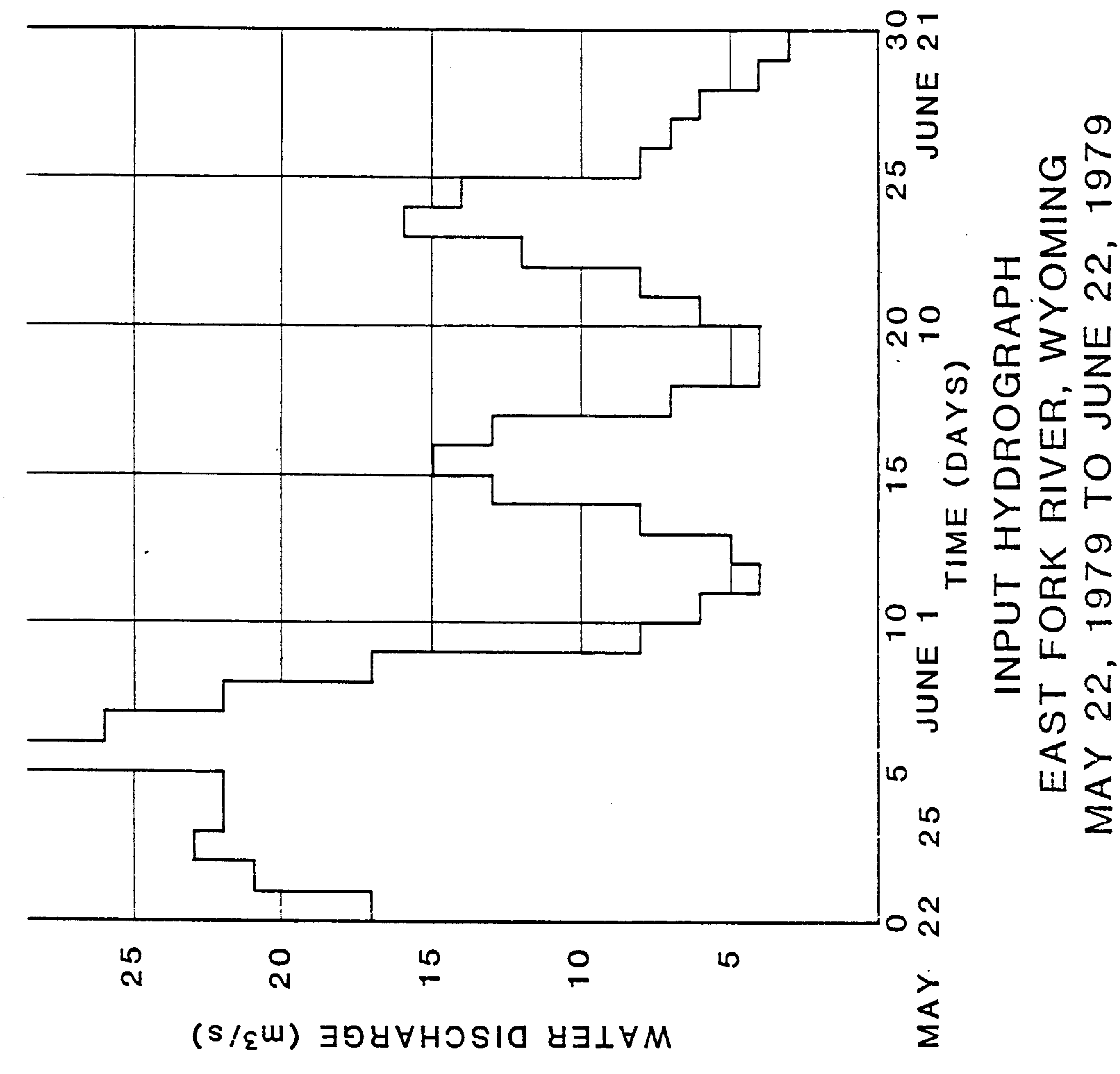
Δy = Fill or Scour Depth

AL = Active Layer Thickness

IAL = Inactive Layer Thickness

J = Time Step

Figure 11



WATER DISCHARGE (m^3/s)
25
20
15
10
5
0
MAY 22
25
5
JUNE 1
10
15
20
10
25
30
JUNE 21
TIME (DAYS)
INPUT HYDROGRAPH
EAST FORK RIVER, WYOMING
MAY 22, 1979 TO JUNE 22, 1979

Figure 12

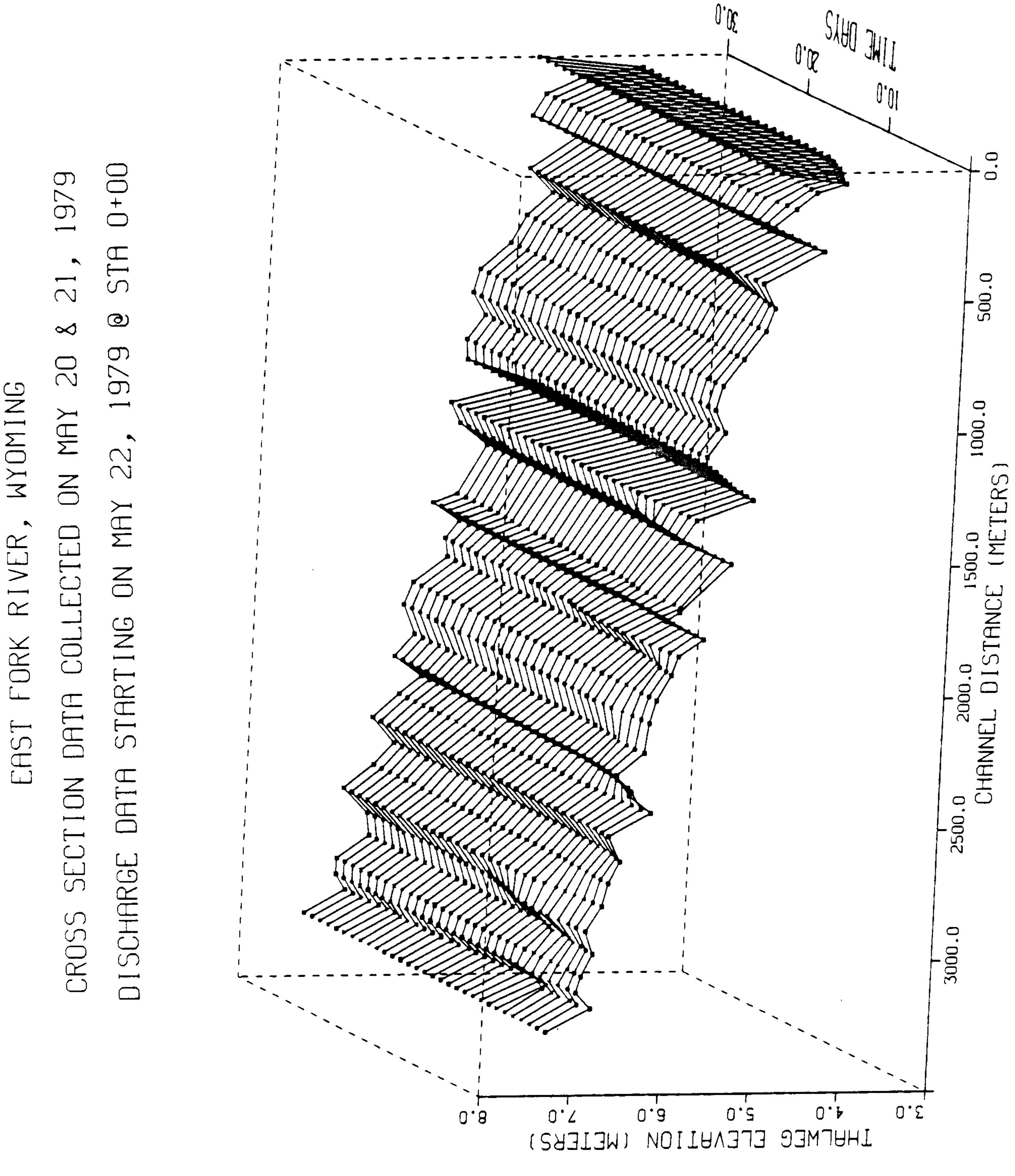

EAST FORK RIVER, WYOMING
CROSS SECTION DATA COLLECTED ON MAY 20 & 21, 1979
DISCHARGE DATA STARTING ON MAY 22, 1979 @ STA 0+00
TIME DAYS
30.0
20.0
10.0
0.0
500.0
1000.0
1500.0
2000.0
2500.0
3000.0
CHANNEL DISTANCE (METERS)
8.0
7.0
6.0
5.0
4.0
3.0
THALWEG ELEVATION (METERS)

Figure 13

EAST FORK RIVER, NEAR BOULDER WY.

Figure 14

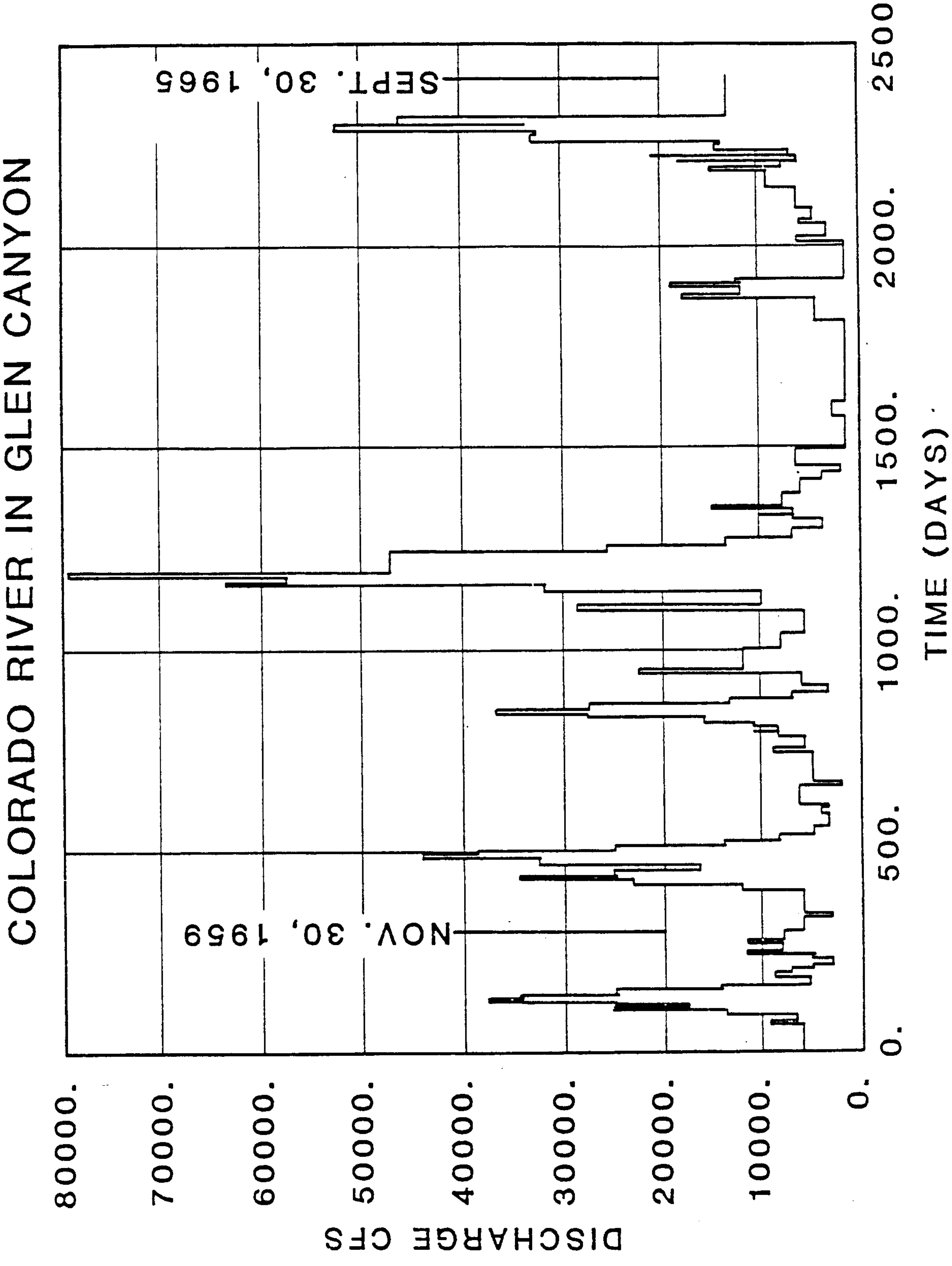

COLORADO RIVER IN GLEN CANYON
NOV. 30, 1959
SEPT. 30, 1965
DISCHARGE CFS
80000.
70000.
60000.
50000.
40000.
30000.
20000.
10000.
0.
0.
500.
1000.
1500.
2000.
2500.
TIME (DAYS)

Figure 15

VOLUME OF MATERIAL REMOVED FROM THE COLORADO RIVER BETWEEN GLEN CANYON DAM AND LEES FERRY (FEB. 11, 1959 TO SEPT. 30, 1965)

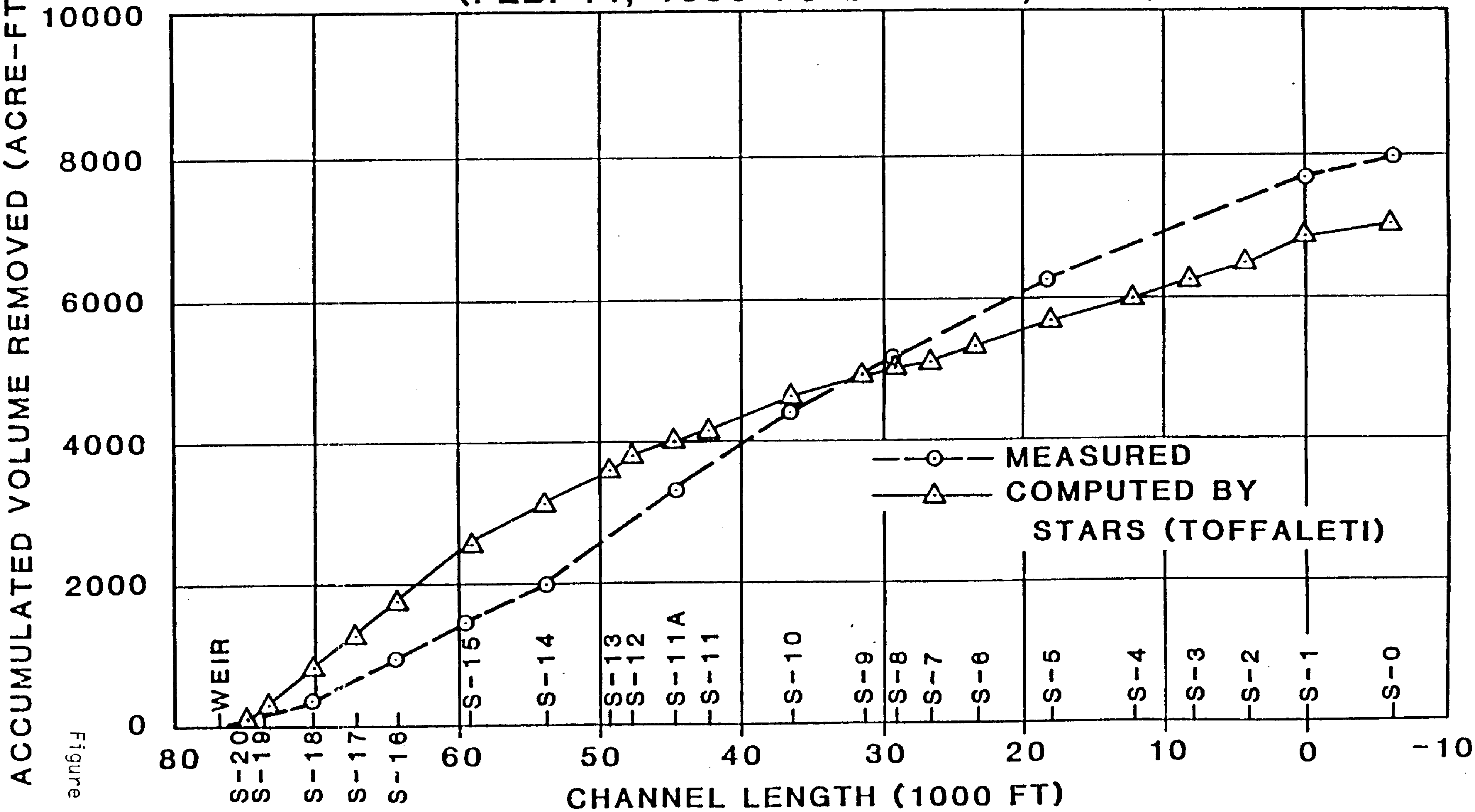


Figure 16

VOLUME OF MATERIAL REMOVED FROM THE COLORADO RIVER BETWEEN GLEN CANYON DAM AND LEES FERRY (FEB. 11, 1959 TO SEPT. 30, 1965)

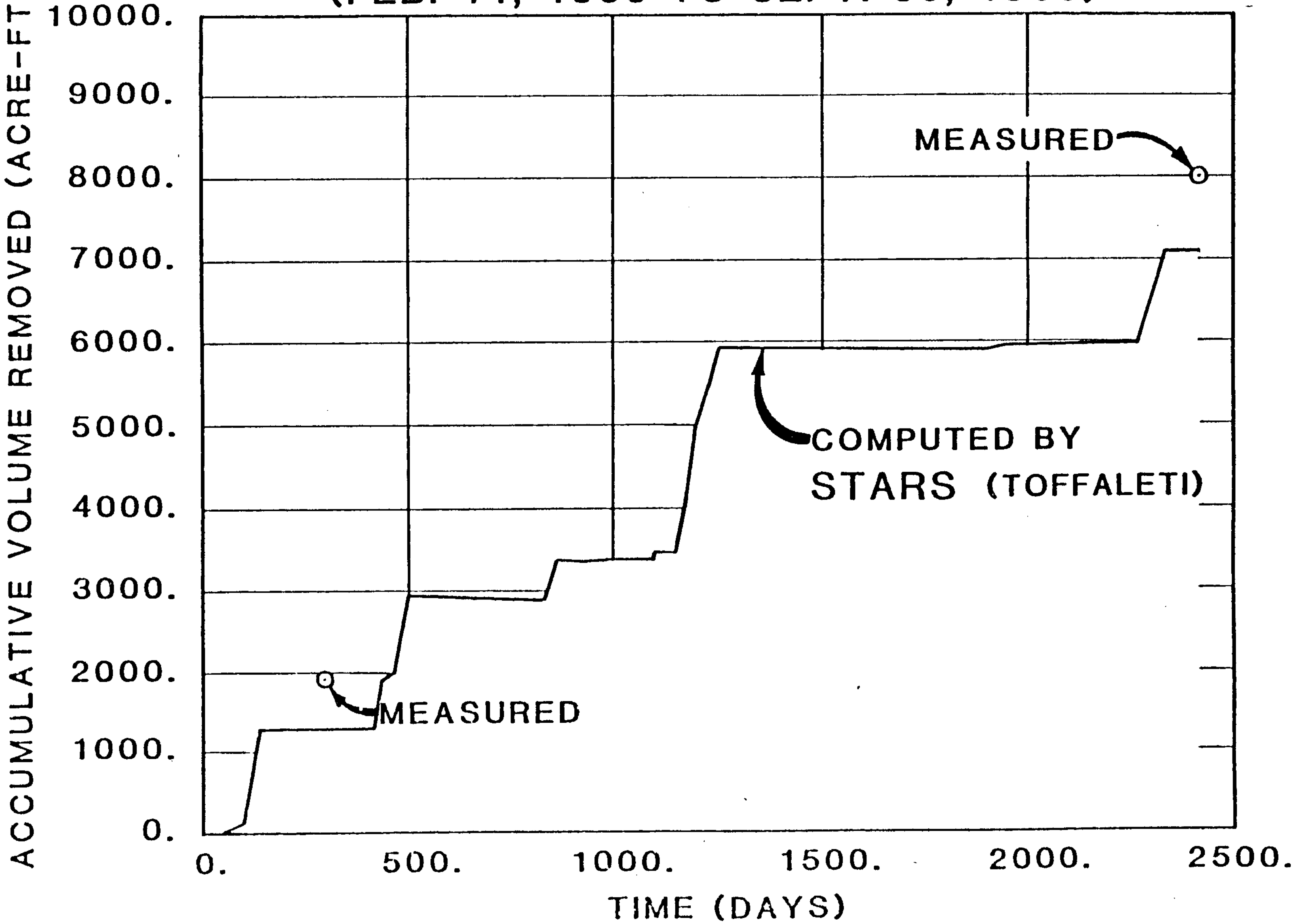


Figure 17

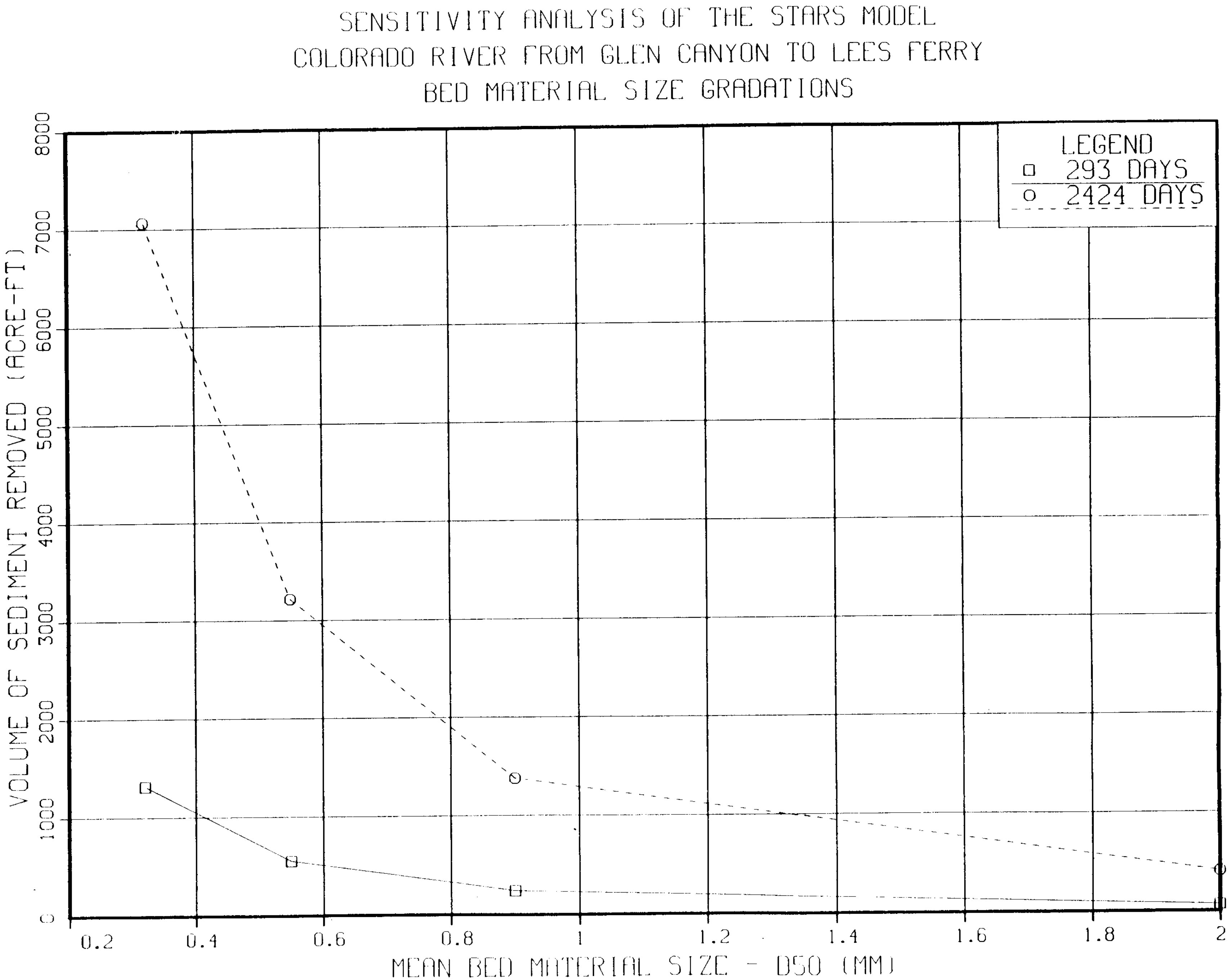
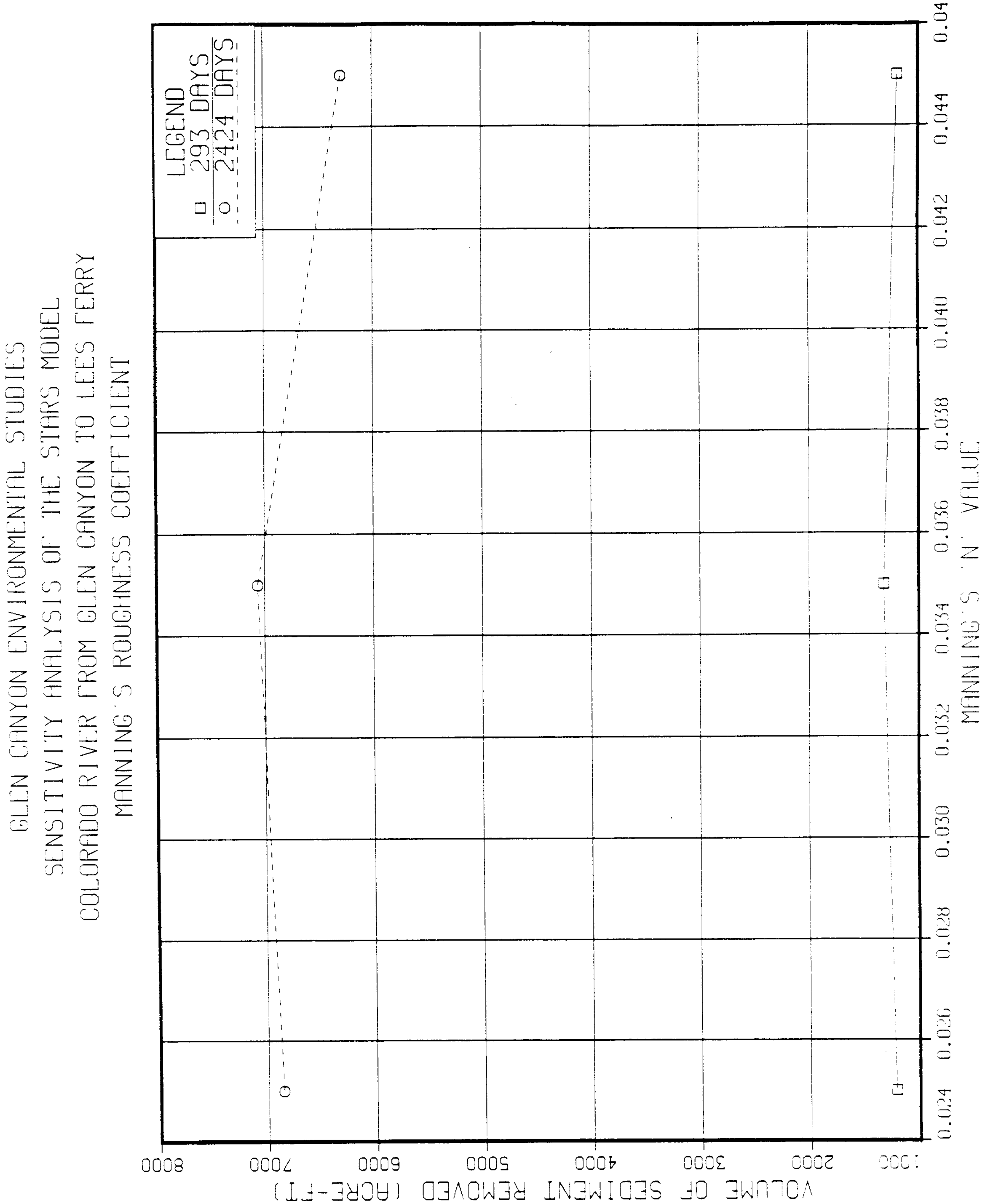

SENSITIVITY ANALYSIS OF THE STARS MODEL
COLORADO RIVER FROM GLEN CANYON TO LEES FERRY
BED MATERIAL SIZE GRADATIONS
LEGEND
293 DAYS
2424 DAYS
VOLUME OF SEDIMENT REMOVED (ACRE-FT)
0
1000
2000
3000
4000
5000
6000
7000
8000
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
MEAN BED MATERIAL SIZE - D50 (MM)

Figure 18



GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
COLORADO RIVER FROM GLEN CANYON TO LEES FERRY
MANNING'S ROUGHNESS COEFFICIENT
LEGEND
293 DAYS
2424 DAYS
MANNING'S 'N' VALUE
0.024
0.026
0.028
0.030
0.032
0.034
0.036
0.038
0.040
0.042
0.044
0.046
VOLUME OF SEDIMENT REMOVED (ACRE-FT)
1000
2000
3000
4000
5000
6000
7000
8000

Figure 19

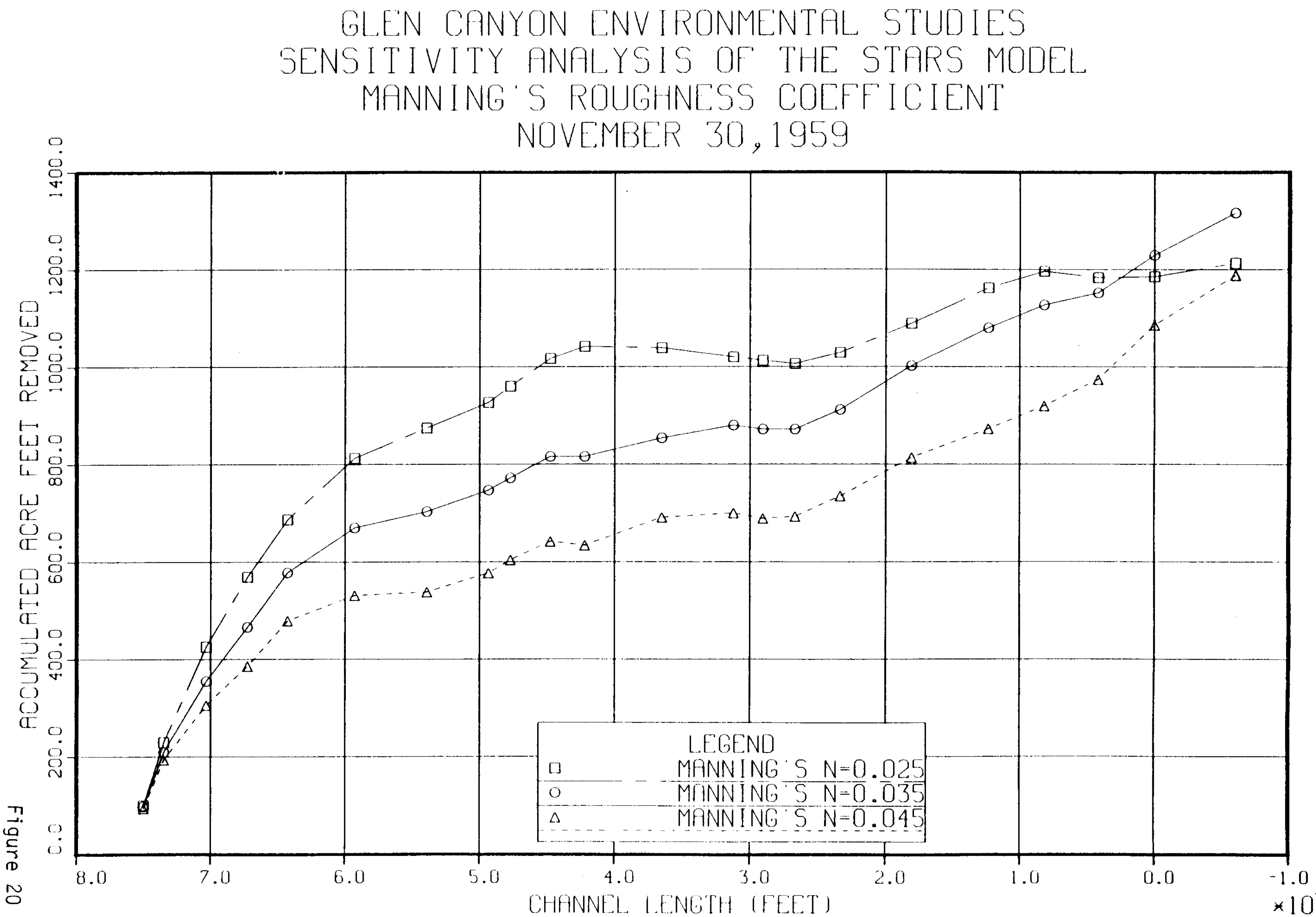

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MANNING'S ROUGHNESS COEFFICIENT
NOVEMBER 30, 1959
ACCUMULATED ACRE FEET REMOVED
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
CHANNEL LENGTH (FEET)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
×10⁴
LEGEND
MANNING'S N=0.025
MANNING'S N=0.035
MANNING'S N=0.045

Figure 20

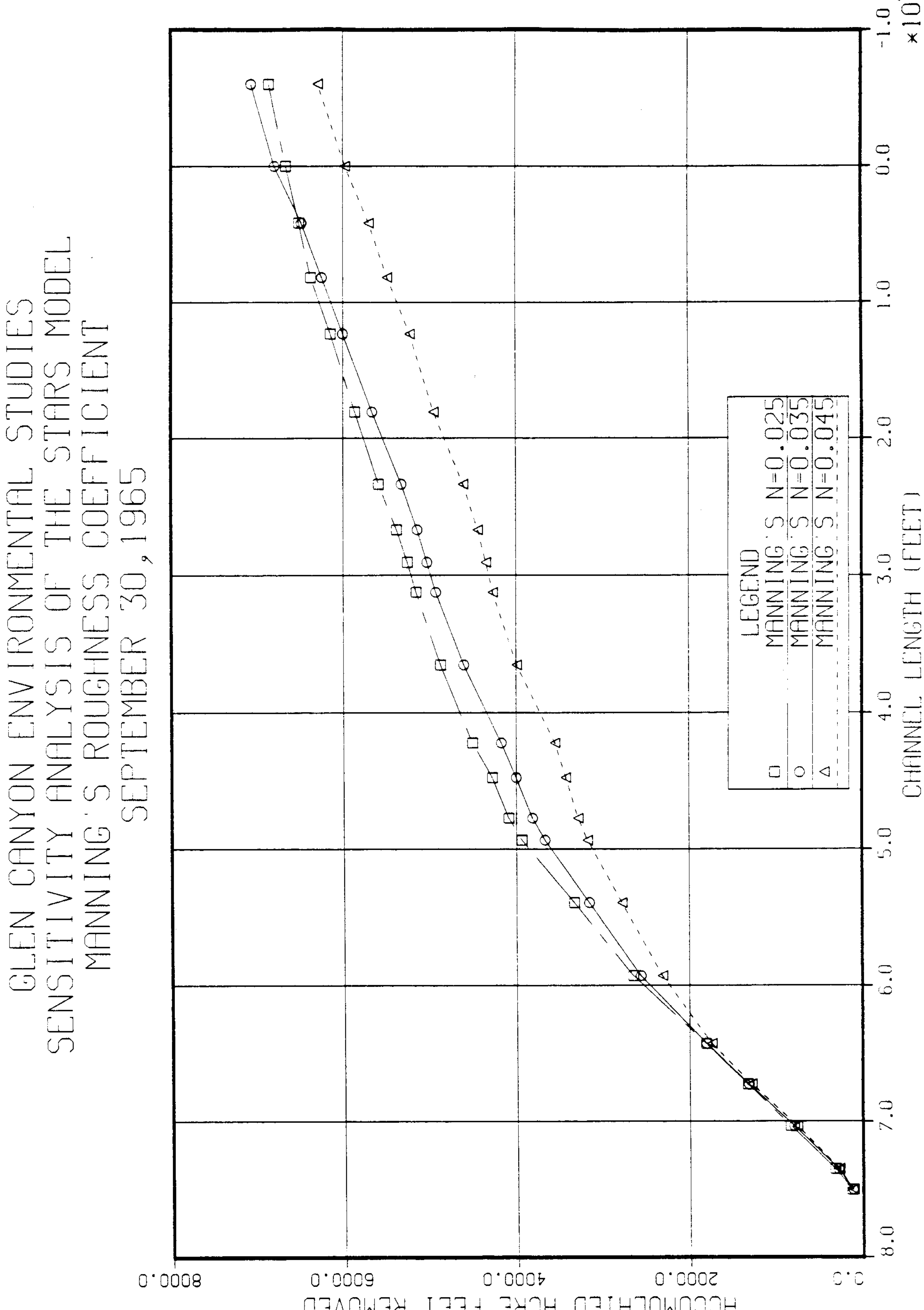

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MANNING'S ROUGHNESS COEFFICIENT
SEPTEMBER 30, 1965
LEGEND
MANNING'S N=0.025
MANNING'S N=0.035
MANNING'S N=0.045
CHANNEL LENGTH (FEET)
ACCUMULATED ACRE FEET REMOVED
*10[4]
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0.0
2000.0
4000.0
6000.0
8000.0

Figure 21

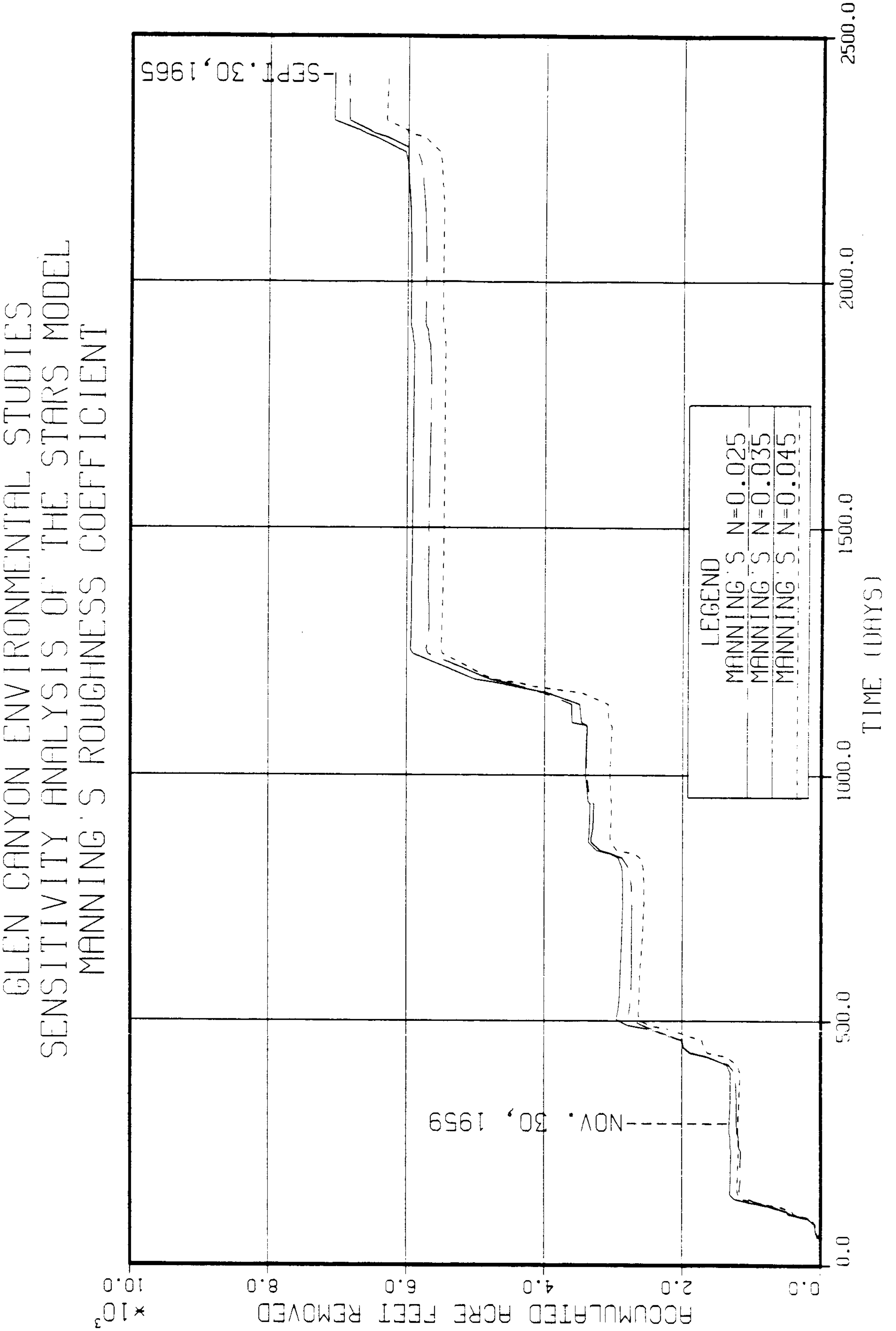

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MANNING'S ROUGHNESS COEFFICIENT
LEGEND
MANNING'S N=0.025
MANNING'S N=0.035
MANNING'S N=0.045
SEPT.30,1965
NOV. 30, 1959
TIME (DAYS)
0.0
500.0
1000.0
1500.0
2000.0
2500.0
ACCUMULATED ACRE FEET REMOVED
$\times 10^3$
0.0
2.0
4.0
6.0
8.0
10.0

Figure 22

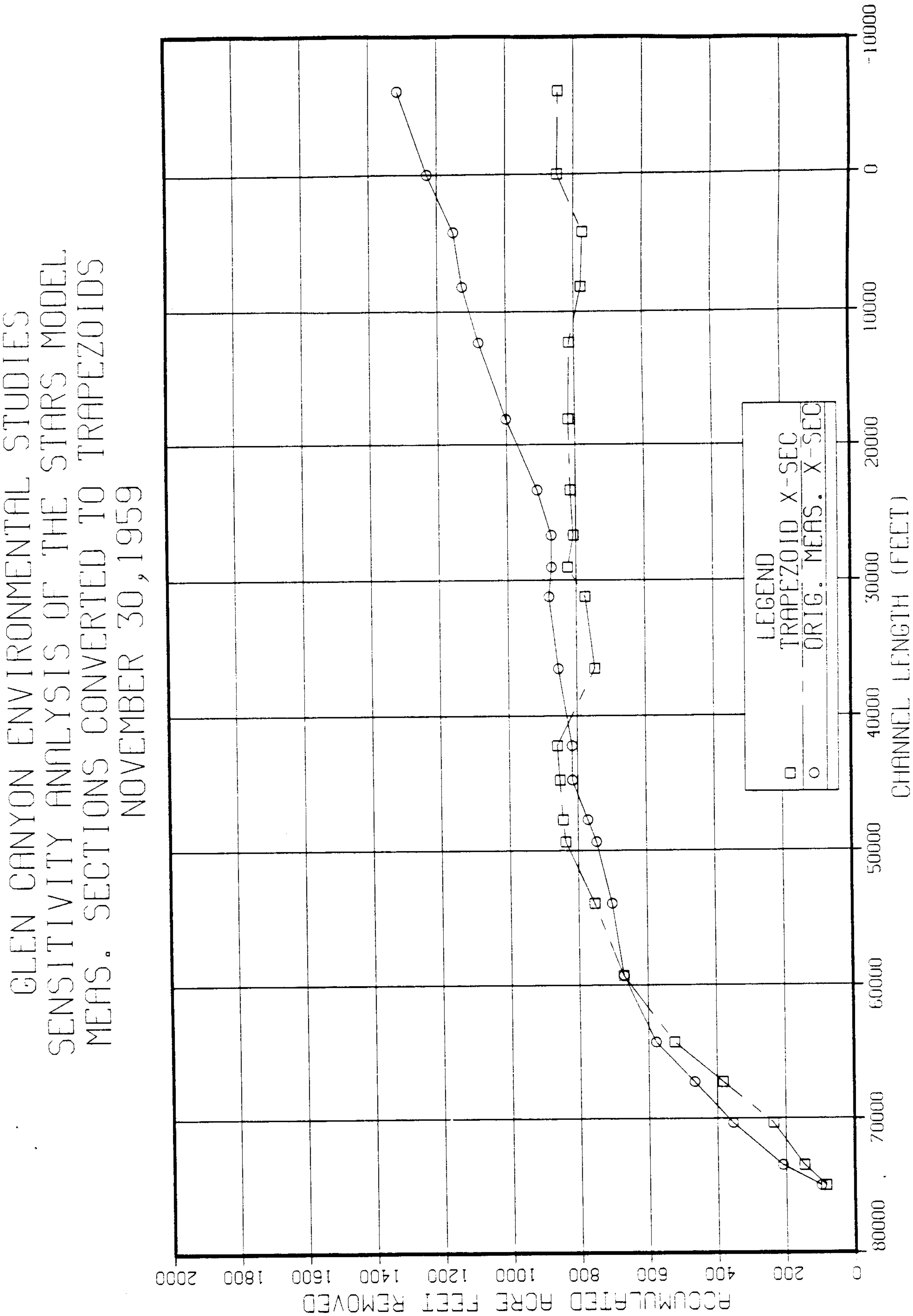

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MEAS. SECTIONS CONVERTED TO TRAPEZOIDS
NOVEMBER 30, 1959
LEGEND
TRAPEZOID X-SEC
ORIG. MEAS. X-SEC
CHANNEL LENGTH (FEET)
ACCUMULATED ACRE FEET REMOVED
-10000
0
10000
20000
30000
40000
50000
60000
70000
80000
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Figure 23

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MEAS. SECTIONS CONVERTED TO TRAPEZOIDS
SEPTEMBER 30, 1965

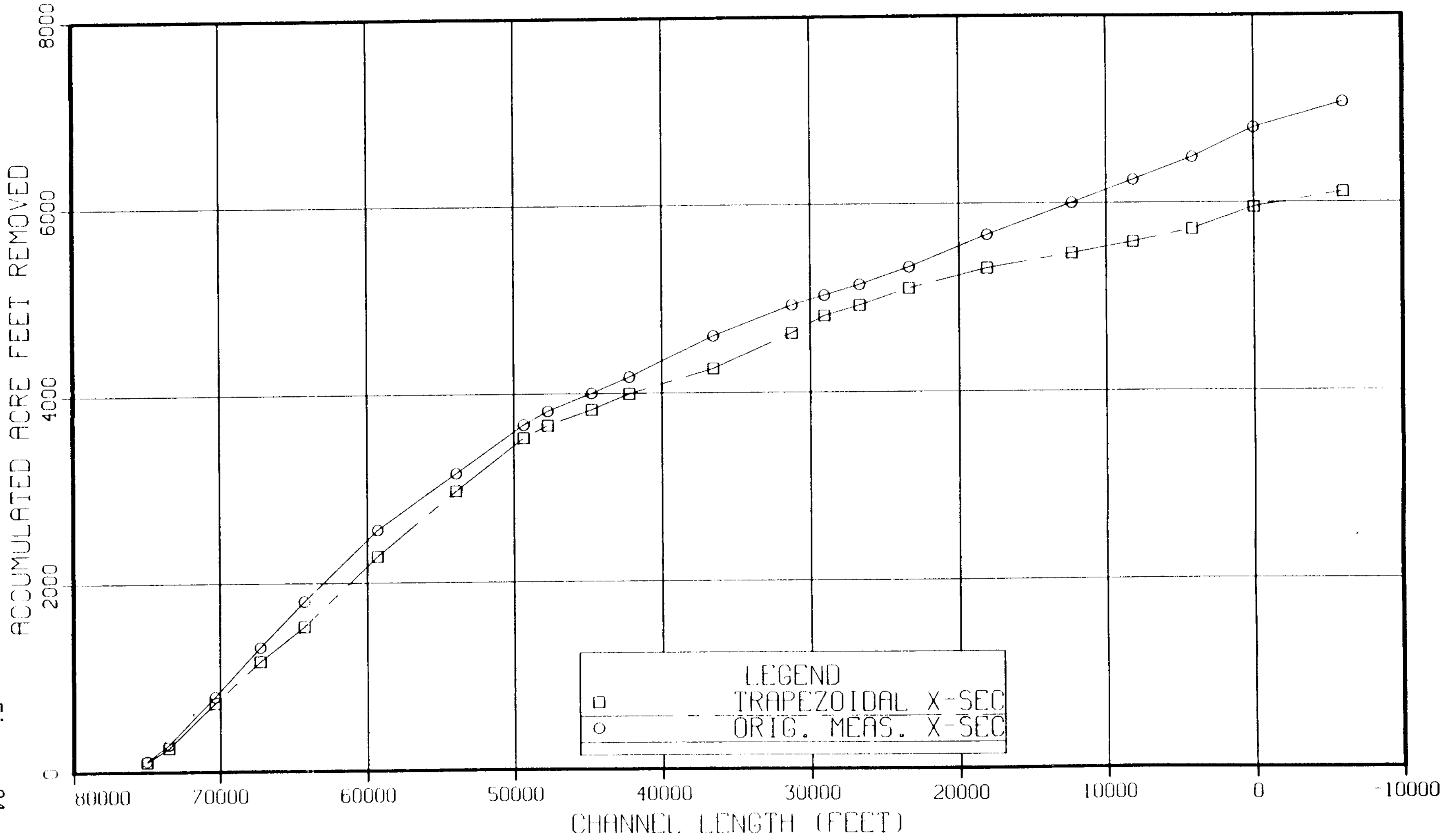


Figure 24

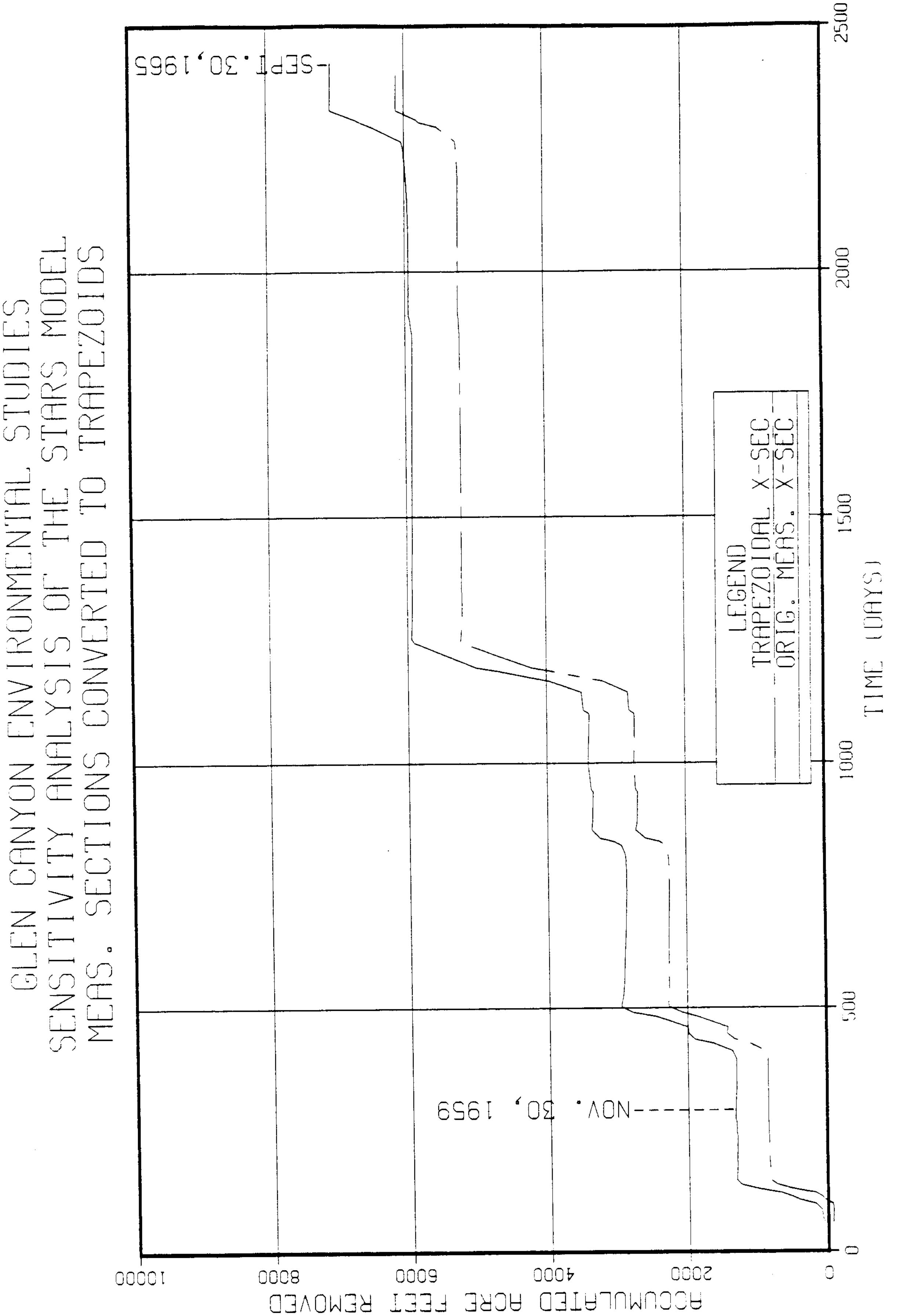

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
MEAS. SECTIONS CONVERTED TO TRAPEZOIDS
LEGEND
TRAPEZOIDAL X-SEC
ORIG. MEAS. X-SEC
SEPT.30,1965
NOV. 30, 1959
TIME (DAYS)
0
500
1000
1500
2000
2500
ACCUMULATED ACRE FEET REMOVED
0
2000
4000
6000
8000
10000

Figure 25

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
NUMBER OF INTERPOLATED SECTIONS
NOVEMBER 30, 1959

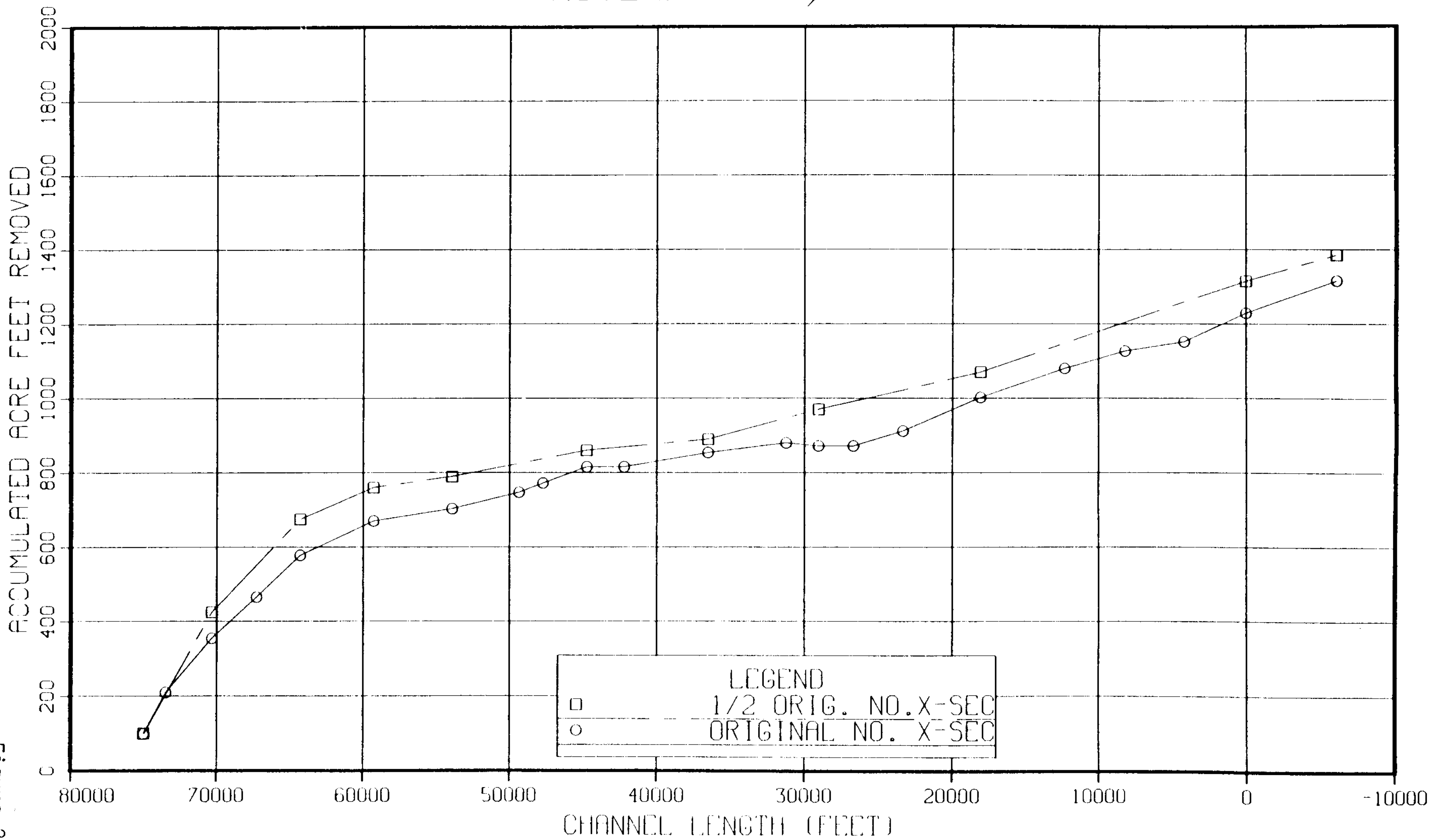


Figure 26

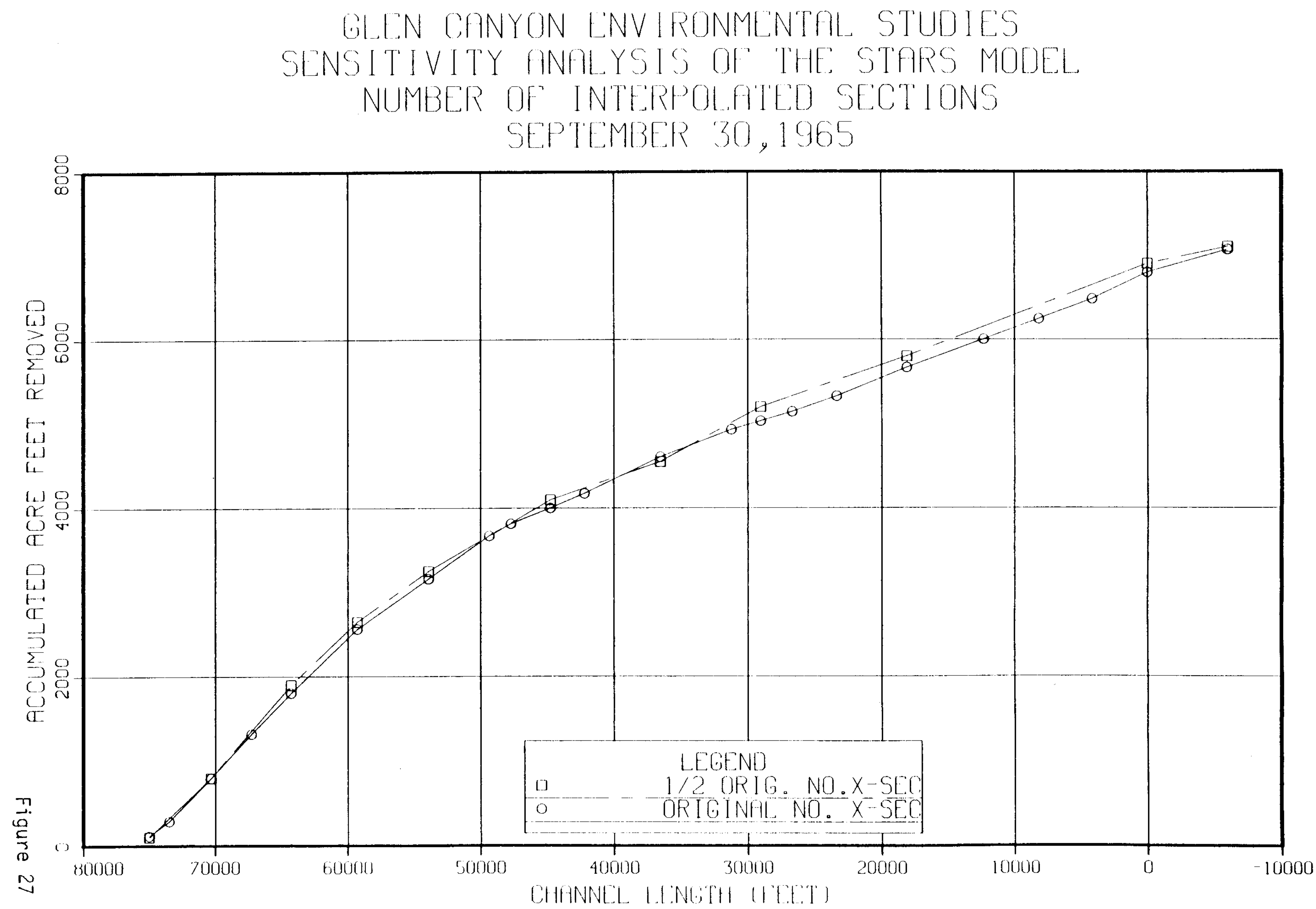

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
NUMBER OF INTERPOLATED SECTIONS
SEPTEMBER 30, 1965
ACCUMULATED ACRE FEET REMOVED
0
2000
4000
6000
8000
80000
70000
60000
50000
40000
30000
20000
10000
0
-10000
CHANNEL LENGTH (FEET)
LEGEND
1/2 ORIG. NO. X-SEC
ORIGINAL NO. X-SEC

Figure 27

GLEN CANYON ENVIRONMENTAL STUDIES
SENSITIVITY ANALYSIS OF THE STARS MODEL
NUMBER OF INTERPOLATED SECTIONS
MANNING'S N = .035

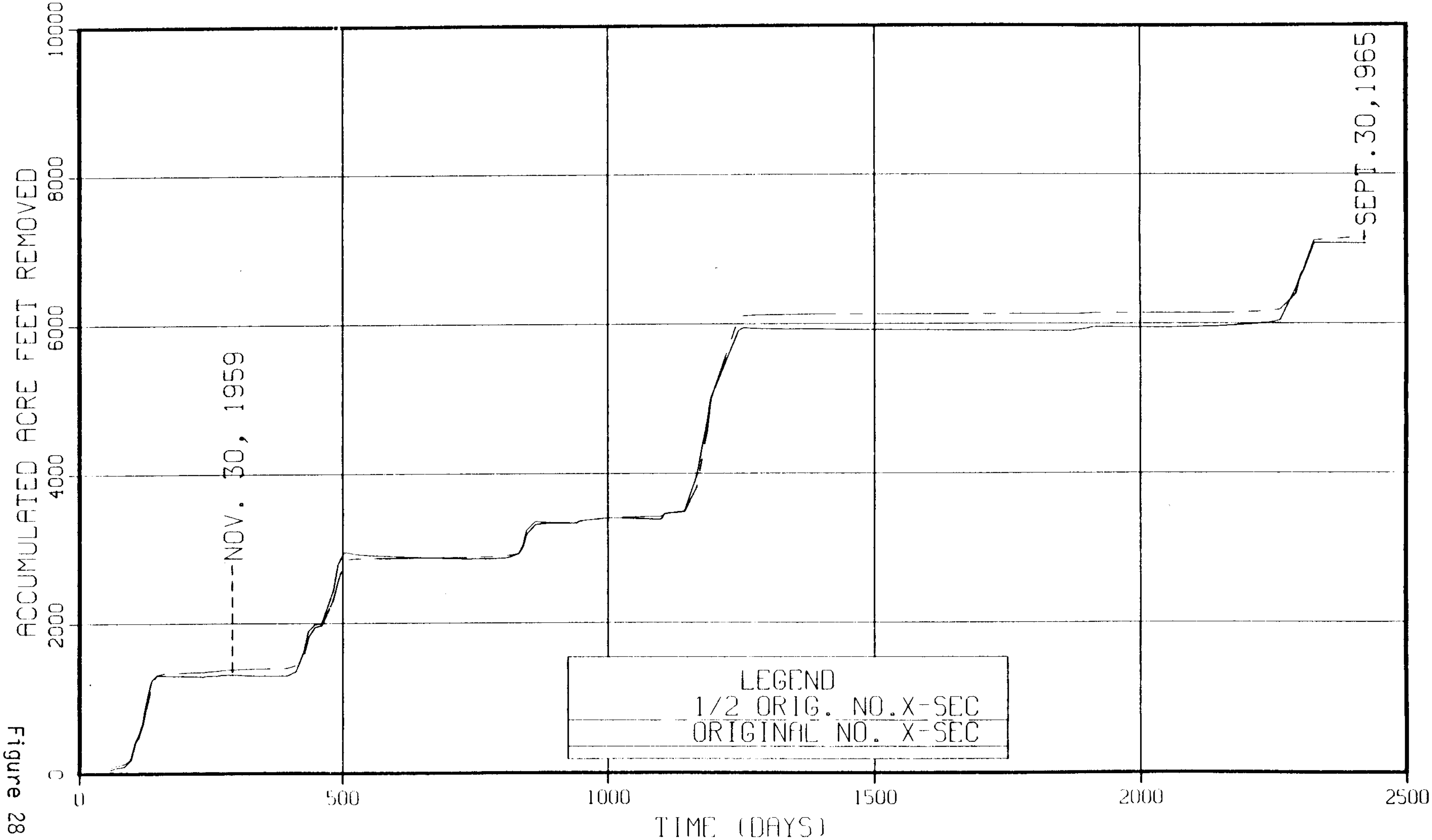


Figure 28