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14. ABSTRACT
In recent years hydraulic structures such as dams have been removed due to deterioration, increased maintenance cost or obsolescence. Investigation of the hydraulic, hydrologic, and sediment transport consequences of the removal of these structures have been very limited, thus necessitating the establishment of analytical techniques and procedures to adequately predict these effects.

To properly evaluate the development of techniques and procedures a model must be selected that closely simulates the actual behavior of the phenomenon being modeled. A mathematical model (HEC-6) was selected because of its success in the prediction of sediment transport when applied to a wide variety of cases. The removal of the Washington Water Power Dam on the Clearwater River near Lewiston, Idaho, was elected for study.

Procedures and techniques of calibration and verification developed, comparison of actual and predicted volume of sediment transported, where the sediment scoured or deposited, and their rates are presented. There is discussion of the applicability of the model to this type of problem, limitations of a one-dimensional model, and interpretation of the results.

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EFFECTS OF DAM REMOVAL: AN APPROACH TO SEDIMENTATION

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EFFECTS OF DAM REMOVAL:
AN APPROACH TO SEDIMENTATION

by

David T. Williams

FOREWORD

The financial, clerical, and graphical support for this paper was provided by The Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers, Davis, California. Initially a Corps sponsored research effort, it was also submitted as a Masters thesis for the University of California at Davis. A more detailed version of this report (with technical data) is available at HEC upon request

I would like to acknowledge Mr. Tony Thomas (Waterways Experimental Station, Vicksburg, Mississippi) for his technical and conceptual help, Professors Ray B. Krone, Edward S. Schroeder, and William K. Johnson, of the University of California, Davis, for their helpful comments and guidance, and The Hydrologic Engineering Center staff.

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EFFECTS OF DAM REMOVAL: AN APPROACH TO SEDIMENTATION

David T. Williams*

I. Introduction

In February of 1973, the Washington Water Power Dam (WWPD) on the Clearwater River, Idaho, was removed because of increased maintenance costs and obsolescence. As a result, changes occurred in the hydraulic and sedimentation characteristics of the river. The purpose of this study is to determine how the observed changes occurred, to develop a suitable analytical technique for such studies, and to evaluate and verify a mathematical model used to predict the observed changes. The changes in the river bed include the rate of deposition or scour along the river bed, the magnitude of deposition or scour at times subsequent to the removal of the dam, and changes in the hydraulic and sediment transport characteristics of the river following dam removal.

In the past most of the studies related to dams have been in the area of construction design and the hydraulic, hydrologic, economic, social, and environmental impact of their placement. No assessments were made concerning the measures (e.g., dam removal) that must be implemented at the end of their design life (typical design life of a dam is 50 years). During the Depression Era (1930's) many dams were constructed that have a designed life that will terminate in the 1980's. Most of these dams require a high level of maintenance as a direct result of age and are becoming increasingly cost ineffective. Large dam systems that have been implemented in later years have made many minor dams obsolete. The disposition of an obsolete and/or decaying dam is a problem that will be addressed even more frequently in the future.

Removal of a hydraulic structure such as a dam causes changes in the hydraulic and sedimentation characteristics of a river which subsequently

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caused adverse effects on both man and the environment. If the effects of the dam removal are predictable through the use of an analytical technique and a mathematical model, measures (e.g., gradual removal) could be implemented to lessen the impact of the adverse effects.

The removal of the Washington Water Power Dan (WWPD) on the Clearwater River was selected for study because of the available sediment data before and subsequent to the dam removal. This data was gathered by the U.S. Geological Survey and the Walla Walla District of the Corps of Engineers and was obtained mainly for an ongoing study of the Snake and Clearwater Rivers.

Clearwater River is a tributary of the Snake River in Idaho and services a drainage area of 9,570 miles. Figure 1 shows a map of the drainage basin. The confluence of the Snake and Clearwater Rivers was defined as River Mile 0 and cross-section locations are in terms of river miles upstream along the Clearwater River.

Washington Water Power Dam was located at River Mile 4.62. In operation since 1928, the dam was approximately 35 feet high and 1100 feet long. The dam was of concrete construction with moveable gates which allowed submerged flow. During the month of February, 1973, the dam was removed by large cranes and minimal explosive demolition. The entire operation was performed during a low flow period.

Located downstream of the confluence of the Snake and Clearwater Rivers is the Lower Granite Dam. The impoundment of water behind this dam began in February 1975. In June 1975, the Lower Granite Reservoir and Lock facilities became fully operational. This impoundment has an important role in the sediment balance of the study area because the backwater effects of the Lower Granite Reservoir extends into the study area and the analysis period includes the time of impoundment.

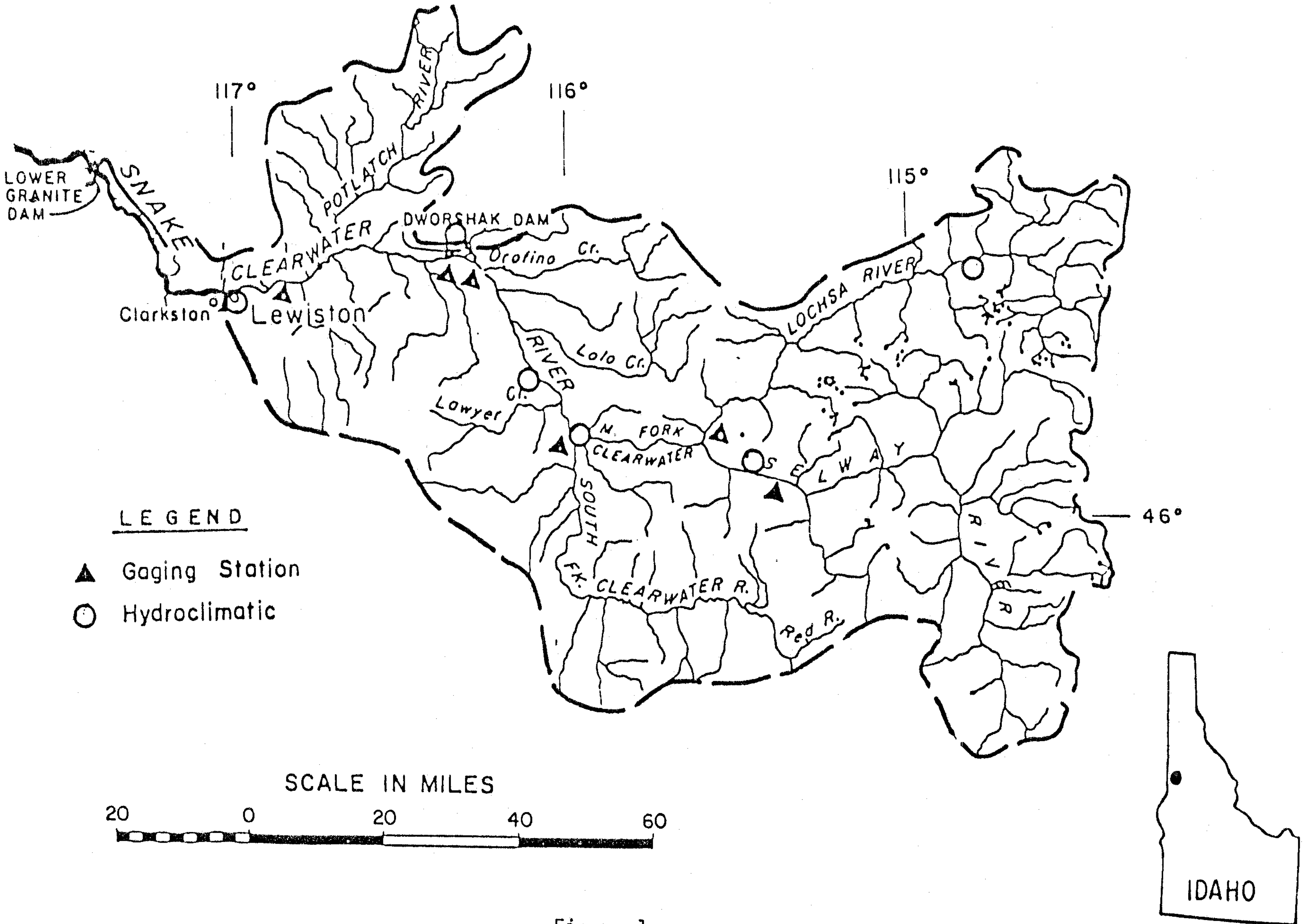


Figure 1

DRAINAGE BASIN, CLEARWATER RIVER, IDAHO

II. Basic Approach: Mathematical Model

The behavior of a 7.83 mile reach of the Clearwater River is simulated by a computer program and results compared to field data to evaluate and verify the computer program. These comparisons are used to determine the suitability of the analytical techniques to studies of this type. All computer applications were conducted at The Hydrologic Engineering Center (HEC), Davis, California.

The mathematical model selected for use in the analysis of dam removal effects is a generalized computer program entitled "HEC-6, Scour and Deposition in Rivers and Reservoirs" and is distributed by The Hydrologic Engineering Center, Corps of Engineers (Computer Program Number 723-62-L2470). This computer program was selected because of the general success in its usage over a wide variety of applications (8) and the accessibility of the program. The sediment transport methods available for use in the program are those developed by Toffaleti, Laursen, Duboys, and Yang. Toffaleti's transport method was used in the study (10).

This simulation computer program is designed to analyze scour and deposition by modeling the interaction between the water-sediment mixture, sediment material forming the stream's boundary and the hydraulics of the flow. This is not a sediment yield program *per se*. It simulates the ability of the stream to transport sediment and considers the full range of conditions embodied in Einstein's Bed Load Function plus silt and clay transport and deposition, armoring and the destruction of the armor layer. Figure 2 shows a Functional Flow Chart of HEC-6 (9).

The limitations of the computer program are related to the one-dimensional aspect of the model, since it is a one-dimensional steady flow model with no provision for simulating the development of meanders or specifying a lateral distribution of sediment load across a cross section. The cross section is

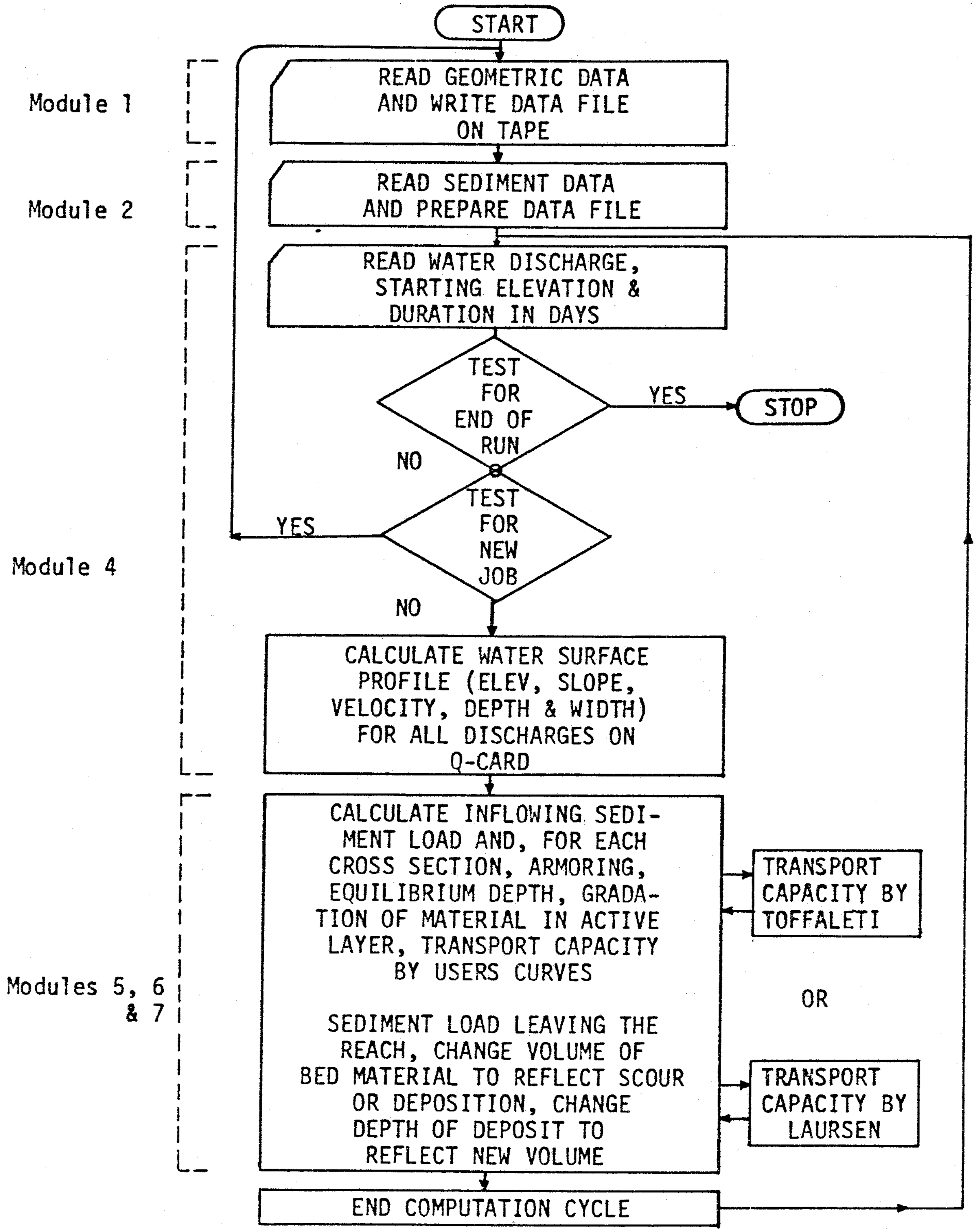


Figure 2

FUNCTIONAL FLOW CHART OF HEC-6

subdivided into two parts with input data -- that part which has a moveable bed, and that which does not; and the boundary between these parts remains fixed for the study. The entire moveable bed part of the cross-section is moved vertically up and down. Bed forms are not simulated except that n-values can be functions of discharge which indirectly permits a consideration of bed forms to be made. Density currents and secondary currents are not accounted for (9).

III. Data Collection and Processing

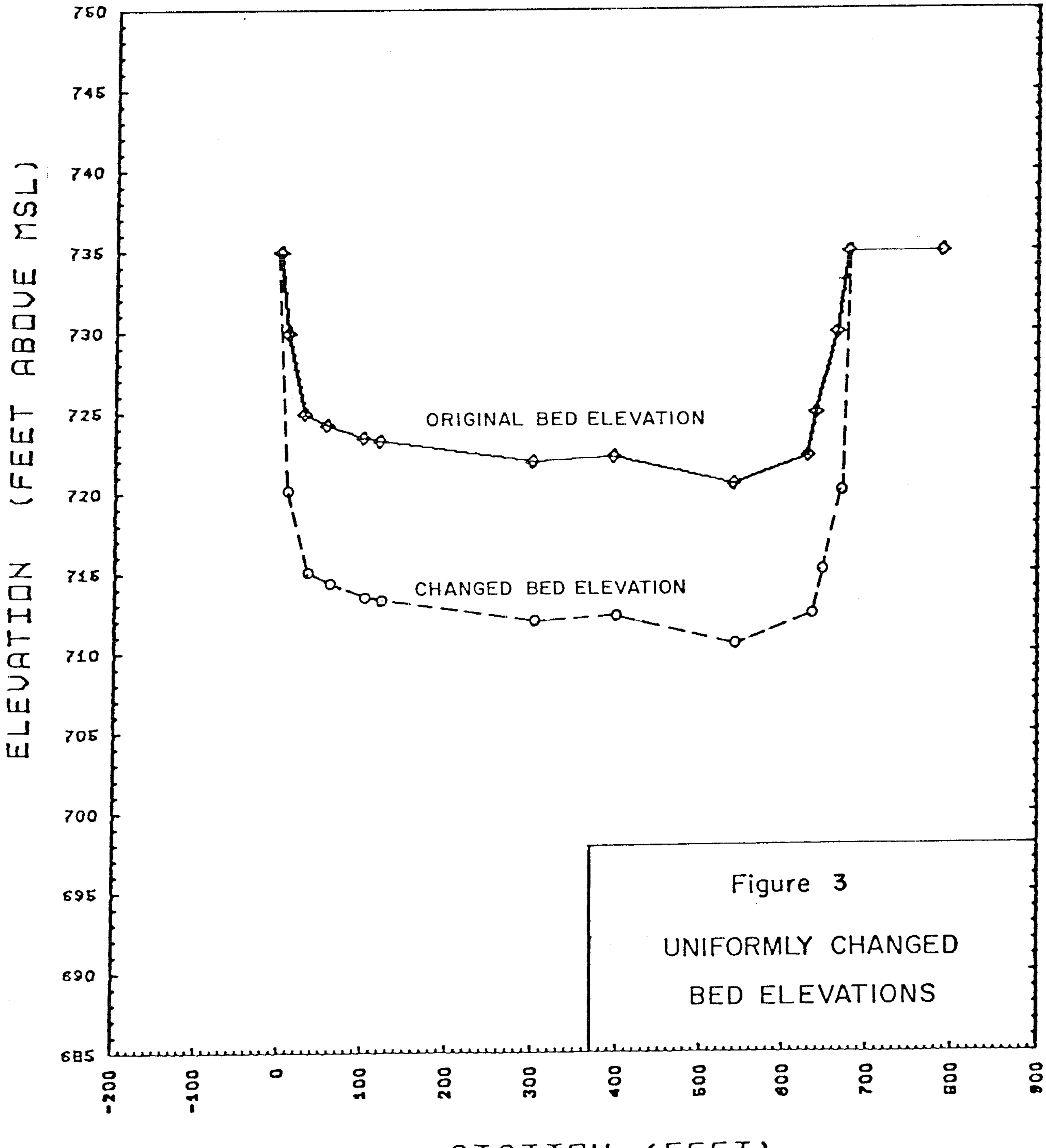
Each of the cross-section geometry measurements used in the study were made by the Walla Walla District of the Corps of Engineers. A sonic fathometer with a resolution of $\pm$ .1 feet was used for the depth determination. These measurements were transferred to a Cartesian coordinate system plot and encoded into a format usable by the model.

All sediment load measurements were made by the U.S. Geological Survey (1, 2, 5, 6) through a cooperative program sponsored by the Walla Walla District. The suspended load was measured by P-1 or P-3 suspended-sediment samplers (3). Both point collection and depth-integrated samples were collected for analysis of concentration and grain size distribution. These measurements were made for various discharges over a 5 year period. Conversion of concentration to tons per day was made by the equation:

tons/day = .0027 X concentration (mg/l) X discharge (cfs)

These discharge vs. suspended sediment load data are plotted in Figure 4. Bed load was measured using a Helley-Smith type bedload sampler (4).

Figure 4 has a scatter of data but a definite relationship exists between the sediment load and discharge. A least-squares fit was developed for suspended and bedloads by the USGS (6). The two sediment loads of the least-squares curve were added to produce the total sediment load curve shown



CLEARWATER RIVER, SECTION 2.89

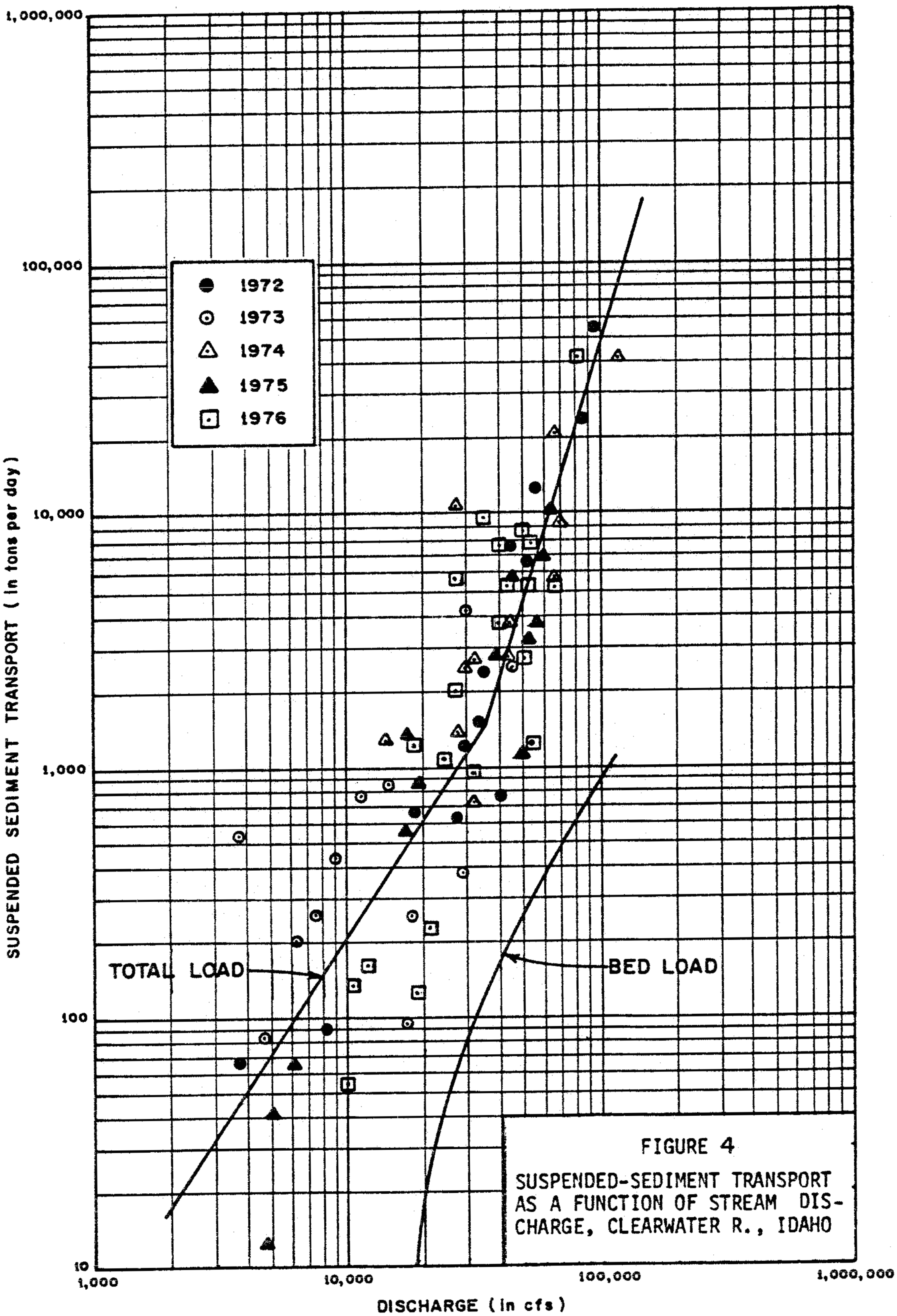


FIGURE 4

SUSPENDED-SEDIMENT TRANSPORT AS A FUNCTION OF STREAM DISCHARGE, CLEARWATER R., IDAHO in Figure 4. From collection of many samples, an averaged grain size distribution of the inflowing sediment load was developed. The corresponding percent of the total load was determined for each grain size class. With the use of the total load curve in Figure 4, the percent of each size class was multiplied by the total load at a certain discharge to obtain the sediment load contributed by the grain size fraction for that discharge. Using the same procedure for other discharges, a discharge-sediment load curve was developed for each grain size fraction. These relationships determine the grain size distribution and weight of the inflowing sediment load for each hydrograph discharge.

Bed material particle size distribution was determined by sieve analysis of bulk samples one cubic foot in volume. Only three bed measurements were made on the Clearwater River. The first measurement was made about two miles above the upstream boundary of the model, the next at about mile 4.74 and the last measurement was made near mile 2.0. In the initial phase of the model calibration, the first measurement was considered to represent the bed from mile 7.83 to mile 5.56. The second measurement represented the bed from mile 5.39 to mile 4.62 (site of Washington Water Power Dam) and the last measurement, mile 4.61 to mile .67.

Historic mean daily flows were obtained for the years 1966 to 1975 at the USGS gage in Spalding, Idaho (7). Located near the upstream boundary of the model, the gage used a calibrated stream-flow gage which related the measured water height to discharge. Future hydrology was predicted by assuming (assumption was made by the author) that the historic events would occur in the same sequence and intensity in the future. The hydrology of 1980 was assumed to be that of 1970, 1981 assumed to be that of 1971, etc.

The stage-discharge rating curve at the downstream model boundary (before Lower Granite Reservoir impoundment) was determined by observed stage heights for a wide range of flows. This rating curve was the downstream boundary condition for the model and determined the starting elevation for water surface profile calculations for any particular discharge. A constant water surface elevation of 738 feet was used after the impoundment of Lower Granite Reservoir in 1975.

A value of .03 for n was selected for the channel and overbanks. This compares favorably with other rivers of this type with calibrated n values of approximately .03. Calibration of this n was not possible due to the lack of water marks or discharge vs. depth measurements upstream of model boundary.

IV. Model Calibration and Verification

Computer runs were made in a "fixed bed" mode (i.e., no bed elevation change) with various discharges. The water surface elevation was calculated at each cross-section with an operating pool elevation of 761 feet at the Washington Water Power Dam (River Mile 4.62). Checks were made to insure that the water surface elevations did not exhibit unusual characteristics.

The model was verified by analyzing known historical stream bed conditions and using them as performance criteria. Figures 5, 6 and 7 show the change in bed elevations upstream of the WWPD. Looking at the lines representing the dam in place condition, the figures show only slight bed elevation change. This was expected because the WWPD has been in operation for a long time. A slight overall deposition trend was calculated upstream of the dam, indicating that the reservoir was not completely filled with sediment at the time of dam removal.

Figure 8 shows the change in bed elevation downstream of the WWPD. It shows slight degradation of the bed elevation with the dam in place. This again is reasonable because the inflowing sediment load to these sections is deficient (caused by the WWPD) compared to the sediment load under natural conditions. The model also showed slight overall scour downstream of the dam.

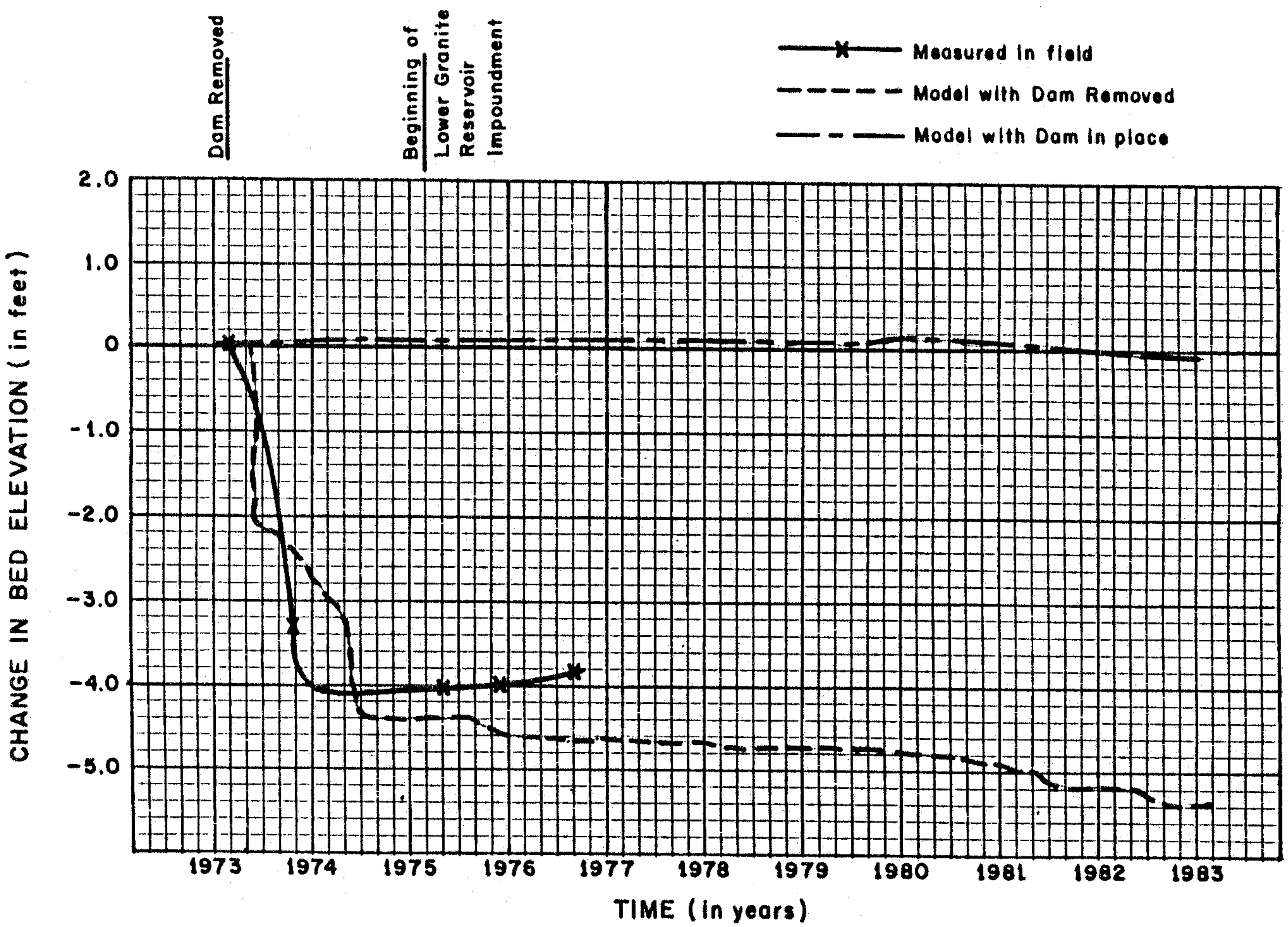


FIGURE 5
CHANGE IN BED ELEVATION
RIVER MILE 4.74
CLEARWATER RIVER, IDAHO

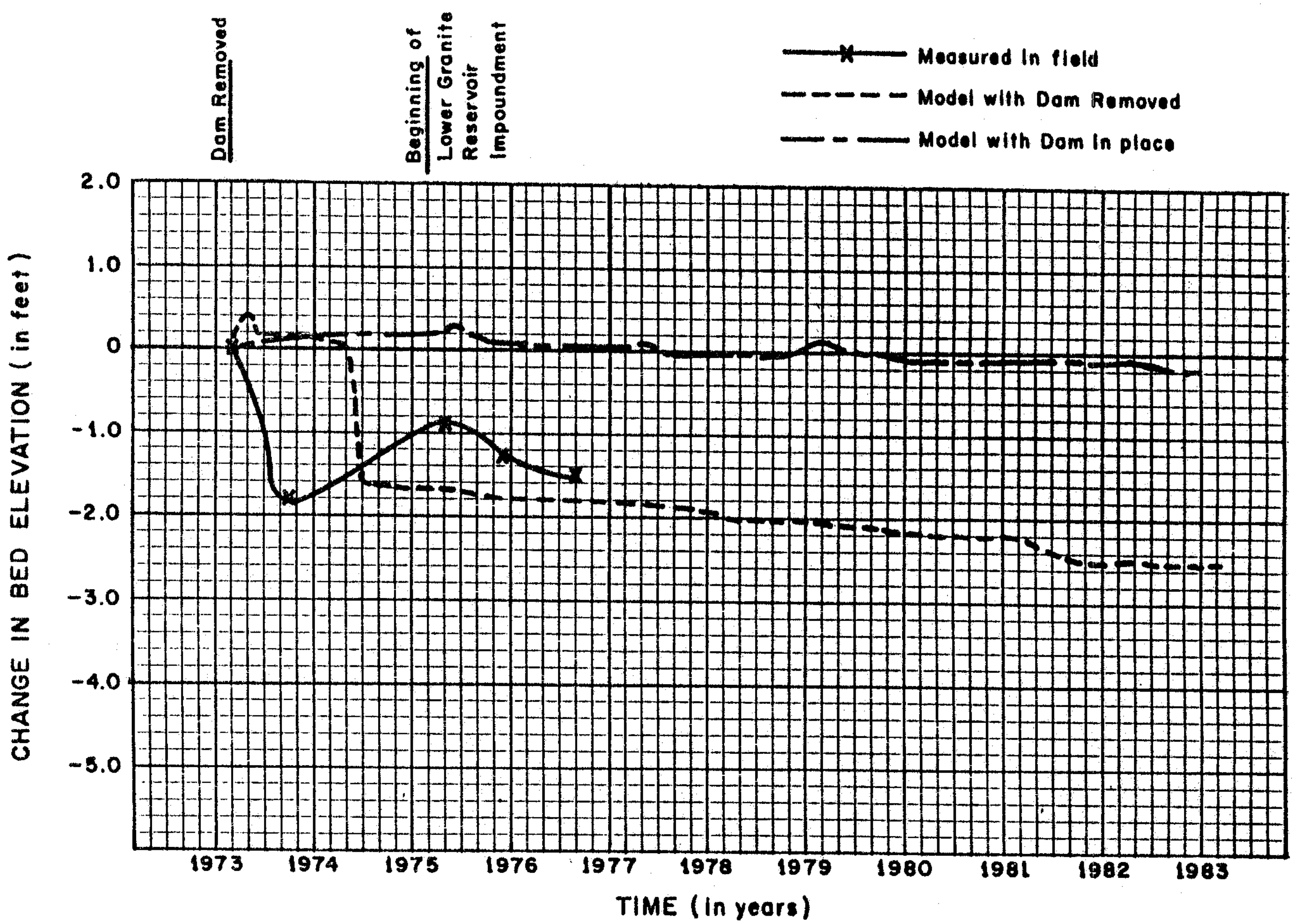


FIGURE 6
CHANGE IN BED ELEVATION
RIVER MILE 5.01
CLEARWATER RIVER, IDAHO

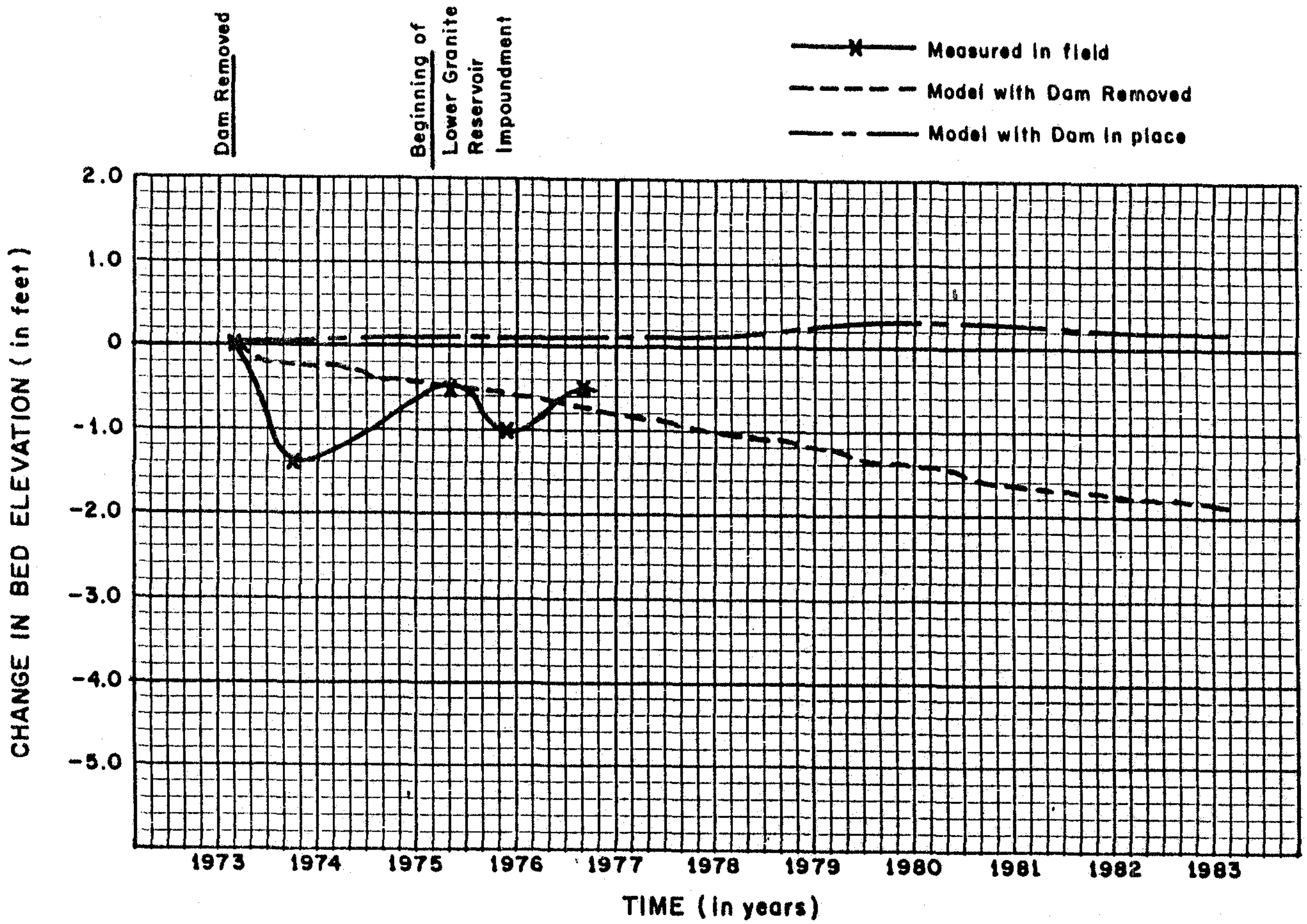


FIGURE 7
CHANGE IN BED ELEVATION
RIVER MILE 5.39
CLEARWATER RIVER, IDAHO

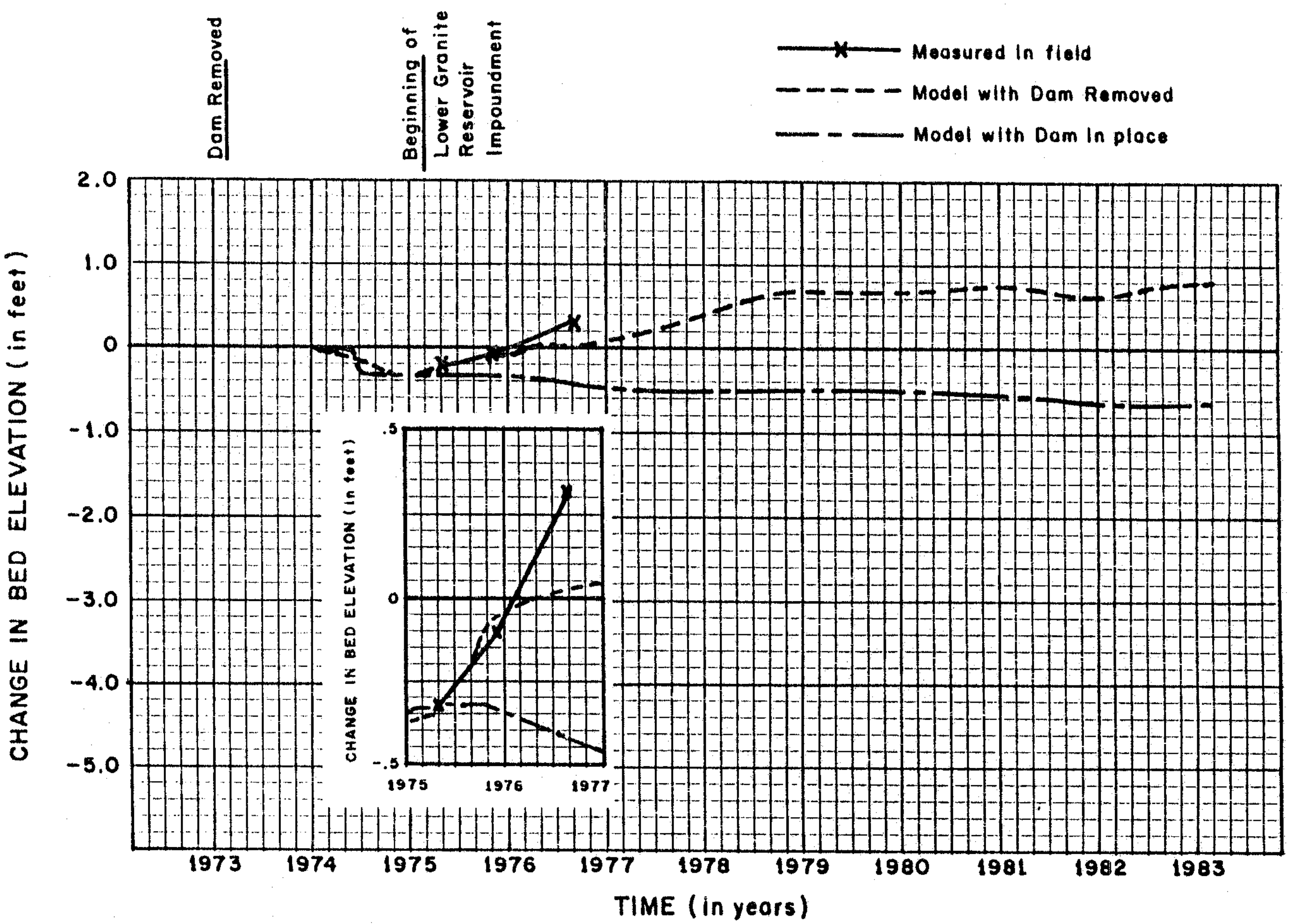


FIGURE 8
CHANGE IN BED ELEVATION
RIVER MILE 3.48
CLEARWATER RIVER, IDAHO

It is difficult to determine whether variations in sediment yield are caused by variations in discharges or changes in the hydraulic regime such as those caused by dam removal. For example, if a dam is removed, the downstream sediment yield should be greater because of the scouring of the sediment pool behind the original dam. However, the sediment yield would be distorted if, during the period of analysis, high water discharges with the associated high sediment discharges occurred. To compensate for this variation caused by the flow, the ratio of sediment outflow to sediment inflow was used to measure scour and deposition trends. This ratio is dimensionless and is independent of water discharge variation. A ratio of 1 indicates no change (i.e., equilibrium: what goes in, goes out), less than 1 indicates sediment is being accumulated (deposition), and greater than 1 indicates sediment is being removed from the bed (scour).

Figure 9 shows the computed change in the inflow/outflow ratio over a 10 year period with the dam in place. Without the Lower Granite Reservoir impoundment, the curve indicates slight deposition (ratio <1) with a tendency to 1 (equilibrium). This leads to the conclusion that the WWPD was still causing slight deposition but that reservoir had almost reached its capacity of sediment. With the Lower Granite Reservoir impoundment, greater deposition occurs within the study area because the inflowing sediment load is being dropped because of the influence of the downstream reservoir. There is a tendency towards equilibrium as the Clearwater arm of the Lower Granite Reservoir begins to fill. It appears that equilibrium will occur sometime after 1983. The inflow/outflow ratio at 1974 in Figure 9 shows initial scour and reason indicates that it should be deposition. This discrepancy is attributed to slight error in the initial condition which the model adjusted as calculations were made over time.

Figure 10 shows the predicted volume of sedimentation within the model boundaries with the WWPD in place. Without the Lower Granite impoundment,

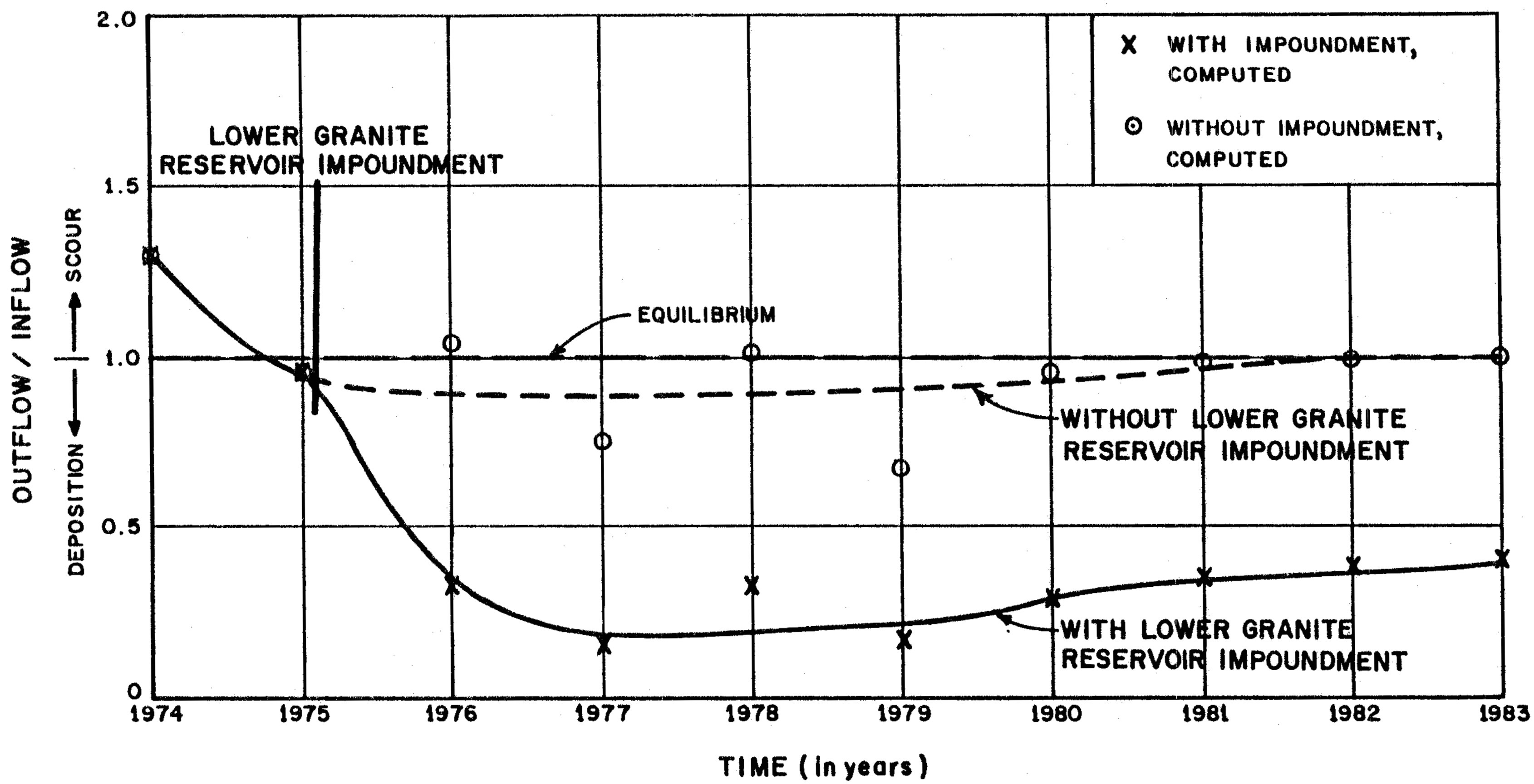


FIGURE 9
CALCULATED RATIO OF SEDIMENT
OUTFLOW TO INFLOW
WASHINGTON POWER DAM IN PLACE

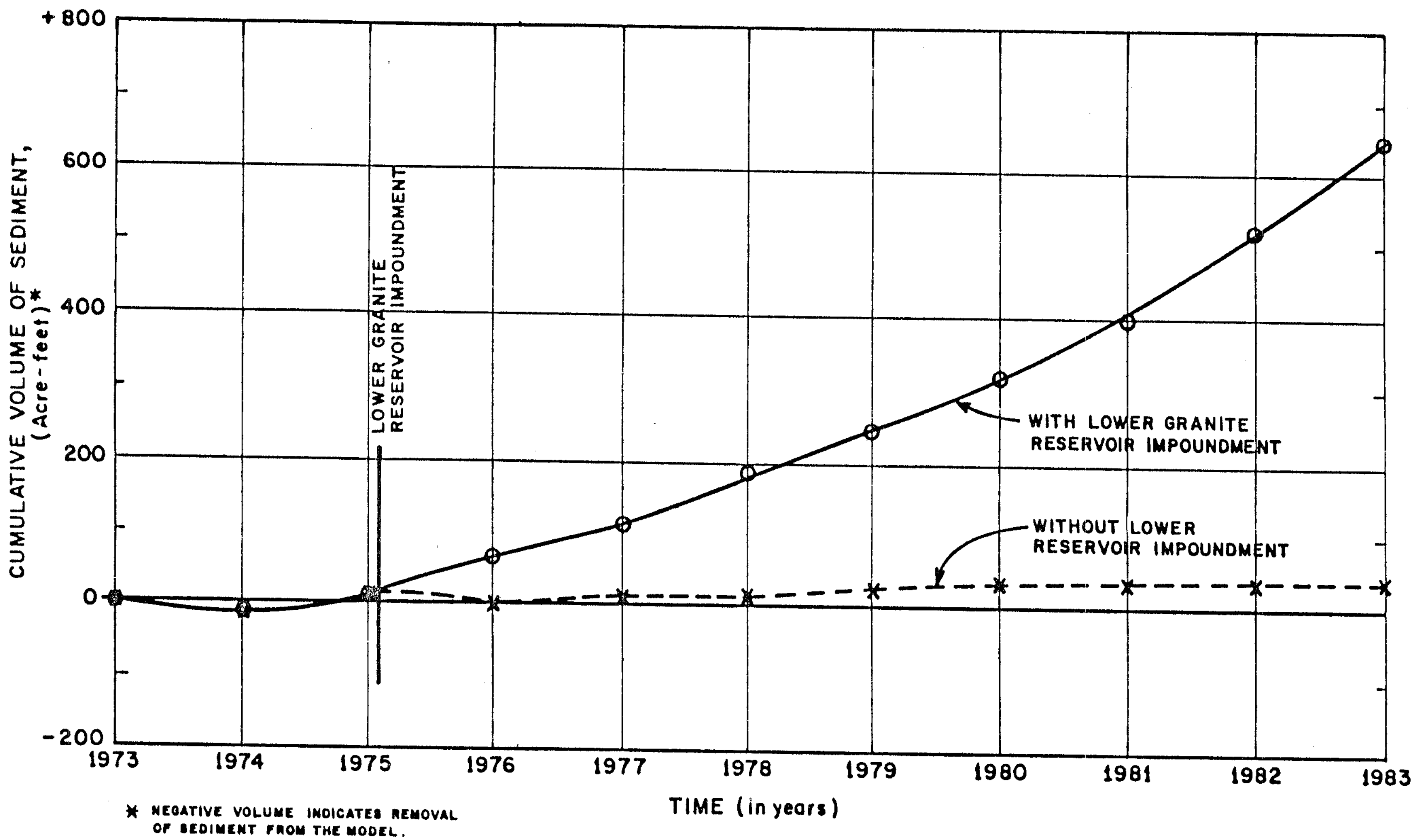


FIGURE 10
PREDICTED VOLUME OF SEDIMENTATION
WASHINGTON POWER DAM IN PLACE

the model showed that an additional deposition of approximately 40 acre-feet would have occurred in the WWPD pool if the WWPD dam had remained in place for 10 more years. With the Lower Granite Reservoir impoundment, deposition in the study area would have been about 650 acre-feet over 10 years. All the deposition occurs downstream of the WWPD. These trends are to be expected under the operating conditions specified.

V. Dam Removal Results and Discussion

Measured bed elevation changes were determined by analysis of measured cross-section geometry for February 1973, September 1973, April 1975, November 1975, and August 1975. Bed elevation change from February 1973 to September 1973 was determined by overlaying the cross-sections (must be of the same scale), planimetering the area below a common elevation datum where both cross-sections meet, finding the difference in the areas, and dividing the resulting area by the width of the bed portion that moved. This procedure was also used to obtain the bed elevation changes for other time increments.

Figures 5, 6 and 7 show the observed change in bed elevations upstream of the Washington Dam site. The comparison between the measured and observed bed elevation change for River Mile 4.74 (Figure 5), the section immediately upstream of the dam site, shows good correlation for both timing and magnitude of bed elevation change. Figure 6 indicates general agreement between the measured and computed magnitudes of bed elevation change over an extended time period. The fluctuations of the measured bed elevations in Figure 7 limit any analysis of the overall tendencies of the bed. Any further analysis would require more data points both within the points actually shown and beyond 1976. The overall magnitude of the computed bed elevation changes were in fairly acceptable agreement with the measured changes. Projections into the future revealed that the sections would slowly continue to scour.

The timing of the measured and computed bed elevation changes for Figures 6 and 7 appear to lag by approximately 10 months. The rate of scour decreases significantly near the end of 1973 for the measured data and the middle of 1974 for the computed.

Adequate information to determine bed elevation changes for 1973 to 1975 were not available for the sections downstream of the dam site. For the purpose of analysis, the April 1975 bed elevation was assumed to be that of the computed elevation at that time and measured bed elevation changes are determined by changes from the April 1975 measured bed elevation.

Since very little bed change occurred downstream of the dam site for both the measured and computed cross-sections, it is rather hard to discuss the accuracy of timing and magnitudes of change. Discussion is then limited to tendencies shown by the model and prototype. As shown in Figure 8, the model calculated initial scour after the WWPD was removed, and both the computed and measured sections showed depositional tendencies after impoundment of Lower Granite Reservoir. Projections into the future indicate continued deposition at these sections. This deposition will probably continue until Lower Granite Reservoir reaches an equilibrium condition.

No suspended and bed load measurements were available to determine the sediment load. Because of this lack of field data, analysis must be concentrated on the reasonability of the model results when compared to what is actually expected to happen.

As shown in Figure 11, the ratio of outflow to inflow indicates rapid scour in the first year after dam removal. Without the Lower Granite Reservoir impoundment, the ratio indicates a decrease in the scour rate after the first year. The projection into the future shows continued but decreasing scour with equilibrium eventually being achieved. With the impoundment there occurs a transition from scour to deposition and then a decrease in the deposition with a tendency toward equilibrium.

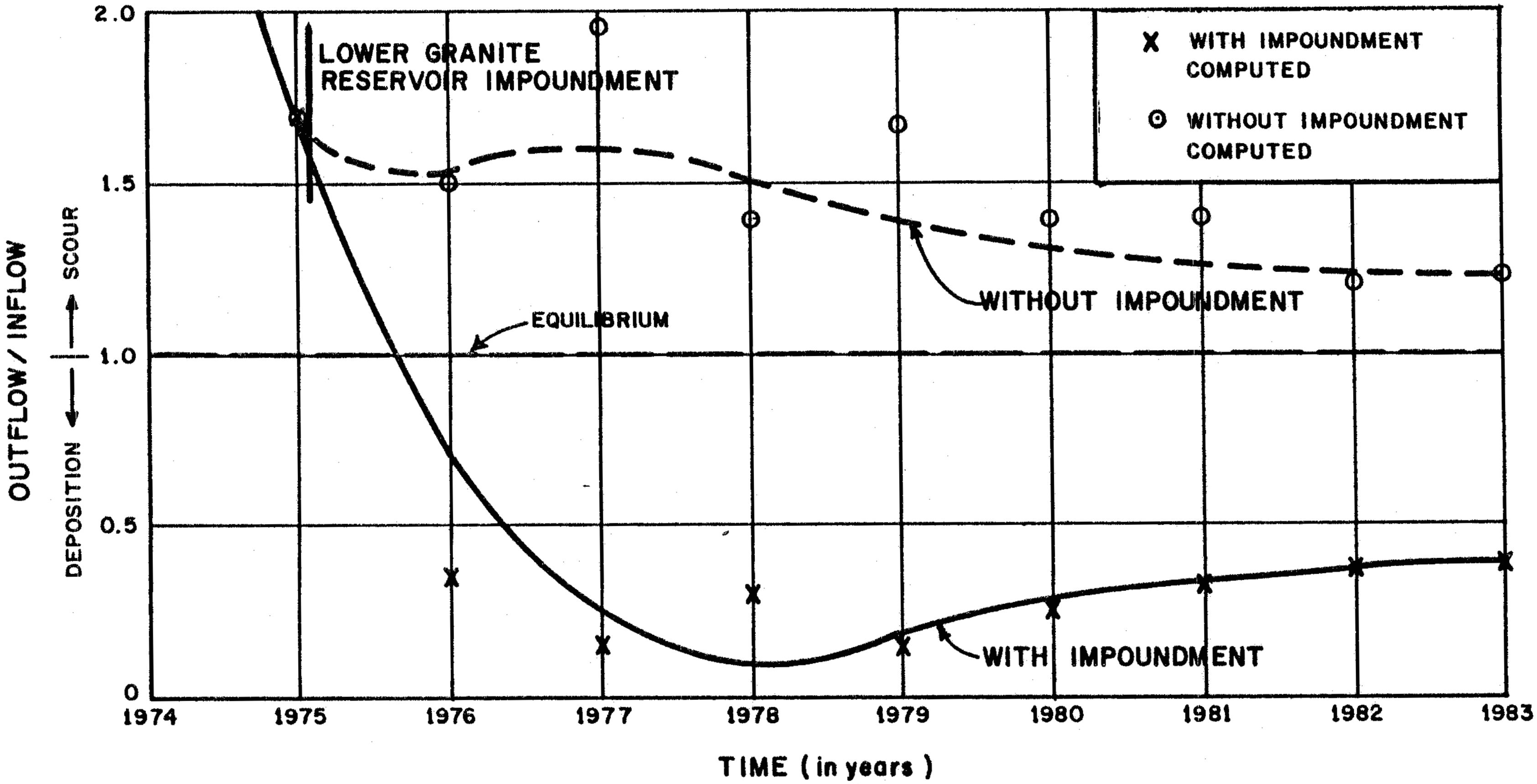


FIGURE 11
CALCULATED RATIO OF SEDIMENT
OUTFLOW TO INFLOW
WASHINGTON POWER DAM REMOVED

The quantity of sediment deposition or scour within the model limits is presented in Figure 12. This plot shows that calculated volume changes were as expected. The cumulative volume became negative (scour) after the dam was removed and continued this trend fairly uniformily for the case of no impoundment. With the impoundment, the graph shows an immediate increasing trend and eventually became positive in 1979. Figure 10 shows that the predicted volume of deposition after ten years with the WWPD in place and Lower Granite Reservoir impounded is 640 acre-feet. In Figure 12 the predicted volume of deposition after ten years, with the WWPD removed and the Lower Granite Reservoir impounded, is 400 acre-feet. This indicates that the total effect of the dam removal after ten years is the removal of 240 acre-feet of sediment from the model limits.

Figures 13, 14, 15 and 16 show the observed particle size distributions of the sediment on the stream bed before WWPD removal and the calculated particle size distribution eight years after removal. Figure 13 shows the bed becoming finer after the dam removal. This is expected because it is the section closest to the Lower Granite Reservoir impoundment. Figure 14 shows the section immediately downstream of the dam site and exhibits a slightly finer particle distribution after the dam removal. The most abrupt bed change is expected at the dam site as shown in Figure 15. Coarsening of the bed is expected due to the increased velocities after dam removal. Figure 16 shows very little bed change because it is out of the influence of the former WWPD pool.

At the end of 10 years of flow through the model with the dam removed, the bed profile was determined and artificial flows were input to determine the new water surface profiles. These new bed and water surface profiles are presented in Figure 17. Thalweg and average bed profiles show a lowering of the bed immediately upstream of the dam site and deposition in the scour hole

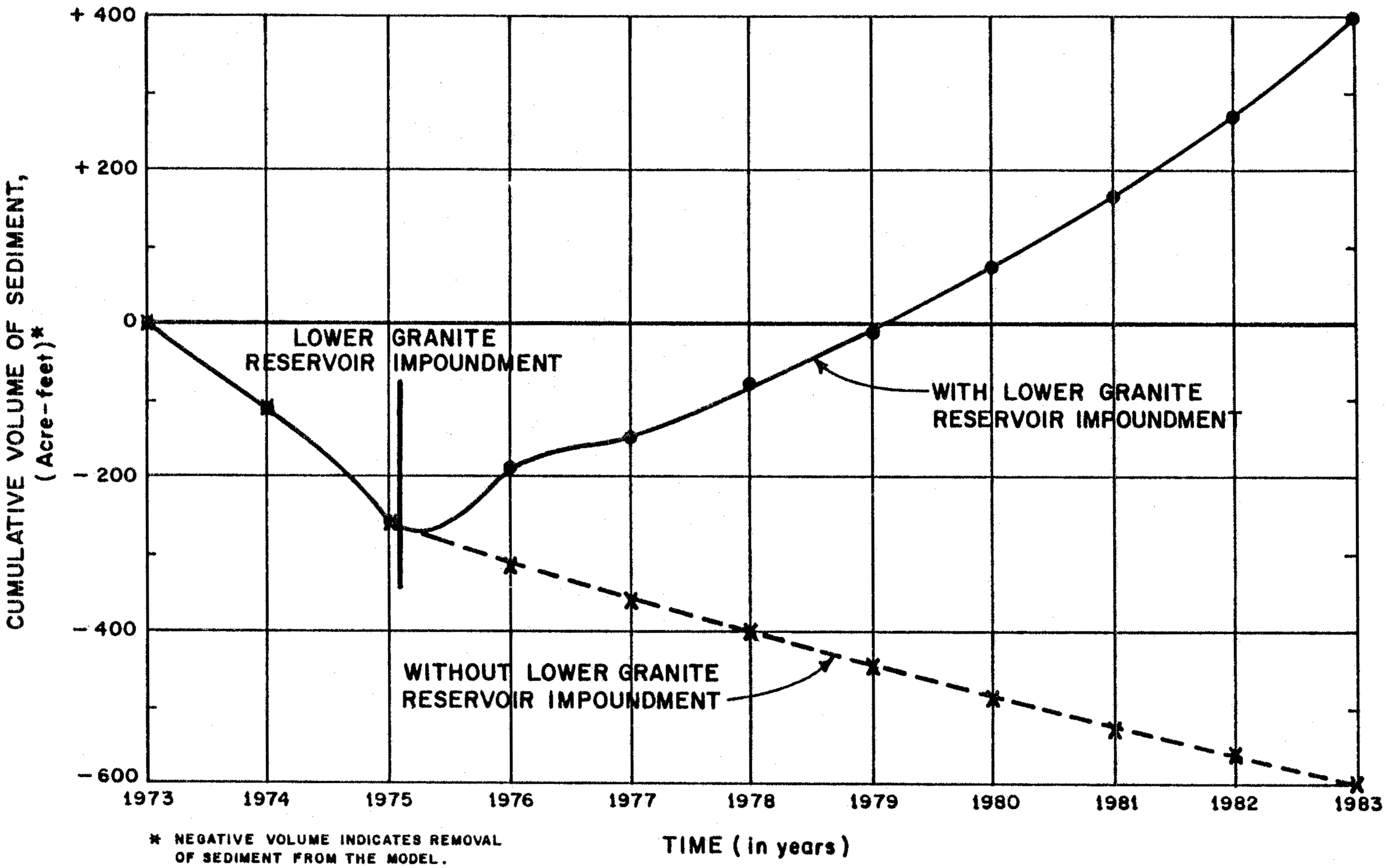


FIGURE 12

CALCULATED VOLUME OF SEDIMENTATION

WASHINGTON POWER DAM REMOVED

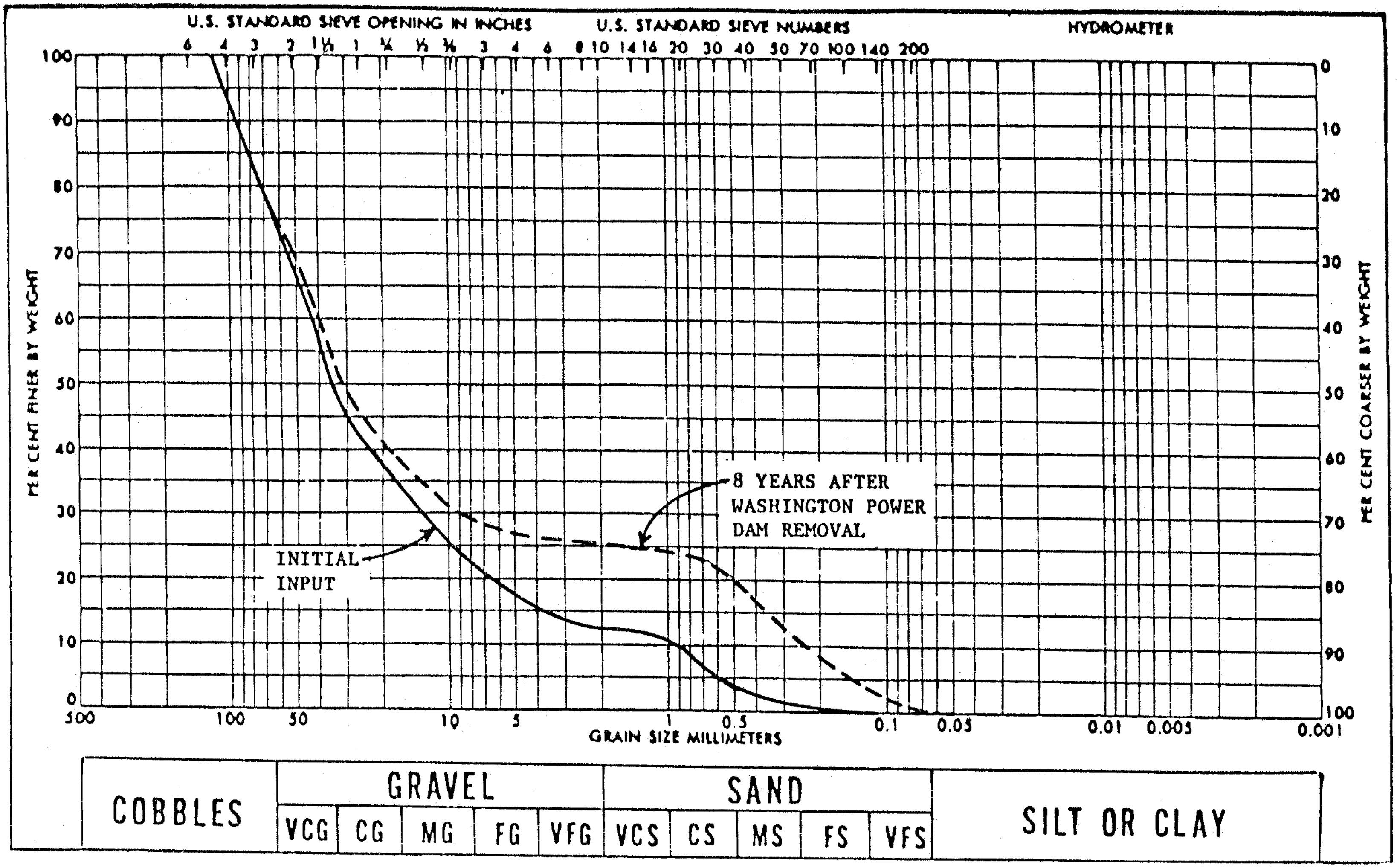


FIGURE 13
PARTICLE SIZE DISTRIBUTION OF BED MATERIAL
RIVER MILE .67, CLEARWATER RIVER, IDAHO

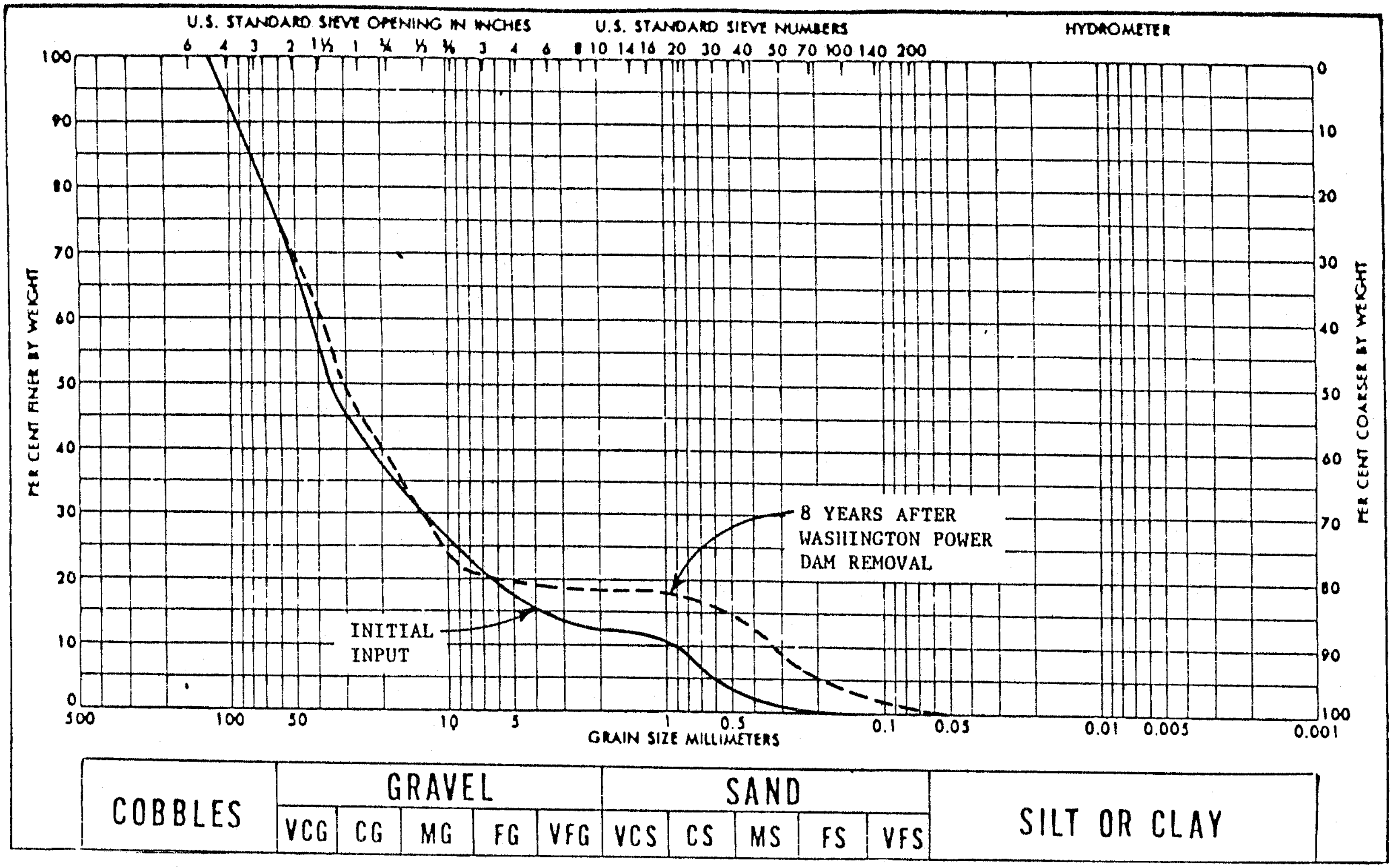


FIGURE 14
PARTICLE SIZE DISTRIBUTION OF BED MATERIAL
RIVER MILE 4.61, CLEARWATER RIVER, IDAHO

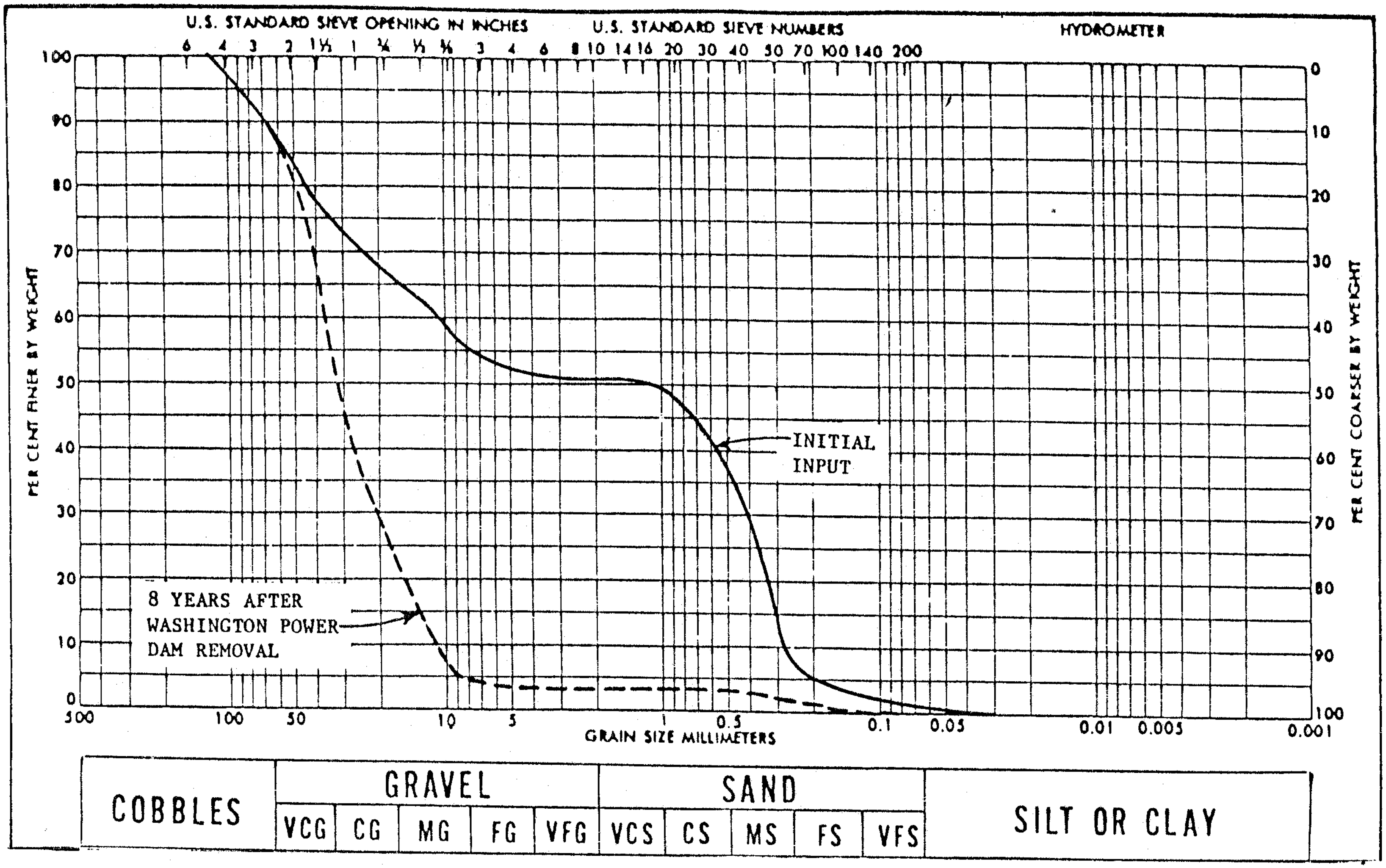


FIGURE 15
PARTICLE SIZE DISTRIBUTION OF BED MATERIAL
RIVER MILE 4.62, CLEARWATER RIVER, IDAHO

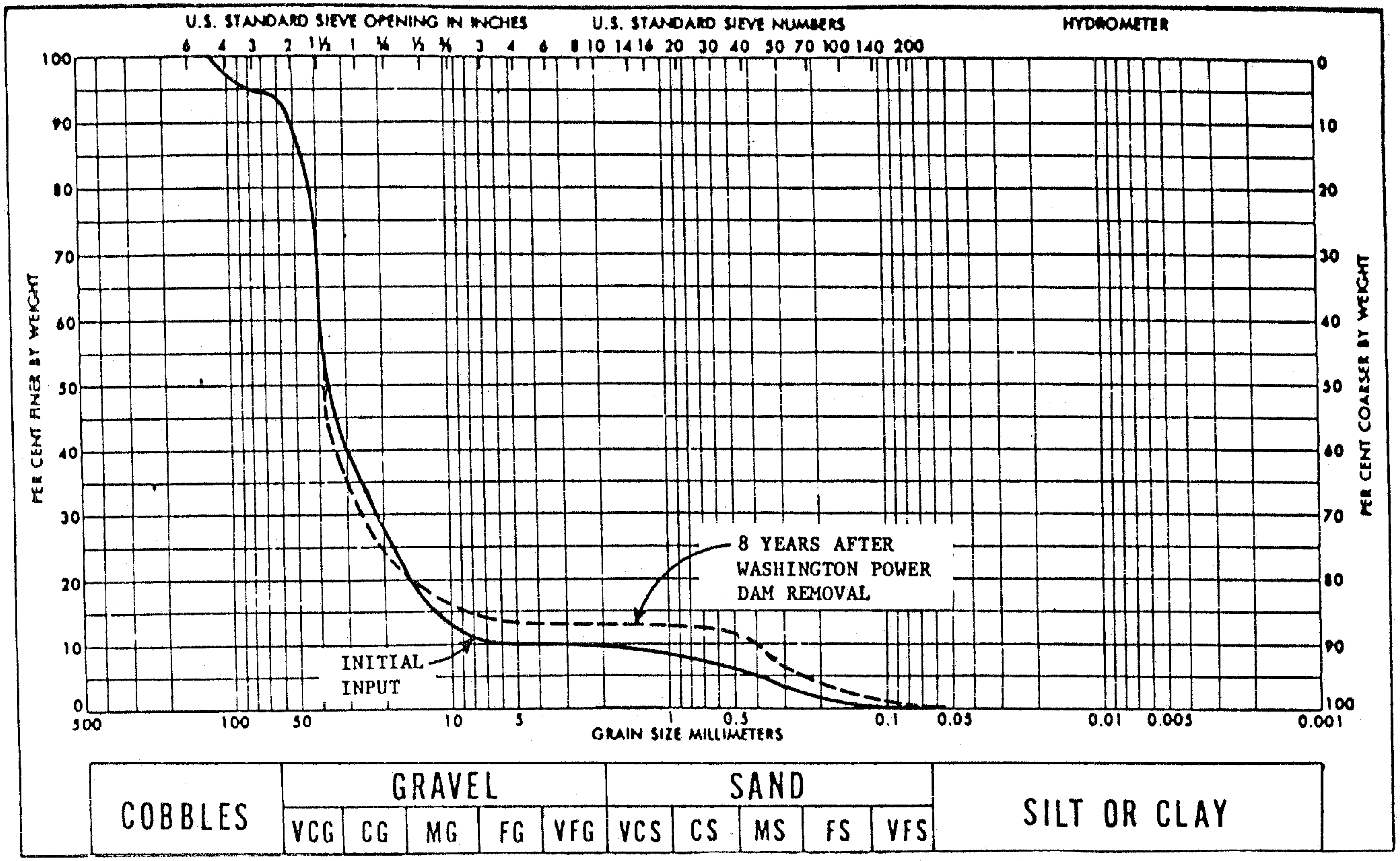
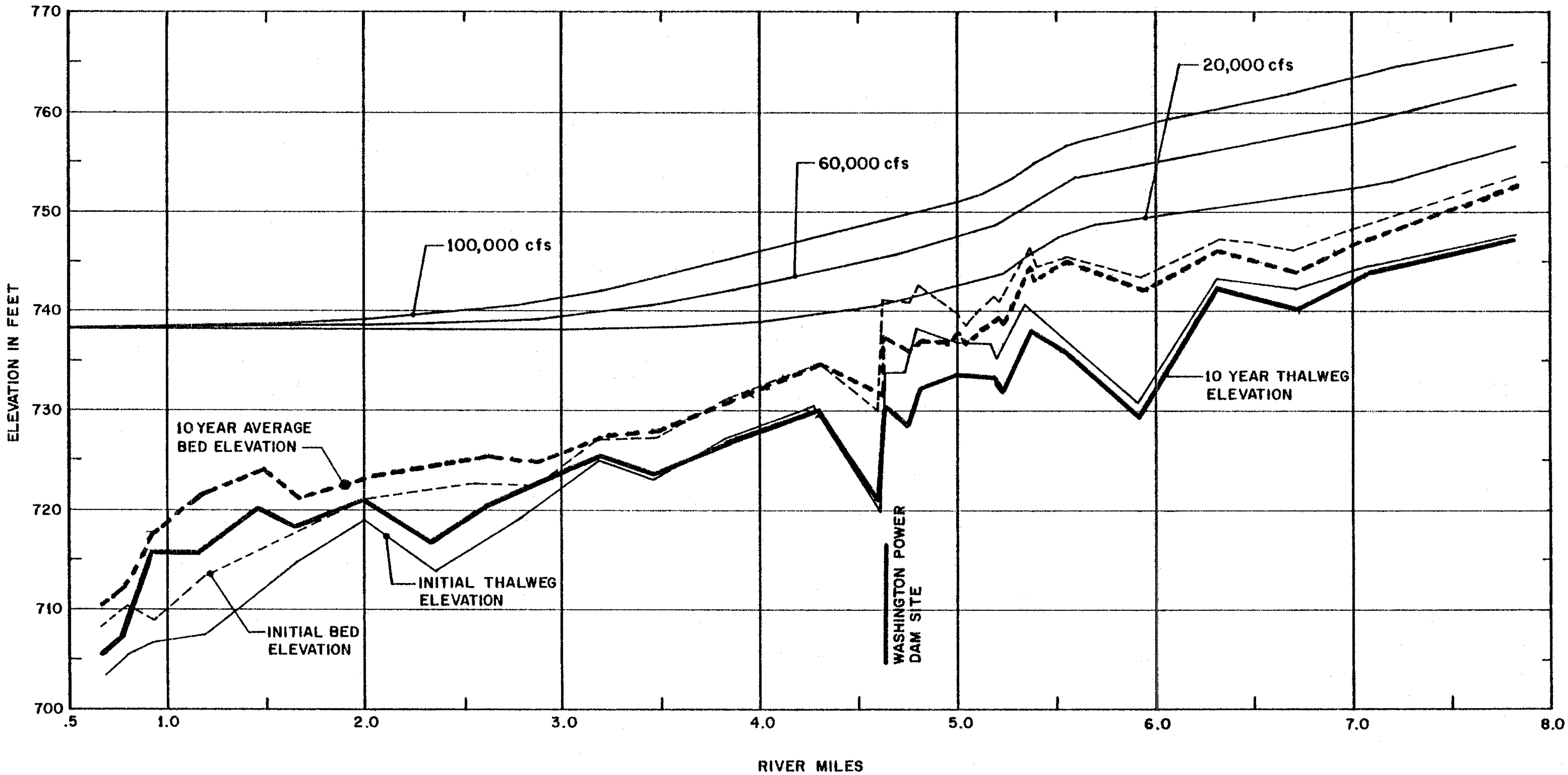


FIGURE 16
PARTICLE SIZE DISTRIBUTION OF BED MATERIAL
RIVER MILE 6.32, CLEARWATER RIVER, IDAHO

Figure 17. Predicted Bed and Water Surface Elevations

10 YEARS AFTER DAM REMOVAL

CLEARWATER RIVER, IDAHO



immediately downstream of the dam site. The influence of the Lower Granite Reservoir impoundment can be seen by the higher elevation from River Mile .67 to 2.0.

VI. Sensitivity Tests

Several sensitivity tests were made to determine the effects of input changes on scour and deposition rates and eventual bed elevations. Changes were made in each of the following: Manning's "n", bed grain size distributions, cross-section distance.

Manning's "n" was changed from .03 to .024 which resulted in only a small change in the scour and deposition rates. Resulting bed elevation change was insignificant.

The bed particle distribution upstream of the Washington Power Dam site was made finer by inputting a bed particle distribution having a D50 of .1 millimeter. This resulted, as expected, in a slight increase in the scour rate. The bed elevations ten years after the dam removal were about 20% lower than with the original bed particle distribution. The timing of the computed bed elevations in Figure 6 could have approximated the measured elevations if the bed particle distributions were made finer. However, the distributions required to do this were significantly different from any of the observed distributions.

Additional cross-sections were inserted in the model with same geometry as the immediate (measured) downstream cross-section. These sections were inserted such that the model had a geometry section every 100 feet along the river axis. This resulted in no appreciable change in scour or deposition.

VII. Conclusions

The comparison of measured and computed final bed elevations, with the dam removed, was very satisfactory. Overall long range trends for each operating condition was as expected. The calculated rate of scour was accurate at the WWPD site (River Mile 4.62) but lagged by approximately ten months at other upstream sections. This difference can be attributed to localized scour and "layering" of the bed particle distribution. Neither can be modeled by HEC-6.

Some of the variations in the rate of scour and deposition can be attributed to the limitations of a one-dimensional model. Dam removal is a multidimensional phenomenon and would best be modeled using a two or three dimensional model. These types of models are limited by the amount and type of data available, computer time/cost, and input requirements. If only the long range average bed elevation changes are desired, a one-dimensional model would be sufficient. If scour and deposition rates are of concern, a one-dimensional model may not fully simulate the physical occurrence and a two- or three-dimensional model may be needed. To the author's knowledge, dam removal has not been modeled using a two- or three-dimensional model. Because of this, going to a multidimensional model does not guarantee a significant increase in accuracy.

Possible sources of errors were previously mentioned. If these errors were minimized by more accurate data and transport relationships, the one-dimensional model may be sufficiently accurate for the objectives of a sediment study. Many of the errors mentioned are also applicable to the two- and three-dimensional models; therefore, any errors from these sources would also occur in these models. HEC-6 can be used confidently on dam removal studies if:

a. Bed particle size distributions are available upstream and downstream of the dam.

b. Only long term scour and deposition rates are of concern.

c. <u>Average</u> bed elevation changes are desired.

d. No unsteady flow phenomena occurs.

e. Cohesive sediment is insignificant.

VIII. Recommendations

The results of the usage of a one-dimensional model for predicting the effects of dam removal were very encouraging. Further study should be made with a one-dimensional model with the use of measured bed particle size distributions at each cross-section. Another case study should be made with bed measurements upstream and downstream of the dam site made before and after dam removal. This would help to determine the applicability of a one-dimensional model and the expected errors due to the limitations of such a model. The results should then be compared with the results of a two- or three-dimensional model to determine if accuracy is increased enough to warrant the use of a multidimensional model and its associated costs and input requirements.

Sensitivity tests have indicated that bed elevations were very sensitive to bed particle size distributions. It is recommended that this type of measurement be made at each cross-section in subsequent studies.

It is recommended that when dam removal studies are made using a one-dimensional model, calculated scour rates be closely examined and interpreted with consideration of the effects of secondary currents, localized scour, and "layered" bed particle size distribution.

APPENDIX I
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