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13. ABSTRACT *(Maximum 200 words)*

This is last volume of the 12 volume report prepared by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers as a contribution to the International Hydrological Decade.

This volume addresses the topics of river morphology, data collection and analysis, reservoir sedimentation, and aggradation and degradation in free flowing streams. The emphasis of the volume is on practical approaches and techniques for analyzing sediment problems. Application of digital computer simulation for calculating the volume and location of sediment deposits in reservoirs, and for predicting aggradation or degradation trends downstream from dams as well as in free flowing streams, is discussed.

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FOREWORD

This volume is part of the 12-volume report entitled "Hydrologic Engineering Methods for Water Resources Development," prepared by The Hydrologic Engineering Center as part of the U.S. Army Corps of Engineers' participation in the International Hydrological Decade. Volume 12 addresses the topics of river morphology, data collection and analysis, reservoir sedimentation, and aggradation and degradation in free flowing streams. The emphasis of the volume is on practical approaches and techniques for analyzing sediment problems. Although many of the methods and procedures described herein have been used successfully in Corps of Engineers' studies, the volume should not be construed to represent the official policy or criteria of the Corps.

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Chapter 1

Introduction

CHAPTER 1. INTRODUCTION

Section 1.01. Objective

The title of this volume, "Sediment Transport," was chosen to focus attention on the movement of sediment material in flowing water. This involves processes of scour, transport and deposition of inorganic material both in free flowing streams and in reservoirs. While some sediment transport formulas are included, they do not form a major part of this volume.

The purposes of this volume are: (1) to identify potential problem areas; (2) to identify which of these can be analyzed with existing mathematical techniques and which must be studied using either movable bed hydraulic models or the prototype; (3) to identify the type and amount of data required for analyzing sediment problems, and (4) to give sufficient guidance so that competent engineers may develop satisfactory solutions to the sediment problems.

Section 1.02. Scope

Basic to all sediment studies is sediment yield from the watershed. The paper entitled "Corps of Engineers Methods for Predicting Sediment Yield" by Mr. Robert H. Livesey is included as Appendix III to provide information in this problem area. Also, the calculation of land surface erosion is presented, but only briefly described.

The basic concept of calculating water surface profiles in natural rivers is extended beyond Volume 6, "Water Surface Profiles," to include the river bed as a movable boundary. The analysis of sediment problems by digital computer simulation is useful for calculating the volume and location of sediment deposits in reservoirs and for predicting aggradation or degradation trends downstream from dams as well as in free flowing streams. The Hydrologic Engineering Center computer program which performs the simulation analysis, "Scour and Deposition in Rivers and Reservoirs," is included in Appendix VII of this volume. This program can be used to evaluate the behavior of a stream bed during the passing of a single flood event or for a long period of hydrographic record.

Techniques are also presented in Appendix VII for calculating growth of the armor layer, destruction of the armor layer and hydraulic sorting of grain sizes.

A very useful technique for calculating the volume of sediment deposits in reservoirs is based on trap efficiency. Application of the technique does not require the electronic computer.

Since present analytical techniques do not completely define sediment problems, a good understanding of the behavior of natural and controlled streams is essential for interpreting any calculated results. A brief discussion of river morphology is included to aid in this regard.

In summary, attention is directed toward the analysis of water born sediments in defined channels. The regime concept is not treated in detail. Wind blown sediment is not included. The impact of sediment on water quality - that is, quality constituents that might adhere to and be transported with sediment particles - is discussed in Volume 11. The growth and decay of bed forms and two and three dimensional hydrodynamic models are not included in this volume. Coastal processes are not addressed.

In general, the formulas which are included have been incorporated into analytical methods and have been applied to a wide range of problems throughout the United States. Their performance has been satisfactory when the methods were applied with the appropriate understanding of river morphology and the limitations of present theory. Even the most advanced methods require a great deal of engineering judgment to insure a correct interpretation of results.

Not all analytical techniques in use in the Corps of Engineers are included in this volume. This does not imply that techniques which are included are the "best" ones, nor does it imply that techniques which were not included are inferior. It simply reflects the fact that there are a large number of methods in use, there is only a limited amount of space available to present them, and the methods presented have been found to be generally satisfactory.

Section 1.03. A Summary Statement

Nature maintains a very delicate balance between the water flowing in a natural river, the sediment load moving with the water and the stream's boundary. Any activity of man which changes any one of the following parameters:

- water yield from the watershed
- sediment yield from the watershed

- water discharge duration curve
- depth, velocity, slope or width of the flow
- size of sediment particles,

or which tends to fix the location of a river channel on its floodplain and thus constrain the natural tendency to meander, upsets the natural balance and initiates the formation of a new one. The objective of most sediment studies is to evaluate the impact on the flow system from changing any of these parameters.

A classical example is the deposition which results when a reservoir is impounded. In terms of the aforementioned parameters, the reservoir causes a change in the hydraulics of flow by forcing the energy gradient to approach zero. This results in a loss of transport capacity with the resulting deposition. The smaller the particles, the farther they will move into the reservoir before depositing. At times fine sediment in the inflow to a deep reservoir does not fully mix. The resultant stratification is conducive to the formation of density currents, and some material may pass through the reservoir.

The obvious consequence of sediment deposits is a depletion in reservoir storage capacity. This is represented schematically in fig. 1.01,

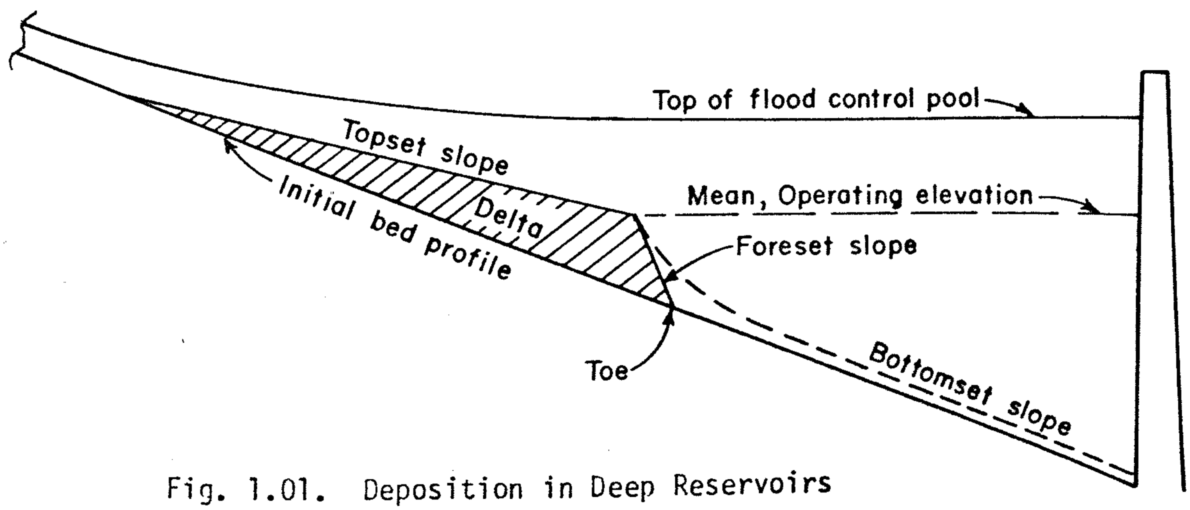

Fig. 1.01. Deposition in Deep Reservoirs

Deposition in Deep Reservoirs. The volume of sediment material in the delta is a function of the project life among other things, and that delta will continue to develop, with time, beyond the project life. Eventually a new channel and floodplain will exist in the delta area.

Identifying this deposition pattern with deep reservoirs raises the question "what is the significance of deep as opposed to shallow reservoirs on the sediment deposition pattern?". Referring to fig. 1.01, consider what would happen if the dam were moved in the direction of the delta deposits and the operating rule for the reservoir did not change. The configuration of the delta would not change until the dam actually reached the toe of the delta itself. At some point, the reservoir could become classified as a shallow reservoir. Therefore, the delta formation shown in fig. 1.01 could be as applicable to a shallow reservoir as it is to a deep reservoir.

The mean operating pool elevation is a major factor in establishing the configuration of the reservoir delta. Therefore, to shift the dam to a location along the present topset slope would completely change the mean operating pool elevation and thereby the shape of the reservoir delta itself.

A number of associated problems can be listed:

- Deposits forming the delta may raise the water surface elevation during flood flows in such a manner to require special consideration for land acquisition. In deep reservoirs, this is usually not a problem within the reservoir area because project purposes dictate land acquisition. However, the delta tends to develop in the upstream direction and cause problems upstream from the reservoir area proper. In shallow reservoirs, on the other hand, the increase in water surface elevation is a problem even within the reservoir area. That is, floods of equal frequency may have higher water surface elevations after a project begins to develop a delta deposit than was experienced before the project was constructed. Land acquisition studies must evaluate such a possibility.

- Aggradation problems are often more severe on tributaries than on the main stem and these locations are often desirable for developing recreational facilities. Analysis is complicated by the lack of basic data on the tributaries - usually less than on the main stem itself. However, the useful life of recreation sites should be evaluated by predicting the rate of delta growth.

- Because of the high moisture level, reservoir deltas often attract phreatophytes which in many areas contribute to water use problems due to their high transpiration rate.

- Reservoir delta deposits are often aesthetically undesirable.

- Particularly in shallow impoundments, the results of reservoir sediment deposits may increase the water surface elevation sufficiently to impact on the ground water table.

- In existing reservoirs, the United States Fish and Wildlife Service is utilizing delta and backswamp areas in the prop gation of wildlife. Since the characteristics of this delta area are so closely controlled by the operating policy of the reservoir, any reallocation of storage would need to consider the impact on present delta and backswamp areas. This represents a type of problem that may be more important in the future if changing priorities among project purposes demand reallocation of storage in reservoirs.

- Looking downstream from the dam, degradation is usually predominant. It is necessary to evaluate the impact of degradation on a tailwater rating curve at the structure. Problems downstream from the dam are sufficiently complex that they are presented in some detail in the following paragraphs.

Downstream from the dam the hydraulics of flow (velocity, slope, depth and width) remain unchanged from conditions in the natural state. However, the reservoir has acted as a sink and trapped sediment material, especially the bed material load. This reduction in sediment yield from the watershed causes the energy in the flow to be out of balance with the boundary material for the downstream channel. Because of the amount of available energy, the water attempts to re-establish the former equilibrium sediment load from material in the stream bed, and this results in a degradation trend. Initially, the degradation trend may persist for only a short distance downstream from the dam since the equilibrium sediment load is soon re-established by removing material from the stream bed.

As time passes, the degradation trend will migrate downstream; however, several factors are working together to establish a new equilibrium condition in this movable-boundary flow system, in addition to this re-entrainment of sediment material. On one hand, the potential energy gradient is decreasing because the degradation migrates from upstream to downstream in direction. On the other hand, the bed material is becoming coarser and, consequently, more resistant to being moved. This tendency in the main channel has the opposite effect on tributaries. Their potential energy gradient is increasing which results in an increase in transport capacity. This will usually increase sediment passing into the main stem which tends to stabilize the main channel resulting in less degradation than one might anticipate. Finally, a new equilibrium condition will be established between the flowing water-sediment mixture and the boundary.

The extent of degradation is complicated by the fact that the reservoir also changes the water discharge duration curve. This will impact for great distances downstream from the project because the existing river channel reflects the historical phasing between flood flows on the main stem and those from tributaries. That phasing will be changed by the operation of the reservoir. Also, the flow will probably encourage vegetation to grow at lower elevations in the channel. The result is a condition conducive to deposition in the vegetation. Actually, numerous examples of aggradation trends may be cited for river channels downstream from dams. The primary problem which results is inadequate channel capacity resulting in inadequate levee height. Consideration should be given to performing detailed simulation studies to determine future channel capacities and to identify problem areas of excessive aggradation or degradation. Particular attention should focus on all major tributaries.

An equally classical problem results when levees are constructed for flood control purposes because the position of the river channel must be stabilized to insure that it remains between the levees. River flow entering the backwater curve to its receiving water, whether that receiving water is the ocean or a lake, loses transport capacity and deposition of the coarser material results in an aggradation trend in the river channel. Consequently, the levee height becomes inadequate to contain the design discharge. The rate at which this process takes place, although slow, is not measured in terms of geological time. Depending on the sediment yield in the basin, significant changes can occur during the 50-100 year life of an engineering project.

A third classical sediment problem is that of maintaining depth of navigation. This problem requires a detailed understanding about the behavior of the movable boundary flow system since it requires fixing the location of a navigation channel within the main channel itself. However, the techniques for performing these studies can proceed under the assumption that the location of the river channel is fixed. Hydraulic model studies can then be employed to design the navigation channel.

The aforementioned sediment problems are all associated with man's activities. However, left to its natural state, a river will continually change its position on the flood plain, its meander pattern and the cross section shape as it responds to the flowing water and sediment mixture.

A good understanding of this process is required before one can adequately interpret the impact of man's activities, for man's activities not only change the rate at which a river channel responds to the flowing water-sediment mixture, but also change the location of sediment sources and sinks from those naturally existing.

The level of detail required for the analysis of any sediment problem depends on the objective of the study. Considering a dam site as an important natural resource, it is essential to provide enough volume in the reservoir to contain anticipated deposits during the project life. If the objective of a sediment study is just to know the volume of deposits for use in screening studies, then trap efficiency techniques provide a satisfactory solution. The important information that must be available, then, is the water and sediment yields from the watershed and the capacity of the reservoir. However, if the sediment study must also address the land acquisition for the reservoir, then knowing only the volume of deposits is not sufficient. The location of deposits must also be known, and the study must take into account sediment movement. The approach presented in this volume is to analyze such a problem with digital simulation of flow in a mobile boundary channel. Sorting of grain sizes must be considered since the coarser material will deposit first, and armoring must be accommodated since scour is involved. This simulation technique actually becomes a movable-bed analytical model. It is useful to predict erosion or scour trends downstream from a dam, general aggradation or degradation trends in river channels, and the ability of a stream to transport the bed material load. Such a technique does not have to define the location of a navigation channel in order to be useful; in fact, there is no analytical technique that is suitable for calculating where, within the river channel, a navigation channel will be stable.

The simulation technique is structured entirely for computer solution. The amount of data that has to be analyzed includes all the basic geometric and hydraulic data required for water surface profile calculations plus data describing the size and gradation of sediment material in the stream bed and banks, the size and amount of inflowing sediment material and the water discharge hydrograph. In addition, long periods of hydrograph record are generally utilized since sediment studies attempt to predict trends throughout the project life. The number of calculations is extremely large. For example, predicting deposition in a shallow reservoir having a 50 year design life can require a calculation of some 600 to 1000 water surface profiles plus the routing of sediment material through the reservoir for the water discharge associated with each one of the profiles.

Data acquisition programs have evolved to satisfy needs. With only few exceptions, data, when collected at all, are collected for estimating annual sediment yield where suspended sediment is the primary contributor. This is definitely one problem area. However, there are other problem areas. For example, data should also be collected in a systematic program to study channel morphology. This would require measuring the bed load to determine the amount moving, the gradation of the load and the sorting that goes on among the various grain sizes. The link to understanding the feedback mechanism in the water-bed interaction probably lies in understanding bed load and the lateral movement of river channels. Attempts to simulate the behavior of a movable bed analytically will continue to require considerable qualitative judgment until this link is understood. Even present techniques require data on gradation of material in the stream bed and in the sediment load. Sampling the bed load will be required to obtain this type of data. These data should be collected by personnel intimately familiar with both sediment movement and analytical techniques until a better understanding of the nature of the problem is developed. All data acquisition programs should utilize "standard" equipment and techniques.

Section 1.04. The Interpretation of Analytical Results

The analysis of sediment problems is not a simple extension of fixed bed hydraulic theory so that it becomes movable boundary hydraulic theory. Sediment problems vary in degree of difficulty from the relatively simple determination of the volume of deposits in a deep reservoir to aggradation and degradation studies in free flowing streams and rivers. Whereas fixed bed hydraulic theory is well developed, the analysis of movable bed problems is complicated by the fact that the body of theory available for performing analyses is incomplete. The interactions between flowing water and a movable boundary are not well understood, although the water and boundary are components of a closed loop system. At best, the available theory addresses only bits and pieces of that system.

It is often uncertain as to how to apply the available theory to obtain satisfactory results. Guidelines are conspicuously absent. Case after case is presented to demonstrate the inconsistency of results that one can obtain for the same problem analysis by using different methods -- all of which are recognized in the literature as acceptable methods.

Nevertheless, the engineer is constantly faced with the analysis of sediment problems. Perhaps the following suggestions will be helpful. It is good practice to follow a three step procedure: (1) calibrate the analytical technique, (2) verify the procedure by performing a "base test" for comparison with observed conditions, and (3) interpret the impact of any changes by reference to that base test rather than by absolute magnitudes. Due to the difficulty of obtaining consistent **prototype data** and the uncertainties involved, good engineering judgment is required in determining the source of discrepancies between calculated results and measured values. This is especially important in simulation of the movable boundary, but the same approach is valuable even in trap efficiency studies.

Another useful technique is to select several formulas for use in each phase of the study and compare results. Sensitivity studies will often help to identify the most appropriate formula for the problem at hand.

Chapter 2

Terminology and Properties of Sediment

CHAPTER 2. TERMINOLOGY AND PROPERTIES OF SEDIMENT

Section 2.01. Introduction

The terminology in sedimentation work is somewhat unique. Some terms appear to be general in nature, such as bed load, or bed material load, and yet they have been defined rather precisely. Other terms appear to be very well defined and yet are somewhat general in nature; particle size classification is an example. The fact that particle size is an important variable is obvious, and yet there are several different standards for classifying sediment material according to particle size. Many of these use the words "sand, silt, and clay," but particle size diameter for material called sand is different from one classification standard to another. This is also true for silt and clay.

In general, the physical properties of sediment are important to both quantity and quality studies. Consistency within the United States in determining these properties required the establishment of a special interagency sedimentation project. The project is under the auspices of the Committee on Sedimentation of the Water Resources Council, and is engaged in the development and standardization of sampling equipment, sampling techniques, and methods for analysis of samples.

It is useful to organize sediment properties in three groups:

Properties of sediment particles

- Size and shape
- Classification scale

- Shape factor
- Specific gravity
- Fall velocity
- Gradation of sample

Properties of sediment deposits

- Initial unit dry weight
- Consolidation with time
- Unit dry weight of mixtures

Properties of the water-sediment mixture

- Concentration
- Sediment load
- Sediment yield

Section 2.02. Properties of Sediment Particles

a. Particle Size and Shape

Particle size refers to the "diameter" of a particle. There are several ways to measure diameter but the most common are by sieving or by measuring the velocity with which the particle falls through quiescent water at a standard temperature. The latter procedure produces an equivalent spherical diameter -- that is, the diameter of a sphere of the same specific weight that would have the fall velocity that was observed. Sieving is the most common technique for measuring the sizes of sand and gravel particles.

Particle size is probably the most significant physical property. It affects the resistance to erosion, the transportability of sediment, and subsequent behavior in the consolidation of sediment deposits. For example, very small particle sizes, up to about 0.004 mm, exhibit a strong influence from electrical charges on their surface. They are said to be cohesive. Material having this range of grain sizes is called clay, and when sediment problems involve clay a special body of analytical theory is employed to account for the impact of electro-chemical characteristics of the water on those of the sediment material. Particle sizes between 0.004 mm and about 0.0625 mm are in a transition range. They are too large to feel much influence from the electromotive forces and too small to mobilize much inertia against being moved by flowing water. This range is classified as silt. When particle size exceeds 0.0625 mm electromotive forces are insignificant. These particles are noncohesive and are classified as sand, gravel, cobbles, etc. Knowledge of mechanical forces is sufficient to analyze the behavior of noncohesive sediment. Consequently, transport theory for noncohesive material is more advanced than that for cohesive material.

b. Classification by Grain Size

The grain size classification scale established by the American Geophysical Union is the standard used to relate grain size to size class throughout this volume. The median diameter of a size class is that for which 50% of the material in that class is finer and 50% coarser.

Table 2.01. Grain Size Classification

Size Class	Grain Diameter (mm)	Median Diameter (mm)
Clay	less than .004	-
Very fine silt	.004 to .008	.0057
Fine silt	.008 to .016	.0113
Medium silt	.016 to .032	.0226

Table 2.01. Grain Size Classification (cont.)

Size Class	Grain Diameter (mm)			Median Diameter (mm)
Coarse silt	.032	to	.0625	.0447
Very fine sand	.0625	to	.125	.0884
Fine sand	.125	to	.250	.1768
Medium sand	.250	to	.50	.3536
Coarse sand	.50	to	1.00	.7071
Very coarse sand	1.00	to	2.00	1.4142
Very fine gravel	2.00	to	4.00	2.8284
Fine gravel	4.00	to	8.00	5.6569
Medium gravel	8.00	to	16.00	11.3137
Coarse gravel	16.00	to	32.00	22.6274
Very coarse gravel	32.00	to	64.00	45.2548

c. Particle Shape Factor

Sediment particles are seldom spherical. Clays are very elongated and, to a lesser extent, so are the larger particles. The following expression has been proposed as a measure of particle shape by using dimensions normal to each other:

$$\text{grain shape factor} = c/\sqrt{a \cdot b} \qquad (2\text{-}01)$$

where a and b refer to the two smallest dimensions and c to the largest. The primary influence of grain shape in the noncohesive particles is on fall velocity. Whereas this is recognized in concept, it has not been formally incorporated into a satisfactory analytical expression.

d. Specific Gravity

The specific gravity of sediment particles is another property that impacts on the fall velocity, and consequently, the hydrodynamic properties of the sediment particle. The value commonly used for quartz sand is 2.65.

e. Fall Velocity

A property of sediment which is very important in transport calculations is the velocity at which a single particle would fall through quiescent water. This velocity is related to the grain size, specific gravity, particle shape and temperature of the water. Usually, the fall velocity is calculated from the sediment particle diameter as though that particle were a sphere. Although it seems, intuitively, that the fall velocity should be corrected for the shape of the particle, presently there is not enough information to make such a correction. Therefore the fall velocity is calculated assuming the particle is a sphere. The following table 2.02 shows fall velocities for quartz sand (which has a specific gravity of 2.65) as a function of temperature and particle size.

Fall velocities for other sizes or for other specific gravities may be calculated with the following equation:

$$w^2 = \frac{4}{3} \cdot \frac{g \cdot d}{C_D} \left(\frac{\gamma_s - \gamma}{\gamma} \right) \tag{2-02}$$

C_D = drag coefficient

d = particle diameter

g = acceleration of gravity

w = fall velocity

γ = specific weight of fluid

γ_s = specific weight of the sphere

Table 2.02. Sand Grain Settling Velocity Versus Temperature, SP.G. 2.65, Shape Factor 0.9 [1]

TEMP °F	SETTLING VELOCITY IN FT/SEC							
	VFS	FS	MS	CS	VCS	VFG	FG	MG
35	.013	.045	.130	.305	.590	1.00	1.41	1.95
36	.013	.045	.131	.307	.592	1.00	1.41	1.95
37	.013	.046	.132	.310	.594	1.00	1.41	1.95
38	.014	.047	.133	.312	.596	1.00	1.41	1.95
39	.014	.047	.135	.314	.598	1.00	1.41	1.95
40	.014	.048	.136	.316	.600	1.00	1.41	1.95
41	.015	.049	.137	.318	.602	1.00	1.41	1.95
42	.015	.050	.138	.320	.604	1.00	1.41	1.95
43	.015	.051	.140	.321	.606	1.00	1.41	1.95
44	.016	.051	.141	.322	.608	1.00	1.41	1.95
45	.016	.052	.142	.323	.609	1.00	1.41	1.95
46	.016	.053	.143	.325	.610	1.00	1.41	1.95
47	.016	.053	.144	.326	.612	1.00	1.41	1.95
48	.017	.054	.145	.328	.614	1.00	1.41	1.95
49	.017	.055	.146	.330	.616	1.00	1.41	1.95
50	.017	.055	.147	.331	.618	1.00	1.41	1.95
51	.018	.056	.148	.333	.620	1.00	1.41	1.95
52	.018	.057	.150	.334	.621	1.00	1.41	1.95
53	.018	.057	.151	.336	.623	1.00	1.41	1.95
54	.018	.058	.152	.338	.624	1.00	1.41	1.95
55	.018	.059	.153	.340	.626	1.00	1.41	1.95
56	.019	.059	.154	.341	.627	1.00	1.41	1.95
57	.019	.060	.155	.343	.629	1.00	1.41	1.95
58	.019	.061	.156	.344	.630	1.00	1.41	1.95
59	.019	.061	.157	.346	.632	1.00	1.41	1.95
60	.020	.062	.158	.347	.633	1.00	1.41	1.95
61	.020	.063	.160	.349	.635	1.00	1.41	1.95
62	.020	.063	.161	.350	.636	1.00	1.41	1.95
63	.020	.064	.162	.351	.638	1.00	1.41	1.95
64	.021	.065	.163	.353	.639	1.00	1.41	1.95

TEMP °F	SETTLING VELOCITY IN FT/SEC							
	VFS	FS	MS	CS	VCS	VFG	FG	MG
65	.021	.065	.165	.354	.640	1.00	1.41	1.95
66	.021	.066	.166	.356	.641	1.00	1.41	1.95
67	.021	.067	.167	.357	.643	1.00	1.41	1.95
68	.022	.067	.168	.359	.644	1.00	1.41	1.95
69	.022	.068	.170	.360	.646	1.00	1.41	1.95
70	.022	.069	.171	.361	.647	1.00	1.41	1.95
71	.022	.070	.172	.362	.649	1.00	1.41	1.95
72	.023	.071	.173	.363	.650	1.00	1.41	1.95
73	.023	.071	.175	.364	.652	1.00	1.41	1.95
74	.023	.072	.176	.365	.653	1.00	1.41	1.95
75	.024	.072	.177	.366	.655	1.00	1.41	1.95
76	.024	.073	.178	.367	.656	1.00	1.41	1.95
77	.024	.073	.180	.368	.657	1.00	1.41	1.95
78	.024	.074	.181	.370	.658	1.00	1.41	1.95
79	.025	.074	.182	.371	.659	1.00	1.41	1.95
80	.025	.075	.183	.373	.660	1.00	1.41	1.95
81	.025	.075	.184	.375	.661	1.00	1.41	1.95
82	.025	.076	.185	.376	.662	1.00	1.41	1.95
83	.025	.077	.186	.378	.663	1.00	1.41	1.95
84	.026	.077	.187	.380	.664	1.00	1.41	1.95
85	.026	.078	.188	.381	.665	1.00	1.41	1.95
86	.026	.078	.190	.383	.666	1.00	1.41	1.95
87	.026	.079	.192	.385	.667	1.00	1.41	1.95
88	.027	.079	.194	.386	.668	1.00	1.41	1.95
89	.027	.080	.195	.388	.669	1.00	1.41	1.95
90	.027	.080	.196	.390	.670	1.00	1.41	1.95
91	.028	.081	.197	.391	.671	1.00	1.41	1.95
92	.028	.081	.198	.392	.672	1.00	1.41	1.95
93	.028	.082	.199	.393	.673	1.00	1.41	1.95
94	.028	.082	.200	.394	.674	1.00	1.41	1.95

[1] From reference 7.

For Reynolds numbers, $\mathbb{R}$, less than 0.1, Stokes law gives

$$C_D = 24/\mathbb{R} \tag{2-03}$$

where

$$\mathbb{R} = w \cdot d/\nu \tag{2-04}$$

ν = kinematic viscosity of fluid

$\mathbb{R}$ = Reynolds number

For Reynolds numbers greater than 0.1 there is no simple expression for the drag coefficient relationship, and the following curve is utilized with equations 2.02 and 2.04 to calculate fall velocity by successive approximations.

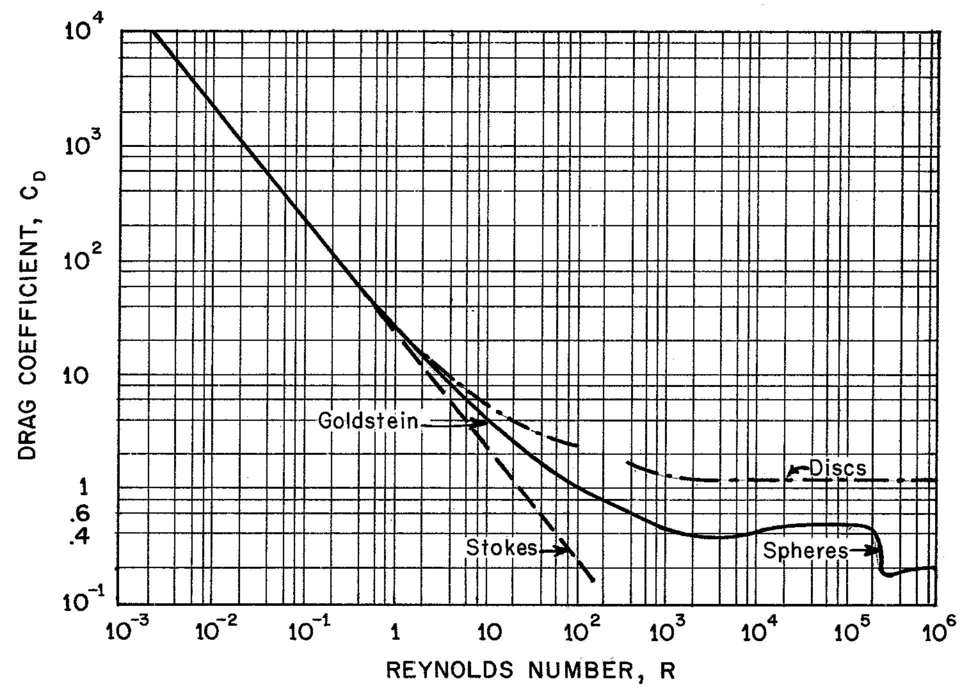

Fig. 2.01. Drag Coefficient of Spheres as a Function of Reynolds Number

f. Gradation Curve

An important property of the sediment sample is its gradation. Each sample will usually contain a range of grain sizes, and it is customary to break this range down into classes to determine the percentage by weight of the total sample contained in each class interval. The individual percentages are accumulated and the graph showing grain size vs. the accumulated percent of material that is finer than that grain size results in a gradation curve. This curve presents one set of statistics for that sample as shown in the following example (fig. 2.02). Gradation can change drastically from sample to sample. Furthermore, four different gradations are significant: the gradation of the suspended load, the gradation of the bed load, the gradation of the material comprising the bed surface and the gradation of material beneath the bed surface. These will all be significantly different, with respect to time, for the same flow event. Gradation curves are often plotted on log-normal probability paper.

Section 2.03. Properties of Sediment Deposits

a. Unit Weight of Sediment Deposits and Consolidation with Time

The weight per unit volume of sediment deposits is denoted "unit weight." The fact that it could be calculated from the unit weight of water, the specific gravity of the sediment particles and the void ratio of the sediment deposit is academic because the void ratio varies substantially. Field tests are required to determine unit weights. The unit weight of a sand deposit can be considered constant with time, but ~~clay and silt deposits consolidate~~ by over 200 percent. Deposits which are always submerged take longer to consolidate than those which are occasionally exposed to the air.

The following unit weights are often used when field data cannot be obtained.

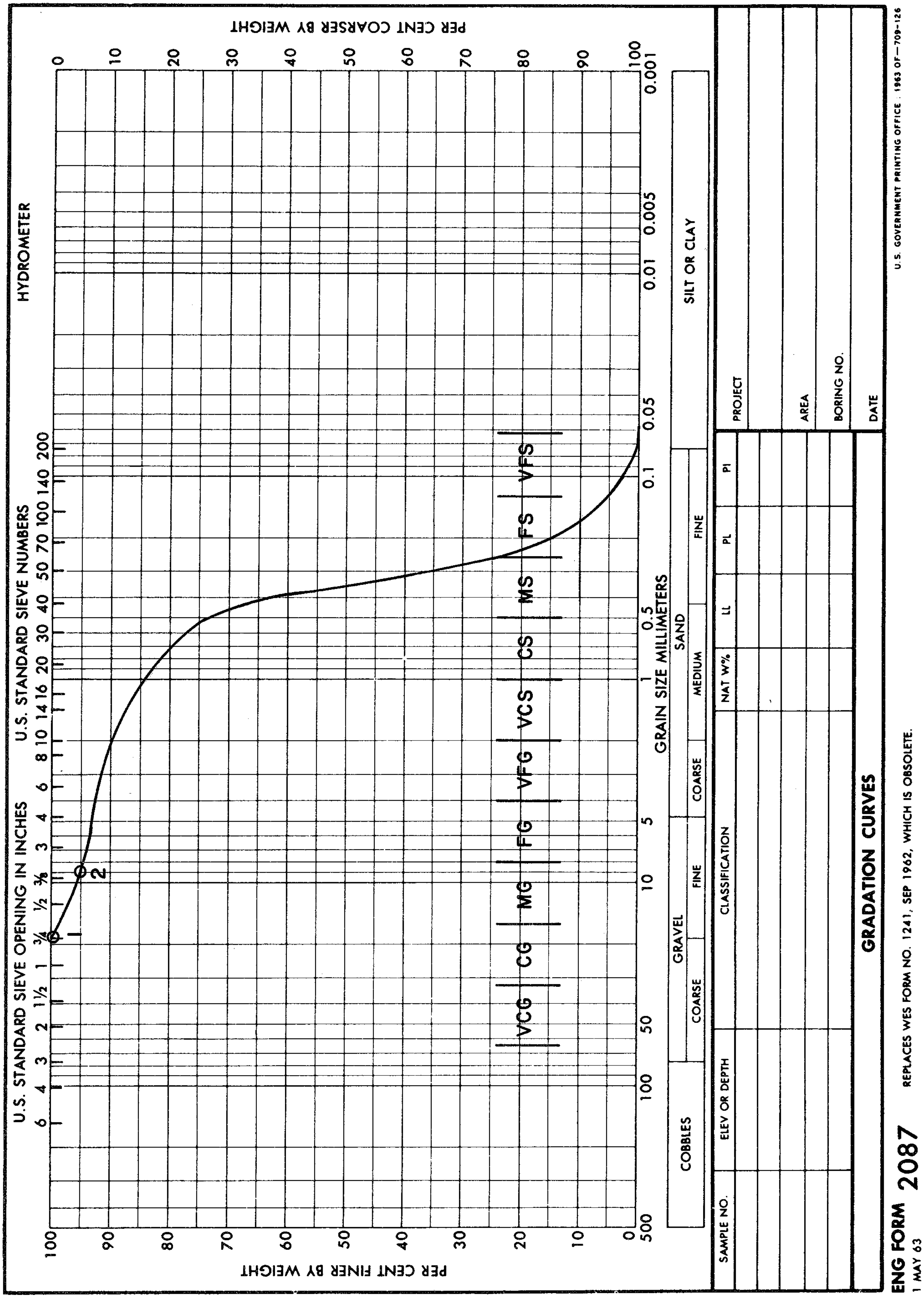

Fig. 2.02. Gradation Curve for a Bed Sample

Table 2.03. Unit Dry Weight for Sediment Deposits (1)

Material Classification	Initial Deposits lb/cu ft	Fully Compacted Deposits lb/cu ft	Consolidation Coefficient	Remarks
Sand	93	93	0	Always submerged
Silt	65	82	5.7	Always submerged
Clay	30	78	16.0	Always submerged
Silt	74	82	2.7	Moderate reservoir drawdown (2)
Clay	46	78	10.7	Moderate reservoir drawdown
Silt	79	82	1.0	Considerable reservoir drawdown (2)
Clay	60	78	6.0	Considerable reservoir drawdown

(1) Reference 1, page 829
(2) Significant because drawdown permits aeration and aeration results in density changes.

b. Unit Dry Weight of Mixtures

The following equation is utilized to calculate the unit weight of a mixture of sand, silt and clay.

$$\gamma_T = \frac{\gamma_{sand} \cdot \%_{sand} + \left[\gamma' + K' \cdot \log_{10}(T-1.0)\right] \cdot \%_{silt} + \left[\gamma'' + K'' \cdot \log_{10}(T-1)\right] \cdot \%_{clay}}{100} \tag{2-05}$$

where

γ_{sand} = unit weight of sand

$\%_{sand}$ = amount of sand in total deposit in percent

γ' = unit weight of initial silt deposits

K' = consolidation coefficient for silt

γ'' = unit weight of initial clay deposits

K'' = consolidation coefficient for clay

T = life of deposit in years

$\%_{clay}$ = amount of clay in total deposit in percent

$\%_{silt}$ = amount of silt in total deposit in percent

γ_T = composite unit weight T years after deposition occurred

c. Impact on Water Quality

As one might suspect, those sediments having electrical charges, the clay material, play the most active role in water quality analysis. There is evidence that heavy metals, pesticides, hydrocarbons, radioactive wastes and other pollutants are attracted to these sediments and consequently zones of deposition may exhibit rather high concentrations of these pollutants.

Section 2.04. Properties of the Water-Sediment Mixture

a. Concentration

The dry weight of a sediment sample in milligrams divided by the weight of the water-sediment sample in liters is the common unit for sediment concentration. An alternate unit is parts of sediment per million parts of the water-sediment mixture. The first definition is preferred.

b. Sediment Load Terms

Sediment load refers to rates of sediment movement in the stream. Quantities should be expressed as tons per day and may be calculated from sediment concentration and water discharge in tons. Six different sediment load terms are encountered in sediment literature: suspended load, bed load, wash load, bed material load, measured load and unmeasured load. These terms go together in pairs to produce the total sediment load as follows:

$$\begin{array}{cccccc} & \underline{\text{Based on mode of transport}} & & \underline{\text{Based on availability in stream bed}} & & \underline{\text{Based on method of quantifying}} \\ \text{Total load} = & \begin{bmatrix}\text{suspended load}\\ + \\ \text{bed load}\end{bmatrix} & = & \begin{bmatrix}\text{wash load}\\ + \\ \text{bed material load}\end{bmatrix} & = & \begin{bmatrix}\text{measured load}\\ + \\ \text{unmeasured load}\end{bmatrix}\end{array}$$

Suspended load refers to those sediment particles which are transported entirely within the body of fluid with very little contact with the bed.

Bed load is that portion of the sediment load that moves essentially in contact with the bed. There is not a standard criteria for defining bed load. However, it is common to consider that load moving within two grain diameters of the bed is bed load. This point is not trivial when comparing one analytical technique with another. The quantity of bed load is very sensitive to thickness of the flow depth used in calculating it. However, it usually amounts to a small fraction of the total load. This definition recognizes that grain size alone is not sufficient to classify material as suspended load or bed load. Hydraulics of flow is also involved. Coarse material may move as suspended load in high energy flow and bed load in low energy flow. Suspended plus bed load will equal the total sediment load moving at that point in the stream.

Wash load, on the other hand, refers to that portion of the suspended load which is not found in the bed of the stream. That is, the gradation of the material in the stream bed is coarser than the gradation of material in the wash load. This is an important distinction for the later discussion on analytical techniques since all transport formulas are based on the presence of material in the stream bed. The amount of wash load, on the other hand, depends solely on the supply of sediment entering the stream and cannot be calculated with transport formulas. (In many alluvial streams the wash load is finer than 0.0625 mm.)

Additional insight into the meaning of "wash load" was given by Dr. Hans Albert Einstein in reference 6 (pages 17-36) as follows: "either the availability of (sediment) material in the watershed or the transporting ability of the stream may limit the sediment load at a cross section. In most streams the finer part of the load, i.e., the part which the flow can easily carry in large quantities, is limited by its availability in the watershed. This part of the load is designated as <u>wash load</u>. The coarser part of the load, i.e., the part which is more difficult to move by flowing water, is limited in its rate by the transporting ability of the flow between the source and the section. This part of the load is designated as <u>bed-material load</u>."

Wash load is often thought of as the clay and perhaps silt material moving in the stream. However, in coarse bed streams, such as those with gravel cobble beds, wash load might also include sand sizes since these are limited by supply. One should be careful, however, to realize that the amount of sand on the stream bed at low water may be quite different from the amount at that same location during high water. Therefore, it is not possible to infer that the gradation of bed material is the same during a flood as it is during low water. In all likelihood, observations during high water would reveal the presence of much more sand material in the stream bed than is present in samples of bed material taken during low water. The companion term to wash load is bed material load. As the name implies, grain sizes in the bed material load are those grain sizes which are also found in substantial quantities in the stream bed. Most analytical techniques concentrate on calculating the bed material load. This will oftentimes be only a small fraction of the total load moving, and yet it is the fraction that contributes the most information in channel morphology studies. The importance of bed material load is so great that most of the effort heretofore in the development of analytical techniques has centered on being able to calculate the bed material load moving in a stream.

The term, measured load, refers to all of the sediment load that can be measured with sampling equipment, which today is the suspended load to within 3 inches of the bed. Sampling equipment that measures the concentration of suspended material is highly developed relative to other sediment sampling equipment. It can operate over a range of depth or at a point; be hand held or operate from a cableway; and can measure a range of particle sizes up to 2 mm. This range of operation provides very acceptable results when one is interested in predicting total sediment yield from the watershed because that type of sampling would usually capture all but about 10 percent of moving sediment. However, in channel morphology studies the remaining 10 percent, the unmeasured load, is the most significant fraction.

The final term, unmeasured load, refers to that portion of the sediment load which is not measured and is usually the material either greater than 2 mm or moving within 3 inches of the bed. It is usually determined by calculations using the measured load as a guide. However, in coarse bed streams, the size of material moving in suspension will often exceed 2 mm, and the unmeasured load takes on more significance. In terms of total sediment yield, the unmeasured load may still be a very small amount.

However, in terms of channel aggradation or degradation trends, it will be a very significant load.

c. Sediment Yield

Sediment yield is the annual amount of sediment delivered from a drainage area, i.e., the total annual sediment load passing a gage on a stream. It is expressed in tons per year. A companion term is unit sediment yield, and this is the annual sediment yield divided by the drainage area - for example, tons/year/square mile. It is customary to correlate the annual sediment yield in tons with the annual water yield in acre feet as shown in the following figure. The relationship is usually satisfactory and the scatter that does exist will often exhibit a trend which can be used to further understand sediment production in the basin. (For example, the five high points in fig. 2.03 were excluded from the regression analysis because they occurred during five years starting in the dry 1930's whereas the remaining points are data from the late forties through the fifties and reflect current land use in the basin.)

Occasionally annual sediment yield is expressed in volume units, but this is not recommended. Transport equations require weight and sediment measurements and are presented as weight per unit time. To transfer from volume to weight requires data on unit weight of deposits which not only is difficult to determine but also changes with time.

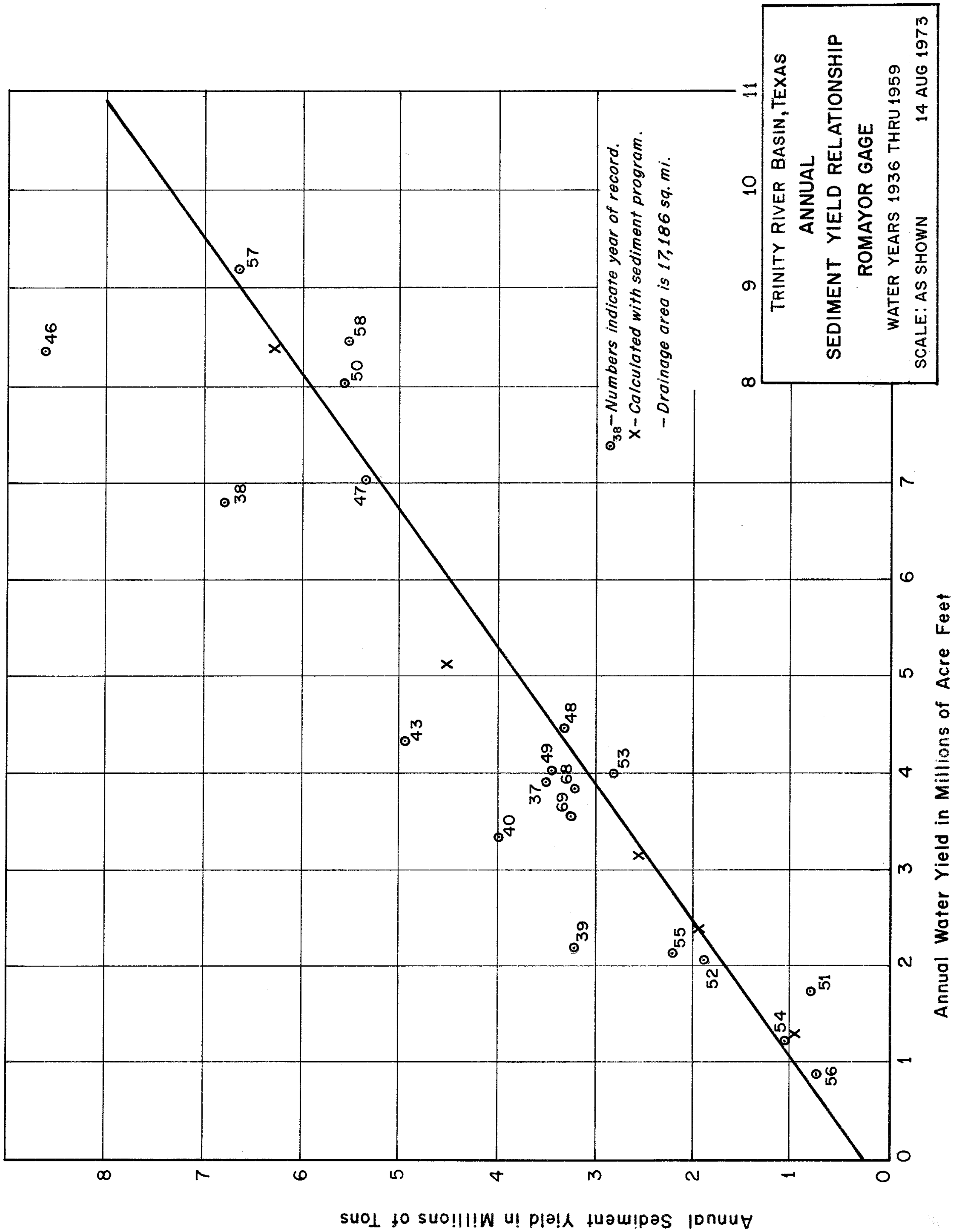

Fig. 2.03. Sediment Yield

Correlations between annual water yield and annual sediment yield indicate that a better approach for transferring sediment yield data from one basin to another is to relate the intensity of sediment production, tons/acre to the intensity of water production, cfs/acre, in the model basin, determine the water yield from the basin of interest and then transfer the sediment data through the observed correlation. Even when the basin of interest is ungaged, the water production can be approximated by techniques for transferring water data from gaged areas. Usually, water data is more readily available than sediment data.

Neither of these techniques establish the coarser load fraction of the sediment yield (i.e., medium sand and up) because these sizes move as a function of their availability in the stream bed and the hydraulics of flow. Fortunately the coarse material does not contribute substantially to the total sediment yield -- usually less than 5 or 10 percent. The importance of coarse material is discussed later in terms of channel regime.

Occasionally, units of volume are used to express sediment yield. This is particularly true when yield is calculated from measuring the accumulation of deposits in a reservoir. Two difficulties arise from this method: (1) the trap efficiency of the reservoir must be estimated and (2) the unit weight of deposits must be available so sediment volumes may be converted to weights for subsequent use in analytical studies. Trap efficiency is often very difficult to establish since one representative value must be determined for all magnitudes of flood events. This is discussed in more detail in Chapter 5. Unit weight of the actual deposits should be measured. The "typical" values of trap efficiency presented in this volume are not sufficiently accurate for use in such calculations.

Chapter 3

River Morphology

CHAPTER 3. RIVER MORPHOLOGY

Section 3.01. Introduction

Rivers are dynamic not only in the sense that water in motion is dynamic but also in the sense that the size and alignment of their channels are continually changing. Work to set the fluid body in motion is provided by the potential energy gradient from the relief of the watershed. The river channel serves as a focal point for energy dissipation as flow from the entire watershed is collected there. In fixed bed hydraulics, energy is dissipated by friction, expansion and contraction losses as discussed in Volume 6, "Water Surface Profiles." In natural streams, however, part of the energy is used to transport the water, and part is used to transport the sediment material which moves in the water. The energy equation advanced in Volume 6 to describe the conservation of energy for flow within a fixed boundary does not adequately describe flow in a movable boundary because it does not provide a term for the energy required to transport the sediment material. At this point in time, no generally acceptable equation has been advanced to describe the movement of water-sediment mixture in a movable boundary.

Section 3.02. Lane's Equation of Dynamic Equilibrium

The fact is generally recognized, however, that nature maintains a delicate balance among the water-sediment mixture flowing in a natural stream, sediment material forming the boundary of the stream channel, and the hydraulics of flow. In 1955 Lane summarized this balance with a qualitative statement which included the bed material load, Q_s, sediment size, D50, water discharge, Q, and energy gradient, S, as follows:

$$Q_s \cdot D50 \approx Q \cdot S \tag{3-01}$$

He concluded that a channel is maintained in dynamic equilibrium by balancing changes in the sediment load and sediment size, with compensating changes in the water discharge and the energy gradient. Although many empirical equations have been developed around the variables in this expression, its main value is to show qualitatively the impact of changes in the water-sediment mixture on the behavior of the river channel conveyance system.

Section 3.03. Dynamic Equilibrium of Stream Bed Profiles

If the yield of bed material load should increase while the water discharge remains constant, according to expression 3-01, either the effective size of particles in the sediment load must decrease (the sediment load must become finer) or the system will be out of balance. A system which is out of balance in this manner will adjust itself by increasing the energy slope until the inflowing bed material load can be transported.

If, at some future time, the inflowing bed material load returns to its original value, the aggradation trend will cease and degradation will begin. Starting at the upstream end, sediment material will be removed from the stream bed and the slope will return to its original value.

Although this is a very simple illustration, it, and numerous variations, can be observed in nature. Whereas the sediment load was assumed to increase in the above illustration, a more natural situation is for the water discharge to remain a constant value, the effective sediment size to be fairly constant and the energy slope to vary from point to point as in a natural river. Expression 3-01 indicates the sediment load must change when the energy slope does, and this requires sediment reservoirs from which material can be withdrawn as the energy gradient increases and into which material can be deposited when the energy gradient decreases. The stream bed provides those reservoirs, and the exchange of material involves, primarily, the coarser particles on and near the bed surface.

It will be convenient for subsequent discussions to identify a location where sediment material is being deposited as a <u>sink</u> and a location from which sediment material is being removed as a <u>source</u>. Part of the great complexity surrounding river behavior is the shifting of sources and sinks. Shifting can be related to two factors:

(1) The locations of sinks and sources are related to the location of hydraulic controls.

(2) If the volume of bed material at a source is exhausted, entrainment of material will shift to the next available location downstream and this may be a former sink.

As discussed in Volume 6, "Water Surface Profiles," the energy gradient along a stream is controlled by cross section shape and size in key locations called control sections. The energy gradient becomes steeper as flow approaches the control location. Reaching a maximum at the control, the energy gradient decreases, often abruptly, only to repeat the process at the next control downstream. Consequently, expression 3-01 would identify the control location as the downstream limit of a source.

During the passing of a large flood, more and more of the hydraulic controls become ineffective. Thus, new source/sink locations are established and old ones eliminated. Center bars may form where none had existed before simply because an unusually large percentage of the total flow was forced into the channel at one of these new control locations. Just upstream from a center bar, formed in this fashion, one will find the deeply scoured area that will become a new sink when normal flow conditions return.

Section 3.04. The River One Observes

Flood events pass quickly and a river channel seldom reaches an equilibrium condition during a single event. This complicates all attempts to correlate observed channel conditions with flow and sediment load. The river one observes reflects three magnitudes of flood events: (1) the low flow events which actually develop a low water channel which meanders within the river channel; (2) the normal flood events which mold the river channel; and (3) the most recent "superflood" event which molded the floor of the valley. It is important to recognize that conditions immediately following a superflood will reflect one extreme stage of equilibrium in the river, but quite a different stage of equilibrium will evolve after a sufficiently long period of normal years. This is particularly significant in levee design where the water surface profile for the highest equilibrium condition must be determined.

It is not safe to associate the superflood event with geological time. Certainly a Standard Project Flood (defined in Volume 5, "Hypothetical Floods") would be a superflood and the 100 year flood would also most likely qualify.

As used here, "superflood" identifies a flood event which is sufficiently large so its friction slope approximates that of the valley rather than the channel slope.

Expanding on the second factor presented above, the water discharge does not have to change for the locations of sources and sinks to shift. When all available sediment material is removed from a source area the water is left with an excess of transport capacity. Material previously deposited at a downstream location, perhaps, will become the first source for satisfying that excess. This constant shifting of sources and sinks would eventually smooth out the profile and produce a rather uniform movement of material if the water discharge became fairly constant. However, fluctuations in the water discharge hydrograph prevent this from happening.

Section 3.05. Rivers in Regime

a. Width, Depth and Slope Equations

Rivers, it is said, have four degrees of freedom: width, depth, slope, and meander pattern. The following equations are advanced to describe width, depth, and indirectly, the slope.

$$B = C_B^{\alpha_B} \qquad (3\text{-}02)$$

$$D = C_D^{\alpha_D} \qquad (3\text{-}03)$$

$$V = C_V^{\alpha_V} \qquad (3\text{-}04)$$

where

B = width

C_B, C_D, C_V = empirical coefficients in the width, depth and velocity equations, respectively

D = depth

Q = representative water discharge

V = average velocity of flow

$\alpha_B, \alpha_D, \alpha_V$ = empirical exponents in the width, depth and velocity equations, respectively

To satisfy the principle of continuity it follows that:

$$\alpha_B + \alpha_D + \alpha_V = 1 \tag{3-05}$$

and

$$C_B \cdot C_D \cdot C_V = 1 \tag{3-06}$$

Investigations, reported by Leopold, et al.(1953), at 20 river cross sections in the Great Plains and the Southwestern United States resulted in the following average values:

$$\alpha_B = 0.26, \qquad \alpha_D = 0.40, \qquad \alpha_V = 0.34$$

It should be pointed out that these exponents are not necessarily transferable from one stream to another, or, for that matter, from one location to another on the same stream. Average values for exponents are given for 158 gaging stations in the United States in reference 12.

Undoubtedly, the experienced student of river geomorphology can gain considerable insight about the behavior of rivers by applying these regime equations. However, they confront the novice with some rather difficult basic questions, such as: "Where should one select a cross section for study? How does one determine a representative discharge? Why is sediment load omitted from the equations? Why conduct a study at stream gage locations since they are not typical of the reach?" Nevertheless, this regime approach provides a point of view about the behavior of alluvial streams which should not be overlooked.

b. Meander Patterns

The fourth degree of freedom, the tendency to meander, is a natural fact; and, therefore, river engineers usually avoid designs which produce straight rivers. Canals are often straight or only slightly curved, but they remain so because of a high level of maintenance activity and because the water discharge is relatively constant.

The term "meandering" is used to refer to the S-curve pattern so typical of alluvial streams as well as to the movement of the river channel by the formation and destruction of bends. Accepting meander as an independent degree of freedom, the dynamics of the process become an outstanding consideration. Flood control with levees requires that the meandering tendency be controlled. At the present time, the meandering process is not well understood. "Channel loops form and migrate, bends lengthen, points extend, cutoffs occur and the process is repeated in such a manner that the width of the belt over which this takes place is rather constant in a river reach. . . .According to Krumbein and Sloss, it has been estimated that the average width of the meander belt is 15 to 20 times the width of the stream."[1] Levees are usually located within this meander belt.

Constraining the natural tendency of the channel to meander impacts on the behavior and sediment transport capacity of the river. This is not understood well enough to present even a qualitative analysis of the problem.

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[1]Reference 2, p. I-17.

However, it seems that if the channel is free to shift laterally, aggradation trends due to deposition of the coarser sands are offset by the river's freedom to select a location through smaller particle sizes. The point bar that results becomes a sink for the coarser sands. When the freedom to make such shifts is taken away because of bank stabilization, the coarser sands deposit on the stream bed, rather than point bars, with a resulting aggradation trend. When designing levees, one should consider the consequence of having to raise the levee at some future time to just maintain the capacity to pass the design flood. The implication is that a well-designed data collection program is essential.

Modification of the meander pattern by constructing cutoffs is a design consideration. However, equation 3-01 indicates the slope of a stream will not change unless either the water discharge, sediment load or effective grain size of material being transported is changed. Therefore, one might be skeptical about affecting a permanent lowering of the water surface profile by the construction of cutoffs.

The study of meander patterns involves the analysis of long reaches of rivers. Permanent controls need to be located, if available, to identify these reaches. An artificial control established at one location can impact on the meander pattern of the river channel at downstream locations. It is important, therefore, to design over long reaches and implement these designs to insure that construction at one point does not cause undesirable conditions to develop at some downstream point.

Section 3.06. Dominant Discharge

The possibility of selecting one representative water discharge that can be considered to have a dominant effect on river regime is very attractive, not from the standpoint of basing all studies of river behavior on that flow, but from the point of view that such a representative discharge offers a beginning point for studies.

Whereas the concept appears to be sound:

> "There is not general agreement on the proper value or method of determining this discharge. Carlston concluded that the dominant discharge which partially controls meander wavelength lies between the mean annual discharge and mean of the maximum monthly discharges. He also states there is some evidence that slope controls the meander wavelength. On the basis of logical reasoning that the dominant channel-forming discharge should be based on the time-duration-weighted bed-material-sediment transport capacity of the streamflow, an analysis of this type for the Arkansas River at Little Rock was conducted by the U.S. Army Engineer Division, Southwestern, Dallas, Texas. This study indicated that the dominant discharge covers a range from about 125,000 (half bank-full) to 175,000 cfs, or about three times the mean annual flow of 48,000 cfs."[2]

Another approach for determining dominant discharge was presented by Johnson in a paper entitled "Current Dutch Practice for Evaluating River Sediment Transport Processes," reference 13. It involves the development of

[2]Reference 2, p. II-20.

a diagram depicting the total amount of sediment being transported during each interval of stage experienced at a gage and the calculation of the first moment about the abscissa to locate the dominant water level. The dominant discharge is associated with this water level by using a stage-discharge rating curve. A sample K-diagram is shown in the following figure.

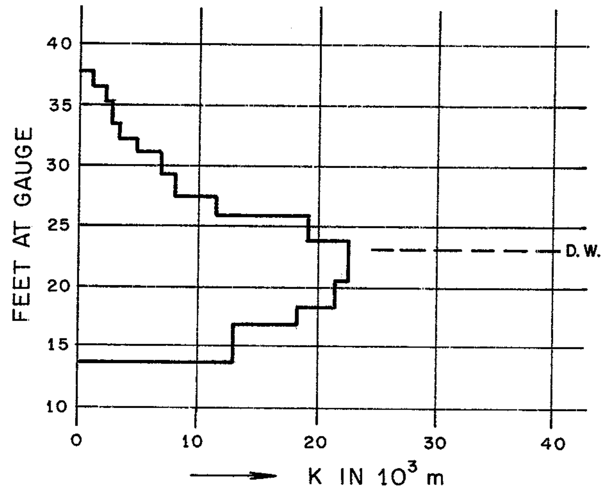


Fig. 3.01. K-Diagram

The abscissa, K, is calculated as follows:

$$K = \frac{m \cdot G \cdot p}{h \cdot \Delta h} \tag{3-07}$$

where G = bed load transport, m^3/day

h = gage height

K = sediment load weighted by flow depth and class interval

m = time interval in days during which stage was within the class interval, Δh

Δh = class interval assigned to depth scale

The dimensionless coefficient, p, is defined as follows:

$$p = 1 + \left[\frac{0.25 \cdot B \cdot d^{3/2} \cdot \sqrt{g \cdot \sigma}}{G}\right]^{2/3} \tag{3-08}$$

where

B = width of river channel at the water surface, meters

d = effective grain size diameter in the bed load (d_{50}), meters

g = acceleration of gravity, meters/sec^2

G = bed load transport, units of m^3/second

p = a constant related to the least energy consumption hypothesis (reference 15)

$$\sigma = (\rho_s - \rho)/\rho \tag{3-09}$$

ρ = density of water

ρ_s = density of sediment particles

The bed load may be determined in a variety of ways. The analytical procedure proposed by Johnson is the Meyer-Peter and Muller equation. Reference 14 discusses this equation, and a brief summary is presented here.

The original form of the Meyer-Peter and Muller formula, in metric units, for a rectangular channel is

$$\gamma \cdot \frac{Q_B}{Q} \left(\frac{K_B}{K_G}\right)^{3/2} h \cdot s = 0.047 \cdot \gamma_s'' \cdot d + 0.25 \left(\frac{\gamma}{g}\right)^{1/3} G_1''^{\,2/3} \tag{3-10}$$

where

d = effective grain size of bed material

g = acceleration of gravity, m/sec^2

G" = bed load transport in metric tons/sec/meter of width (submerged weight)

h = water depth, m

Q = total, water discharge, liters/sec

Q_B = that portion of the total discharge which is responsible for the bed load transport, liters/sec

K_B = the Strickler roughness coefficient for the bed in $m^{1/3}$/sec

K_G = the grain roughness in $m^{1/3}$/sec

S = slope (dimensionless)

γ = specific weight of water, metric tons per m^3

γ_s'' = submerged specific weight of sediment particles $(\gamma_s - \gamma)$, metric tons/m^3

The relationship between specific weight and density is

$$\rho = \gamma/g \tag{3-11}$$

Rearranging terms in equation 3-10 leads to the following

$$G'' = 8 \cdot \gamma_s'' \cdot d^{3/2} \cdot \sqrt{g \cdot \rho} \cdot \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047\right]^{3/2} \tag{3-12}$$

where

$$Q_K = \frac{Q_B}{Q}\left(\frac{K_B}{K_G}\right)^{3/2} \tag{3-13}$$

As expressed in equation 3-12, the units of bed load transport are metric tons/sec/meter of stream channel width, submerged weight. Converting this load to metric tons/sec, submerged weight is accomplished by multiplying by the stream channel width, B.

$$G' = 8 \cdot \gamma_s'' \cdot B \cdot d^{3/2} \sqrt{g \cdot \rho} \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047\right]^{3/2} \tag{3-14}$$

In English units bed load transport is expressed as lbs/sec, dry weight. Changing from submerged to dry weight is accomplished by including the ratio γ/γ_s'' in equation 3-14, and redefining the units of variables as follows.

B = water surface width in channel, ft

d = effective grain size (d_{50}), in ft

g = acceleration of gravity, fps

G = bed load transport, tons/day dry weight

h = water depth, ft

Q_K = dimensionless coefficient

S = slope, ft/ft

γ = specific weight of water, lb/ft^3

γ_s = specific weight of sediment particles, lb/ft^3

γ_s'' = $\gamma_s - \gamma$

σ = γ_s''/γ or $(\rho_s - \rho)/\rho$ = dimensionless coefficient

$$G' = 8 \cdot \gamma \cdot B \cdot d^{3/2} \cdot \sqrt{g \cdot \rho} \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047 \right]^{3/2} \qquad (3\text{-}15)$$

An even more common set of English units for bed load transport is tons/day, dry weight

$$G = 43.2 \cdot G' \qquad (3\text{-}16)$$

In evaluating Q_K it is necessary to determine how much of the total water discharge is used to transport the bed load. This is the water moving in the channel

$$Q_B = K_B \cdot A_B \cdot R_B^{2/3} \cdot S^{1/2} \qquad (3\text{-}17)$$

and

$$K_B = \frac{1}{n_B} \qquad (3\text{-}18)$$

A_B = cross sectional area for channel flow, $B \cdot h$

R_B = hydraulic radius of flow on channel bed, A/B

n_B = channel n-value includes grain and form roughness

The grain roughness may be calculated with the Strickler equation as

$$K_G = \frac{26}{d_{90}^{1/6}} \tag{3-19}$$

where

d_{90} = grain size for which 90 percent of material is finer

and n_G = $1/K_G$ (metric) = $1.486/K_G$ (English)

Taking the first moment of the K-diagram about the abscissa involves

$$DW = \frac{\sum^{I} K \cdot \Delta h \cdot h}{\sum^{I} K \cdot \Delta h} \tag{3-20}$$

where

K = calculated with equation 3-07 for each class interval of depth

Δh = the class interval assigned to depth

h = distance from the midpoint of Δh to the abscissa

I = the total number of class intervals

$$Q_D = f(DW) \tag{3-21}$$

The dominant discharge, Q_D, is read from a stage-discharge rating curve. Note that this value can change from year to year. Its only advantage is to aid in simplifying the early phases of studies and it should not replace the type of analysis, discussed subsequently, which uses a hydrograph of flow.

Section 3.07. The Impact of Tributaries on the Stream Bed Profile

Tributaries fall into two classes: (1) those transporting sediment that is finer than the bed load of the main stem, and (2) those having bed load material equal to or coarser than that of the main stem. The first type will assist the main stem in transporting bed material, resulting in channel degradation and a decrease in slope downstream from the confluence. The second type will exhibit the opposite trend with the confluence area serving as a sink for deposition of bed load until a flood on the main stem removes it.

It is important to note that the river one observes reflects a balance among the terms in expression 3-01, <u>especially</u> downstream from a tributary. When man regulates the main stem flow by a dam, the flow duration curve changes, which changes the dominant water discharge on the main stem. However, the tributary continues to bring in its same bed material load. Equilibrium is upset and the main stem often exhibits an aggradation trend. This trend results in increasing water surface profile elevations and must be taken into account in the design of levees or the acquisition of lands to permit project operation.

Section 3.08. The Importance of Natural Levees

The typical ground profile across many natural streams shows the ground surface to slope away from the channel in both directions.

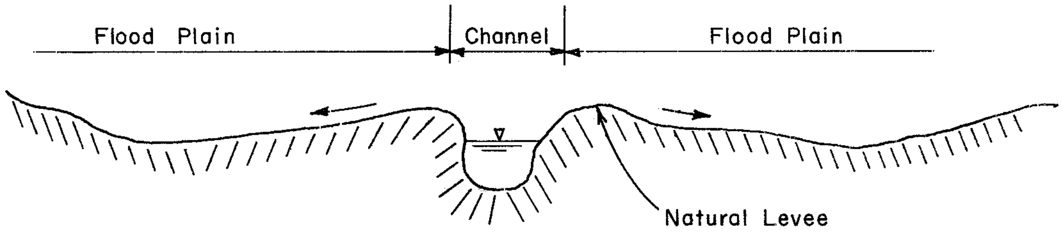


Fig. 3.02. Typical Cross Section Shape

The high ground adjacent to the channel is referred to as a "natural levee" since it is the result of sediment depositing during flood events as water flows out of the channel. The formation of natural levees plays a very significant role in the overall development of a river which is undergoing aggradation. Unfortunately, flow hydraulics associated with the problem are highly three-dimensional, and analytical procedures are not available to study the problem.

Qualitatively, one impact of maintaining a channel in a fixed location appears to be the continuing increase in height of the natural levees. This results in increasing the channel capacity to the point where the equilibrium between flow depth, width and velocity is upset. A consequence is the development of deep scour where the flow is confined and the subsequent deposition forming a center bar where the first expansion occurs downstream.

Chapter 4

Collection and Analysis of Data

CHAPTER 4. COLLECTION AND ANALYSIS OF DATA

Section 4.01. Introduction

Data collection in alluvial streams involves sampling the boundary as well as properties of the water-sediment mixture that is flowing. Most data collection programs are designed to determine the annual weight of suspended sediment which requires measuring water discharge and sediment concentration. This level of information is essential for calculating sediment yield of the watershed. In addition to the suspended sediment load, sampling programs should periodically provide data on the amount of bed load moving. Particle size distribution in the suspended load, in the bed load, and in the bed surface as well as profiles along permanent sediment ranges should also be provided. If degradation studies are contemplated, sampling measurements should include the particle size distribution of material beneath the bed surface. All measurements of sediment loads should include water temperature and a water discharge measurement. Occasional measurements of water surface slopes are desirable. Each of these types of data is discussed in the following paragraphs.

Section 4.02. Suspended Load Measurements

a. Vertical and Lateral Distribution of Sediment

To calculate sediment discharge it is necessary to define the vertical and lateral distribution of concentrations in the cross section and the variation of the mean concentration with time. If this distribution can be defined, sediment samples may be collected routinely at a single vertical in the cross section and the mean concentration calculated by the use of an index. Periodically, the distribution index should be revised by collecting a comprehensive set of data at many verticals. Oftentimes the distribution index will vary with water discharge, therefore it is essential to analyze a range of water discharges before assigning a distribution index. The season of the year is another variable which frequently correlates with the concentration distribution index.

The discharge-weighted mean concentration in a vertical generally is obtained from depth integrated samples collected with standard velocity-weighting samplers. The horizontal distribution of concentration may be obtained from these data. However, the determination of any vertical distribution of concentration requires point sample data in each vertical. The mean concentration in a cross section or a vertical is then computed by weighting the concentration of each individual point sample by the increment of discharge which it represents.

b. Mean Concentration for Section

Two techniques are available for calculating the discharge-weighted mean concentration in the cross section from the mean concentrations of the several sample verticals. If the sample vertical represents centroids of equal discharge (EDI method), the mean concentration is the average of the several verticals or is the mean of the composited samples, provided all samples are of the same volume. If, on the other hand, the sampled verticals are uniformly spaced and the same vertical transient rate is used for all samples (ETR method), the mean concentration is the ratio of the total weight of sediment to the total weight of water-sediment mixture in all the samples.

c. Variation of Concentration with Time

Having obtained the discharge weighted concentrations for the cross sections, the next step in computing sediment discharge is to translate individual values of concentration into a continuous temporal concentration curve. This step may be reasonably simple if values for water discharge or sediment concentration do not vary greatly. However, at a new station, lack of knowledge of these trends together with the large number of variable conditions affecting sediment erosion and transport requires an intensive sampling program, and successful station operation requires continual modification of the sampling program to obtain the best results commensurate with a reasonable expenditure of time and effort. In any case, concentration data should be interpreted and the temporal graph prepared by personnel who have an indepth knowledge of the sampling program, and of the physical and cultural environments affecting the stream regimen and sediment sources. A good understanding of the fundamentals of sediment transport is essential (9).

d. Calculation of Sediment Load from Concentration

The sediment concentration in a sample may be determined as the ratio of the weight of the sediment to the weight of the water-sediment mixture. Because of convenience in the laboratory, it is usually expressed in parts per million and defined as the dry weight of sediment divided by the weight of the water-sediment mixture multiplied by one million. It is customary to publish concentrations as mg/l, however, so the values determined in the laboratory must be converted prior to computation of the sediment discharge. The equation for sediment discharge is as follows:

$$Q_s = Q \cdot C_s \cdot k \qquad (4\text{-}01)$$

where

Q_s = the sediment discharge in tons per day

Q = the water discharge in cubic feet per second

C_s = concentration of suspended sediment in mg/l

k = coefficient which converts volume per second to weight per day as follows:

k = .0027 tons per day when Q is expressed in cubic feet per second or k = .0864 metric tons per day when Q is expressed in cubic meters per second.

e. Conversion of Units

Values of the conversion factor C for converting parts per million to milligrams per liter are given in the following table. When the concentration exceeds 16,000 ppm the following equation should be used to obtain equivalent mg/l.

$$C_s = C \cdot ppm \qquad (4\text{-}02)$$

where

ppm = parts per million and

C_s = the concentration of suspended sediment in mg/l.

Table 4.01. Conversion Factors, C, for Sediment Concentration: Parts Per Million to Milligrams Per Liter[1]

(The factors are based on the assumption that the density of water is 1.000 (plus or minus 0.005), the range of temperature is 0° - 29° C, the specific gravity of sediment is 2.65, and the dissolved-solids concentration is less than 10,000 ppm. This table supersedes table 1 in Guy [1969]).

Concentration Range (ppm)	C	Concentration Range (ppm)	C
0 - 15,900	1.00	322,000 - 341,000	1.26
16,000 - 46,800	1.02	342,000 - 361,000	1.28
46,900 - 76,500	1.04	362,000 - 380,000	1.30
76,600 - 105,000	1.06	381,000 - 399,000	1.32
106,000 - 133,000	1.08	400,000 - 416,000	1.34
134,000 - 159,000	1.10	417,000 - 434,000	1.36
160,000 - 185,000	1.12	435,000 - 451,000	1.38
186,000 - 210,000	1.14	452,000 - 467,000	1.40
211,000 - 233,000	1.16	468,000 - 483,000	1.42
234,000 - 256,000	1.18	484,000 - 498,000	1.44
257,000 - 279,000	1.20	499,000 - 514,000	1.46
280,000 - 300,000	1.22	515,000 - 528,000	1.48
301,000 - 321,000	1.24	529,000 - 542,000	1.50

This table shows that concentrations expressed in mg/l are the same as ppm for values up to 16,000 ppm.

[1] United States Geological Survey, Techniques of Water Resources Investigations, "Computation of Fluvial-Sediment Discharge" by George Poterfield, U. S. Government Printing Office, 1972, p. 43.

f. Particle Size Analysis of the Suspended Sediment

A sufficient number of samples should be analyzed each year to determine representative values for particle size distribution in the water-sediment mixture. The accuracy of such analyses is dependent on, among other things, the quantity and physical characteristics being analyzed. The following table presents the quantity of sediment required for various methods of determining particle size distribution.

Table 4.02. Quantity of Sediment for Particle Size Analysis, in Grams (9)

Method	Minimum	Optimum
Dry sieve	50	100
Wet sieve	0.05	1.0
VA tube (1)	0.05	1.0 - 7.0
Pipet	0.8	3.0 - 5.0
BW tube (2)	0.5	0.7 - 1.3

Table 4.03 shows the type of data needed from suspended measurements. Of course, this amount of detail is not needed from every sample.

g. Correlation Between Concentration or Sediment Load and Water Discharge

Attempts to correlate sediment concentration with water discharge, even when using multiple linear regression in which other parameters such as water temperature or season of the year were included, have been unsuccessful. However, the mass of material moving, expressed in units of tons per day, is often correlated with water discharge to form a

Table 4.03. Summary Data of Suspended-Sediment Particle-Size Distribution, Clearwater River at Spalding, Idaho

Sieve Size (mm)	Date; Discharge (ft^3/sec); Concentration (mg/l)				
	01-19-74 28,000 144[1/]	06-05-74 68,700 113	06-10-74 46,000 31	06-18-74 117,000 131	06-26-74 67,000 30
1.0	-	100.00	100.00	100.00	100.00
.71	-	99.65	98.96	98.74	99.07
.50	100.00	-	-	-	-
.35	-	92.01	77.68	86.73	89.44
.25	99.6	79.31	61.65	75.68	83.84
.18	-	67.99	52.24	66.79	80.48
.12	98.3	62.43	43.38	56.34	76.00
.09	-	56.53	35.07	47.33	70.16
.06	97.0	54.43	29.65	42.84	68.45
.03	89	-	-	-	-
.016	70	-	-	-	-
.008	54	-	-	-	-
.004	41	-	-	-	-
.002	36	-	-	-	-

[1/] Conducted in Sacramento Sediment Laboratory, U.S. Geological Survey.

relationship known as a sediment load rating curve (fig. 1 of Appendix III). Often, the scatter of data is on the order of one log cycle. Nevertheless, many sediment studies require a relationship between the average sediment load and the water discharge, and it is possible to fit a curve through such data so the correct volume of sediment is produced given a specified water discharge hydrograph.

Sediment load rating curves are not always suited for use in calculating sediment yield because of the wide scatter of data. On the other hand, they are convenient and are oftentimes the only data available. Therefore, they are frequently used to estimate sediment yield for engineering projects.

Section 4.03. Bed Load Measurements

River engineers are skeptical about the adequacy of present techniques for producing satisfactory measurements of the bed load. In terms of total sediment yield, that portion of material contributed by bed load is usually small. Therefore, it has not been of a great deal of interest in the solution of practical problems in the past. Recent advances in analytical capability afforded by simulation techniques and the electronic computer make it possible to utilize bed load data in doing channel aggradation and degradation studies. In these studies it is the bed material load that causes channel problems. The USGS recently completed a three-year program of intensive data collection involving measuring the bed load for use in sediment distribution studies on the Clearwater and Snake River arms of Lower Granite Reservoir (1972-1974). The following insight was obtained from that study.

The water sediment mixture contained material ranging from very fine sand to 256 mm cobbles. (For the purpose of this exercise, bed load is defined as that material moving within half a foot of the channel bed since that is the size of orifice in the sampler used in the data collection.) Two samples were collected at each of 10 verticals going across the river and this was repeated on the return trip making a total of 40 samples per measurement. Results showed that both the temporal and spatial fluctuation in bed load is greater than it is for suspended load; therefore, the concept of an index station and a reduced number of samples does not seem appropriate for measuring bed load. Table 4.04 shows typical information from measurements in this program. The Helley-Smith sampler utilized in this program performed very well when compared with a continuous belt bed load sampler in another stream. It is presently undergoing more intensive calibration at the Federal Inter-agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

Bed load measurements without a corresponding particle size analysis are not useful. Techniques which demand information on the bed load movement also require a detailed gradation of the bed load itself.

Table 4.04. Summary Data of Bedload Particle-Size Distribution, Clearwater River near Spalding, Idaho

Sieve Size (mm)	Date; Discharge (ft^3/sec); Transport Rate (tons/day)						
	05-23-74 22,000 6.25	06-04-74 61,000 1,333 1/	06-06-74 80,000 191	06-12-74 60,000 356	06-17-74 124,000 1,136 1/	06-20-74 110,000 3,699	Composite 1974 2/
128	-	-	-	-	-	100.00	100.00
90	-	-	100.00	-	-	80.02	89.60
64	-	-	72.36	100.00	-	53.36	67.97
45	-	-	62.85	93.94	100.00	32.23	52.38
32	-	-	62.85	90.62	98.13	23.06	44.59
22.6	-	100.00	62.32	88.49	97.46	17.38	40.35
16	-	97.16	61.08	87.06	96.72	14.52	38.26
11.3	-	92.96	60.84	86.17	96.04	12.62	36.96
8	-	90.46	60.40	85.81	95.10	11.07	35.92
5.7	-	88.28	60.10	85.64	94.29	9.77	35.08
4	-	87.05	59.92	85.51	93.50	8.91	34.51
2.8	-	85.52	59.71	85.31	92.60	8.13	33.96
2	100.00	84.68	59.46	85.05	91.72	7.57	33.51
1.4	99.88	83.80	59.07	84.63	90.55	7.07	33.04
1.0	98.95	82.49	58.28	83.47	88.33	6.64	32.32
.71	94.50	73.90	55.58	74.34	78.68	5.76	29.02
.50	65.38	42.56	45.73	49.71	54.42	4.00	19.04
.35	27.13	20.80	31.14	24.90	30.07	2.14	9.60
.25	6.90	7.10	12.37	7.01	9.59	.63	2.89
.18	1.29	.68	1.97	.55	1.51	.10	.35
.12	.70	.26	.64	.21	.55	.05	.14
.09	.47	.13	.29	.12	.28	.03	.08
.06	.23	.06	.14	.06	.16	.02	.04
Pan	.00	.00	.00	.00	.00	.00	.00

1/ Computed from incomplete number of samples.

2/ Total sample weight = 189 pounds.

Section 4.04. Sediment Yield

a. Calculation of Sediment Yield

The best method for determining annual sediment yield is to accumulate the mean daily loads. Usually the published daily loads are suspended sediment only and have to be increased by 5 or 10 percent to include the unmeasured portion of sediment passing the gage.

As illustrated in fig. 2.03, Sediment Yield, the quantity of annual sediment yield correlates rather well with water yield. Therefore, calculating sediment yield from observed sediment loads will not necessarily produce the long term average or even a design value for sizing a reservoir. Therefore, a sediment load curve, such as presented in fig. 1 of Appendix III, should be integrated with the long term water discharge-duration curve to produce a design yield for a reservoir study.

Land use is a very important parameter in projecting sediment yield or transferring yield estimates from one basin to another.

Appendix III, entitled Corps of Engineers Methods for Predicting Sediment Yields, presents details of several approaches for estimating sediment yield.

Universal soil loss equation. Some attempts have been made to calculate sediment yield from rainfall, erodability of the soil, ground surface slope, length of overland flow, ground cover and erosion control practices. Reference 10 is one such example. This method utilizes the following equation:

$$Y_e = R_e \cdot K_e \cdot S \cdot L \cdot C_f \cdot P_e \tag{4-03}$$

where

Y_e = potential sediment yield in tons/acre

R_e = the rainfall energy factor

K_e = erodability of the soil

S = slope of ground surface

L = slope length

C_f = cropping factor

P_e = erosion control factor

These terms appear to convey the important factors in the erosion process, and the resulting quantity of sediment depicts the soil loss potential of a specific small land area. However, sediment yield at a stream location encompasses more than just this soil loss potential. The eroded sediment material has to be transported through channels to an outflow point. Perhaps clays and silts in the outflow will correlate with soil loss potential calculated in the above manner, but the total yield of sediments from a drainage basin will depend primarily upon flow hydraulics and the availability of material in and near the stream channel or conveyance system.

b. Transferability of Sediment Yield Data

As one might suspect, the scatter in data becomes much less when relating annual sediment yield to annual water yield than it is at the same gage for daily values of sediment load vs. water discharge. Consequently, annual sediment yield curves provide a very satisfactory mechanism for transferring sediment data from one basin to another or from one point to another in the same basin. This procedure is not satisfactory where there is a substantial difference in land use between the two gage sites. Land use in this sense is meant to be the percentage of land in the basin that is occupied by forest, pasture, row crops or by other uses. The following figure illustrates transferring sediment yield data between two points in the same basin by using

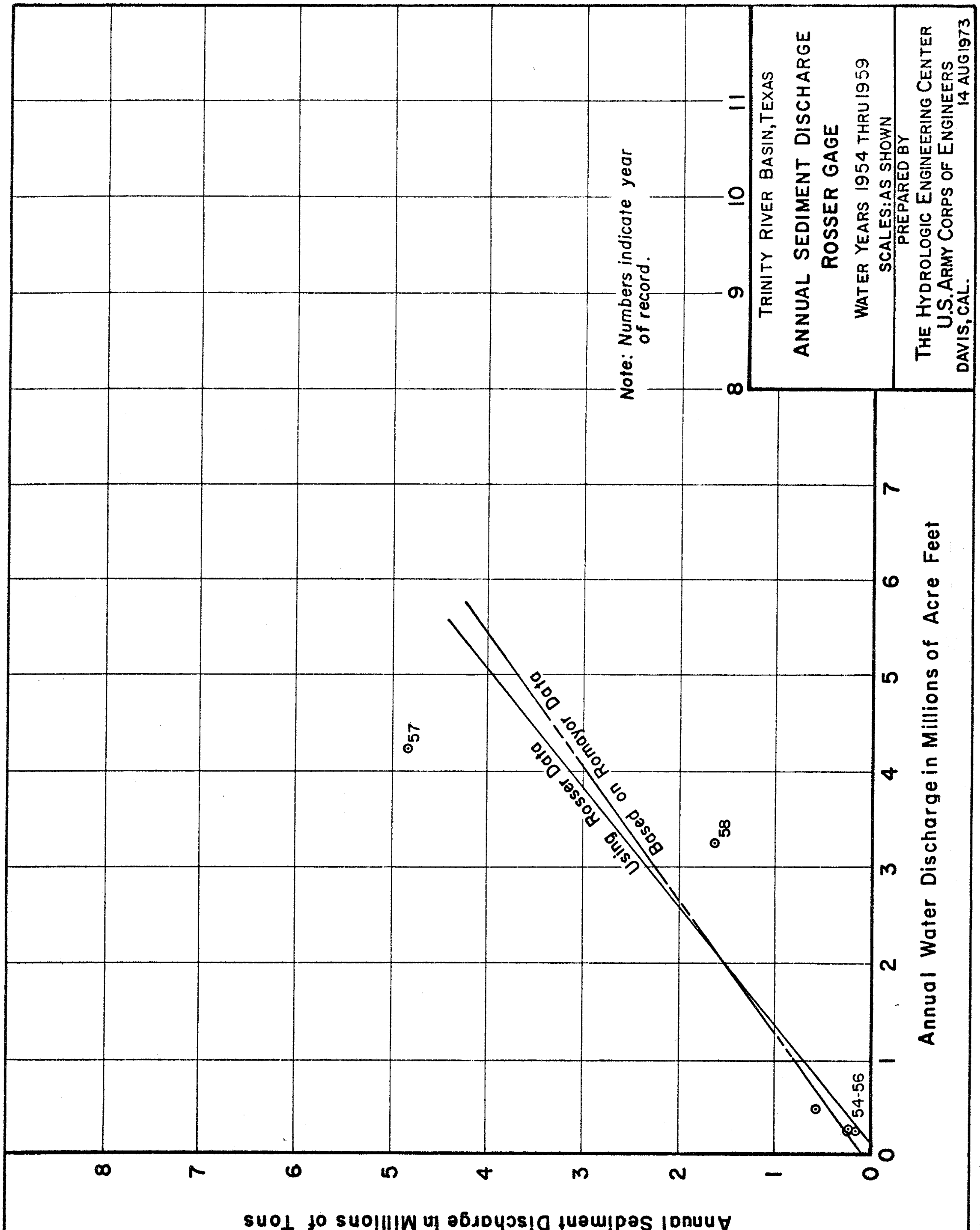


Fig. 4.01. Transferring Sediment Yield Data in a Basin

the water yield relationship. Also a few observed data points are shown. The drainage area is 17,186 square miles at Romayor and 8,146 square miles at Rosser. Fig. 4.02 shows the unit water yield versus distance along the main stem river. Table 4.05 shows the actual calculations for distributing water and sediment yields among the various tributaries in this basin. In general, only that drainage area near streams or gullies contributes substantially to sediment yield.

c. Effect of Land Use Change on Sediment Yield

The impact of land use on sediment yield can be substantial. For example, when a strip mining operation enters a previously all-forested watershed, sediment yield may increase one to two orders of magnitude. This will impact directly on reservoirs in the basin and perhaps even on the channel regime itself.

Section 4.05. Frequency of Measurement

Fig. 4.03 shows the accumulated weight of suspended sediment at Spalding, Idaho as a function of percent of time required. That is, for water year 1974 the total period sampled amounted to about 4 months (30 percent). The total suspended sediment load during that period was 1,200,000 tons. Fifty percent of this material was transported during 5 percent of the year (18 days). Moreover, the river transported more sediment during the two peak days of 1974 than was transported during the entire year in 1973. The shape of the accumulated load curves in fig. 4.03 shows that essentially all of the annual sediment load is transported during flows which are equaled or exceeded 30 percent of the time.

A sediment sampling program has to be very responsive to flow conditions in the river. It should include some sampling throughout

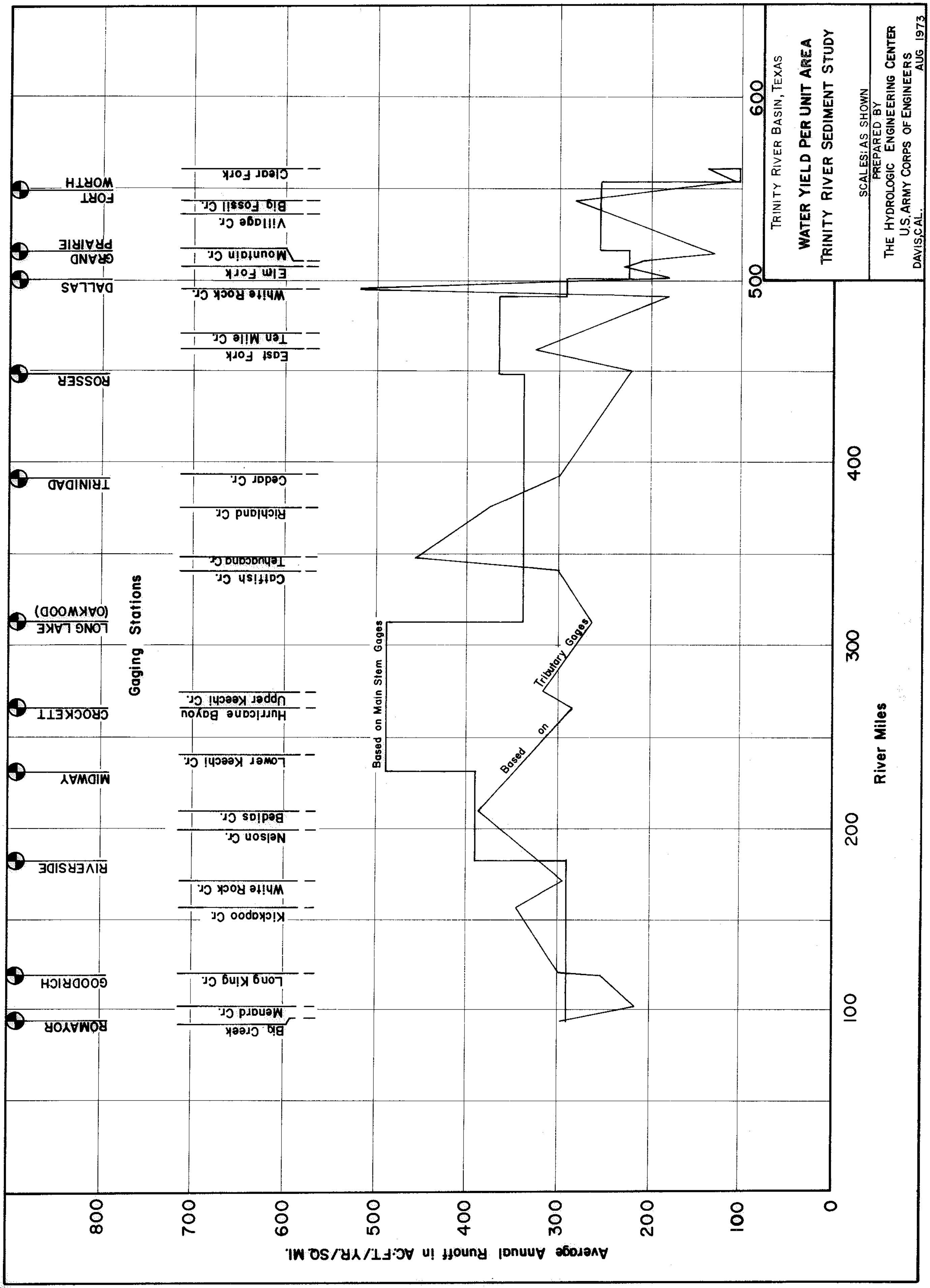


Fig. 4.02. Distribution of Unit Water Yield

Table 4.05. DISTRIBUTION OF SOIL TYPE AND WATER YIELD IN TRINITY BASIN, TEXAS

GAGE NAME	AVG UNIT YIELD OF WATER AF/SQ MI	INCREM. DRAINAGE AREA SQ MI	AVG TOTAL WATER YIELD AC-FT*	%OF TOT ROMAYOR WATER YLD ÷100*	SAND AREA SQ MI	WATER YLD FROM SAND AREA AC-FT*	%OF TOT WATER YLD FROM SAND ÷100*	SILT/ CLAY AREA SQ MI	WATER YLD FROM S/C AREA AC-FT*	%OF TOT WATER YLD FROM S/C ÷100*
W. FORK ABOVE CLEARFORK	100.9	2097.	211587.	.04146	70.	7063.	.00514	1720.	173548.	.06221
			211587.	.04146		7063.	.00514		173548.	.06221
CLEAR FORK	139.7	518.	72365.	.01418	0.	0.	.00000	415.	57975.	.02078
			283952.	.05563		7063.	.00514		231523.	.08299
BIG FOSSIL CR.	256.0	200.	51200.	.01003	0.	0.	.00000	200.	51200.	.01835
			335152.	.06567		7063.	.00514		282723.	.10134
VILLAGE CR.	256.0	250.	64000.	.01254	0.	0.	.00000	250.	64000.	.02294
			399152.	.07821		7063.	.00514		346723.	.12428
MOUNTAIN CR.	223.5	384.	85824.	.01682	0.	0.	.00000	384.	85824.	.03076
			484976.	.09502		7063.	.00514		432547.	.15504
ELM FORK OF TRINITY RIVER	223.5	2657.	593839.	.11635	0.	0.	.00000	302.	67497.	.02419
			1078815.	.21137		7063.	.00514		500044.	.17923
WHITE ROCK CR.	290.7	172.	50000.	.00980	0.	0.	.00000	172.	50000.	.01792
			1128816.	.22117		7063.	.00514		550045.	.19716
TEN MILE CR.	365.6	340.	124304.	.02435	0.	0.	.00000	340.	124304.	.04456
			1253120.	.24552		7063.	.00514		674349.	.24171
EAST FORK, TRINITY RIVER	365.6	1528.	558637.	.10945	0.	0.	.00000	758.	277125.	.09933
			1811757.	.35498		7063.	.00514		951474.	.34104
LOCAL AREA	339.9	202.	68660.	.01345	0.	0.	.00000	202.	68660.	.02461
			1880416.	.36843		7063.	.00514		1020133.	.36565
LOCAL AREA (413.95)	339.9	190.	64581.	.01265	0.	0.	.00000	190.	64581.	.02315
			1944997.	.38108		7063.	.00514		1084714.	.38880
CEDAR CR.	339.9	1110.	377289.	.07392	0.	0.	.00000	1110.	377289.	.13523
			2322286.	.45500		7063.	.00514		1462003.	.52404
RICHLAND CR.	339.9	2048.	696115.	.13639	270.	91773.	.06684	1518.	515968.	.18494
			3018402.	.59139		98836.	.07199		1977972.	.70898
TEHUACANA CR.	339.9	687.	233511.	.04575	440.	149556.	.10893	247.	83955.	.03009
			3251913.	.63714		248392.	.18091		2061927.	.73907
CATFISH CR.	339.9	250.	84975.	.01665	185.	62881.	.04580	65.	22093.	.00792
			3336888.	.65379		311273.	.22671		2084020.	.74699
OAKWOOD LOCAL INFLOW	339.9	200.	67980.	.01332	150.	50985.	.03713	50.	16995.	.00609
			3404868.	.66711		362258.	.26384		2101015.	.75308
UPPER KEECHI CR.	488.6	721.	352281.	.06902	438.	214007.	.15587	283.	138274.	.04956
			3757148.	.73613		576265.	.41971		2239289.	.80265
HURRICANE BAYOU	488.6	357.	174430.	.03418	189.	92345.	.06726	168.	82085.	.02942
			3931579.	.77031		668611.	.48697		2321374.	.83207
LOWER KEECHI CR.	488.6	539.	263355.	.05160	395.	192997.	.14057	144.	70358.	.02522
			4194934.	.82191		861608.	.62754		2391732.	.85729
BEDIAS CR.	388.9	850.	330565.	.06477	635.	246951.	.17986	215.	83613.	.02997
			4525499.	.88668		1108559.	.80740		2475346.	.88726
NELSON CR.	388.9	289.	112392.	.02202	175.	68057.	.04957	114.	44335.	.01589
			4637891.	.90870		1176617.	.85697		2519680.	.90315
WHITE ROCK CR.	291.8	590.	172162.	.03373	385.	112343.	.08182	205.	59819.	.02144
			4810053.	.94243		1288960.	.93879		2579499.	.92459
KICKAPOO CR.	291.8	398.	116136.	.02275	180.	52524.	.03825	218.	63612.	.02280
			4926189.	.96518		1341484.	.97705		2643112.	.94739
LONG KING CR	291.8	227.	66239.	.01298	0.	0.	.00000	227.	66239.	.02374
			4992428.	.97816		1341484.	.97705		2709350.	.97113
MENARK CR	291.8	167.	48731.	.00955	0.	0.	.00000	167.	48731.	.01747
			5041158.	.98771		1341484.	.97705		2758081.	.98860
BIG CR.	291.8	215.	62737.	.01229	108.	31514.	.02295	109.	31806.	.01140
			5103895.	1.00000		1372998.	1.00000		2789887.	1.00000
ROMAYOR GAGE		17186.	5103895.		3620.	1372998.		9773.	2789887.	

*These columns show incremental values with accumulated values offset on the following line.

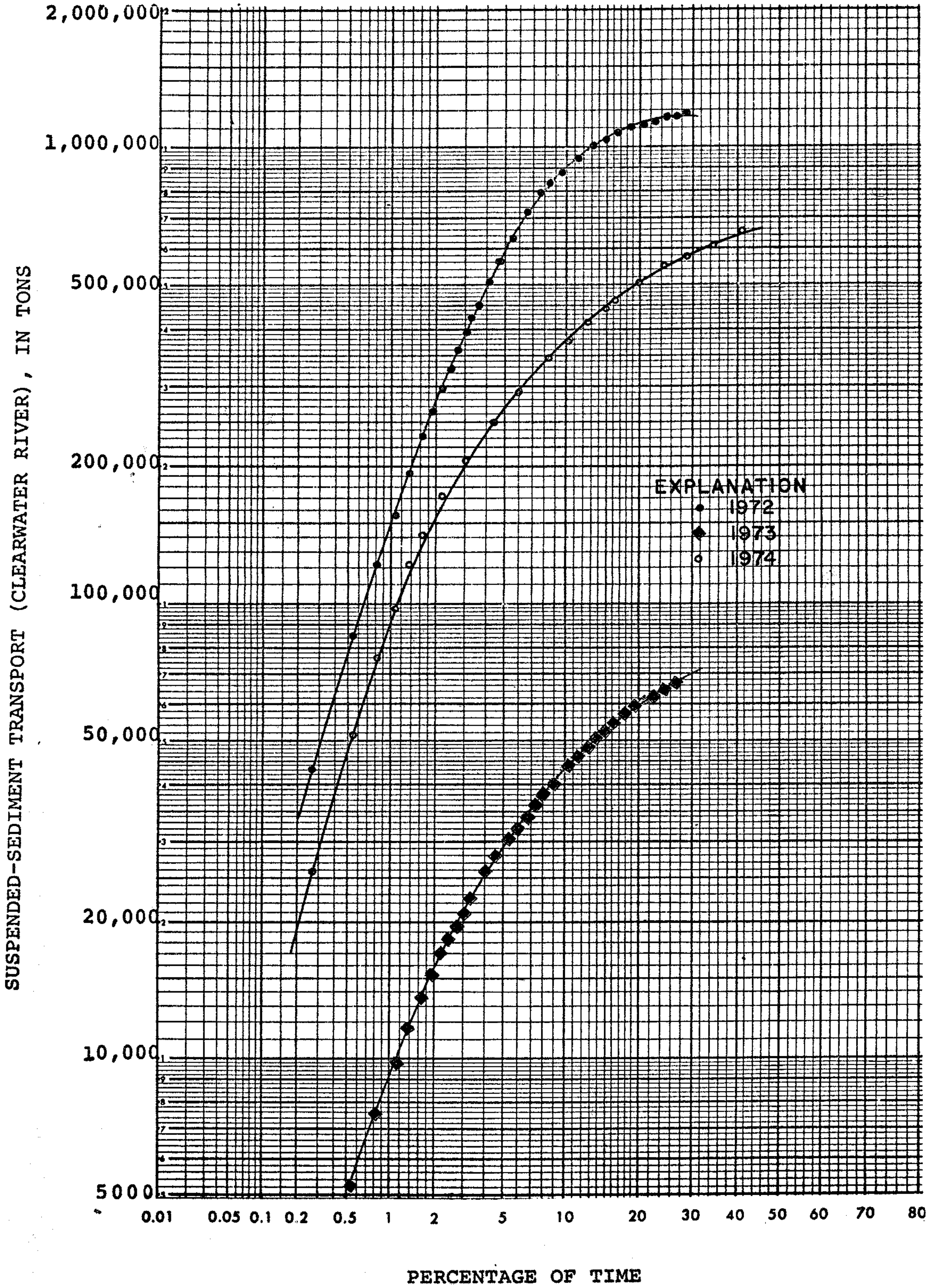


Fig. 4.03. Accumulative Suspended-Sediment Transport as a Function of Time, Clearwater River at Spaulding, Idaho, taken from basic data prepared by U.S. Geological Survey, Boise, Idaho.

the entire year. However, an intensive effort should be made during the flood season. Initially a great variety of information is needed as frequently as the water discharge or flow characteristics change. Gradually the level of effort can be decreased and a firm sampling schedule can be established.

Section 4.06. Sampling to Determine Gradation of the Bed Surface

All sediment transport formulas require an effective grain size and some, such as the Einstein relationship, require detailed information on the gradation of particle sizes for material on the surface of the stream bed. This gradation data, usually expressed as percent finer vs. grain size, must be representative of the entire stream bed surface at that cross section. A further requirement is that a sufficient amount of such data must be available to show how the gradation of the bed surface changes with changing water discharge.

One technique for developing a representative bed gradation curve is to collect a grab sample of material from the stream bed at each vertical during a sediment discharge measurement and analyze each sample to determine its gradation curve. These curves will usually vary a great deal from one vertical to the next, but a representative one may be calculated by weighting each sample by the sediment load in that vertical.

The bed gradation observed during low flow is not representative of the bed during a high flow event. Bed gradation changes in response to the sizes of sediment which are moving as bed material load, and the size of the bed material load varies with water discharge and the supply of material that is available. The supply of material is controlled by upstream sources and sinks. Flow duration is an important factor for determining whether a source of material is exhausted or not and, consequently, this affects the bed gradation. Therefore, bed gradation samples should be taken for a wide range of water discharges and flow durations. Data from each event may be analyzed as discussed above.

It is often impossible to collect bed samples during a flood event. Two techniques are presented for circumventing this problem. The first, and least expensive, is to sample at selected locations during low flow periods; and the alternative is to collect samples of bed load, suspended load, water discharge, water velocity, water depth, slope and width, and to calculate the gradation of bed material that is required to transport the measured loads. These techniques are presented in the following paragraphs.

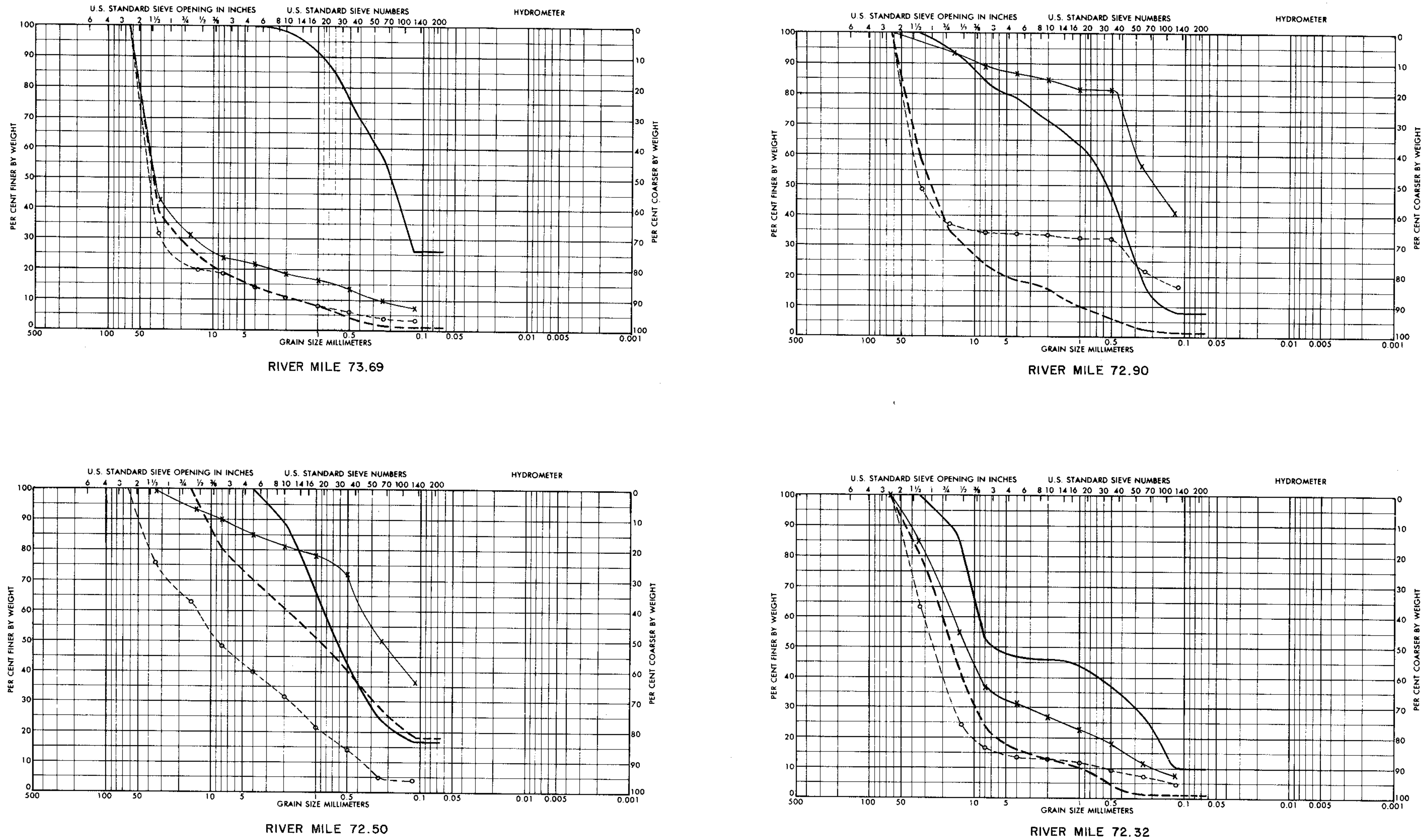
Recent experience with the first technique on coarse-bed streams indicates that samples of material near the water's edge during periods of low flow are representative of the gradation in the stream bed only during periods of low flow. The gradation of samples taken at about midway between the bed and the top bank agreed better with calculated bed gradations in the simulation model during flood flows when the inflowing sediment load was just transported without scour or deposition of the bed.

Figure 4.04 entitled, Gradation of Bed and Bank Material, shows both measured and calculated bed gradation on the Scioto River, Ohio. In this case, the sediment load transported during flood discharges required a smaller effective diameter in the bed material than that transported during low flow events. In both cases the inflowing sediment load was just transported, in the simulation model, with neither scour nor deposition occurring. This comparison suggests that samples from the stream bed should be used when calculating sediment load for low flow events, but when calculating the load for high flow events, one should also consider samples from the stream bank if bed samples were not taken during high discharges.

The second technique for developing bed gradation data is to measure the total bed material load moving, to measure hydraulic parameters and to calculate the gradation of the bed surface that is required to transport that measured load.

Section 4.07.
Sensitivity of Transport Calculations to Bed Surface Gradation

It is desirable to have two samples at each cross section when utilizing the existing simulation models to calculate bed load transport from bed gradation and hydraulics of flow. However, in studies which extend over long distances such a data collection program would require too much investment. Efforts should be concentrated in one short reach with subsequent samples spaced sufficiently far apart to provide guidance in the calibration of the simulation model.



SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

GRADATION CURVES

Legend:

OBSERVED DATA
- ——— Channel Bank
- - - - - Channel Bed

CALCULATED VALUES
- x Q = 36,000 cfs
- o Q = 1,782 cfs

Chillicothe Flood Protection Agency

BED-SURFACE GRADATION

SCIOTO RIVER, OHIO

OCT 1974

Fig. 4.04. Gradation of Bed and Bank Material

In general, bed samples should not be combined into one composite value over a long distance. Such a technique filters out the impact of the hydraulic sorting which goes on continually. In some studies hydraulic sorting is an important consideration.

Coarse material which is present in the bed samples should be included in the analysis. Rather than eliminating the large particles to control bias, it is better to collect a large sample and minimize the impact of one large particle. Recent computations on the Snake and Clearwater Rivers, Idaho, USA, indicate the representative bed gradation curve, defined as that gradation curve which causes the inflowing sediment load to be transported in the simulation model, Appendix VII, lies between a gradation curve developed as percent finer by weight and one which is developed by counting the number of particles and expressing the result as percent finer by that number.

To a large extent, the variability between observed and calculated bed material loads can be attributed to bed surface particle sizes which are not representative of the prototype condition. Sensitivity of calculated results to percentage of material in the bed is shown in the following table.

The first four columns are typical of the calculations required to determine the sediment transport capacity of the bed material load for a given hydraulic condition. The total observed bed material load was 6000 tons/day. Column 5 is included to illustrate the sensitivity of the calculated bed material load to the bed gradation curve.

For example, if the bed samples collected in the field misrepresent the amount of Very Fine Sand on the stream bed by only 1 percent, the resulting calculated bed material load would have been doubled for that size fraction. The larger grain sizes are not affected this much.

This sensitivity alone causes one to question values of bed material load calculated by transport functions. However, particle sizes up through medium sand move predominately as suspended load and can be sampled quite easily. As seen in table 4.06, this is the major portion of the total bed material load.

Section 4.08. Sampling Beneath the Bed Surface

Ordinary data collection programs do not address sampling of the sediment material beneath the bed surface. Those situations involving channel degradation and armoring require such information, however. Not only is the particle size analysis important, oftentimes the depth to bedrock is an important consideration.

The calculations for potential degradation and armoring are not as sensitive to the amount of material in the stream bed as sediment transport calculations are because fine material is not involved. However, it is probably the coarsest 2-3 percent of material in the natural stream bed which accumulates to form an armor layer and arrest degradation trends.

Table 4.06. Sensitivity of the Toffaleti Sediment Transport Formula to Gradation of the Bed Surface

Grain Size	Potential Transport Capacity(1) tons/day	Gradation of Bed Surface	Transport Capacity tons/day	1% Error in Bed Gradation
(1)	(2)	(3)	(4)	(5)
VFS	630000	.0046	2930	6300
FS	200000	.0053	1053	2000
MS	50000	.0370	1852	500
CS	7700	.0374	288	77
VCS	1150	.0643	74	11
VFG	310	.0387	12	3
FG	130	.0384	5	1
MG	60	.0833	5	1
CG	25	.08	2	0
VCG	10	.30	3	0
	(2)	.6890	6224	8893

Notes: (1) This is multiplied by the fraction of material on the bed surface to determine sediment load moving in tons/day.

(2) A summation of this column has no meaning.

The number and location of samples required for degradation studies are difficult and depend on the stream and the problem being analyzed. If the problem involves local scour, the bed samples should be taken within the expected scour zone. If the problem involves general channel degradation, the samples should be spaced out along the channel. The significance of even a few coarse particles should not be underestimated.

Some locations show sediment gradation curves which do not change with depth. Other locations show a distinct trend in the gradation of sediment material with respect to depth -- particularly at several feet below the bed surface. Where channel degradation is anticipated, it is essential to determine the gradation of the material as a function of depth so that this information may be used in calculations for the armor layer.

Section 4.09. Standardization of Sampling Equipment, Techniques and Methods of Analysis

The Committee on Sedimentation of the Water Resources Council has responsibility for standardizing sediment sampling equipment and techniques in the United States. This need grew out of the great impact that sampling equipment and techniques have on the scatter of data. Even with standardization, it is necessary to record the type of equipment and analysis technique used for each sample.

Section 4.10. Permanent Sediment Ranges

Because of the uncertainty in present analytical techniques for handling sediment problems and to give insight into the prototype behavior of sediment problems, permanent sediment ranges are usually established along reservoirs and in channels where aggradation or degradation trends are expected. These ranges are permanently marked and resurveyed periodically to determine the amount of change in the cross section due to scour or deposition.

It is essential that sediment ranges be close together in places where the greatest amount of scour or deposition will occur. In the case of deposition in reservoirs, this would be in the upstream extremity of the reservoir where the inflowing water establishes the backwater curve. In the case of narrow reservoirs, ranges should be located at points of expansion. Ranges may be located further apart through that portion of the reservoir where deposits are not expected.

Immediately downstream from the dam, it is again desirable to locate ranges close together with the distance between them increasing with distance away from the dam. Control locations should be included if they are free to degrade. Sections should be resurveyed annually during the early life of a project. Later the time between resurveys can be extended perhaps up to five years, depending on how rapidly deposition or scour is occurring.

Sediment ranges alone do not provide useful data for calibrating analytical techniques such as the simulation model in Appendix VII. The gradation and amount of total inflowing sediment load, the inflowing water discharge, the water temperature, and the operating policy of the reservoir must also be known. Otherwise, the sediment range data will only be useful for monitoring the rate of deposition in the reservoir. This will not be a linear function with time; consequently, projections into the future will not be possible without an analytical technique.

Chapter 5

Reservoir Sedimentation

CHAPTER 5. RESERVOIR SEDIMENTATION

Section 5.01. Nature of Reservoir Sedimentation Problems

The summary statement in Chapter 1 addressed deposition in reservoirs in terms of the conversion from kinetic and inertial energy to potential energy. This chapter on reservoir sedimentation identifies specific problem areas and methods of solution commensurate with the level of detail required at various stages between the early planning and final design of a reservoir project. Problem areas are associated with project purposes, as well as the physics of sediment movement, and the impact of changes in the bed elevation on the water surface profile. The following table correlates problems with project purposes in the order of increasing complexity of analysis.

The first six study objectives, "Project Feasibility" through "Aggradation of Tributary Channels" have been successfully accomplished using analytical techniques presented in this volume. The "Channelization for Navigation" requirement refers to constricting a river channel with dikes or revetments so that navigation depth is maintained by action of the flowing water rather than by dredging. Good first-approximations to the amount of constriction required have been made using techniques presented in this volume. However, final alignment of control structures (dikes and revetments) and identification of locations requiring over-contraction should be based on movable bed hydraulic model studies.

Table 5.01. Relationship Between Project Purpose and Sediment Problems

	Study Objective	Results Needed from Sediment Study
1.	Project feasibility	Total volume of deposits that will accumulate in the reservoir during the life of the project.
2.	Depletion of storage in single purpose reservoirs.	A total volume is satisfactory for conservation purposes but the vertical distribution is necessary for flood control reservoirs.
3.	Depletion of storage in multiple purpose reservoirs.	A vertical distribution showing storage depletion as a function of elevation.
4.	Reallocation of storage in completed projects.	Impact on the vertical distribution of sediment deposits as a function of elevation.
5.	Land acquisition/levee height design.	The change in average bed elevation at cross sections spaced along the reservoir.
6.	Aggradation of tributary channels.	The change in average bed elevation at cross sections spaced along each tributary.
7.	Channelization for navigation.	The amount of channel contraction required to maintain a specified bed elevation.
8.	Channel degradation and armoring downstream from the dam.	The amount of degradation and the distance it extends downstream from the project.
9.	Density currents through reservoirs.	Concentration of sediment material, elevation and thickness of the density current and sediment load passing the dam.
10.	Siting recreation, water supply or water disposal facilities.	Point values of bed elevation and water depth as related to general and local deposition (or scour).
11.	Navigation channel alignment and port facilities.	The shifting, back and forth across the stream, of point values of bed elevation.
12.	Shore erosion and beach stability.	Both a vertical and horizontal distribution of sediment movement including driving forces of the 3-dimensional reservoir current pattern, overland or local inflow, and action of the ground water table.

Two and three dimensional mathematical formulations of the hydrodynamic equations are presently being developed by several investigators, reference 4. In the future perhaps these will increase analytical capability for density current studies. Presently, these studies require hydraulic model testing.

The study objectives involved with siting facilities and locating navigation channels require hydraulic model analysis. Shore erosion and beach stability virtually require a prototype scale of testing.

Section 5.02.
Data Requirements for Analyzing Deposition in Deep Reservoirs

The amount of data required to perform the various types of studies listed in table 5.01 increases with each item on the list. The first step is to estimate the total amount of sediment that will be available for deposition during the design life of the project. This requires the following data:

Table 5.02. Data for Total Deposition in a Reservoir

Type of Data	Source	Units
Design life of reservoir	Policy	Years
Reservoir capacity	Topographic maps	m^3 or ac. ft.
Water yield of watershed	Streamgage records, computations, or judgment	m^3/year or ac. ft/year
Sediment yield of watershed	Direct measurements, computations, or judgment	m^3/year or ac. ft/year
Composition of sediment material in terms of sand, silt and clay	Direct measurements	Percent
Unit weight of sediment deposits	Direct measurements or computations	lb./ft^3 or tons/m^3

With this level of information one can predict the volume of sediment deposits using trap efficiency techniques. This is an essential step in the early planning for a potential reservoir project.

Assuming flood control is a project purpose, the next level of detail in reservoir sedimentation studies is to divide the total volume of predicted deposits into that volume settling in the flood control pool and that volume settling in the remainder of the reservoir. Fig. 1.01 shows, conceptually, the deposition pattern to expect. This level of calculation requires the following, in addition to data listed above:

Table 5.03. Data for Calculating Deposition in Flood Control Pool

Type of Data	Source	Units
Depth of flood control pool	-	ft. or m
Depth of reservoir	-	ft. or m
Percent of time the water level in the reservoir is at or above the bottom of the flood control pool	Calculations	Percent

The next level of detail in reservoir sedimentation studies is to determine the location of sediment deposits in the reservoir so the new bed profile can be determined. This calculation addresses the land acquisition/levee height and channelization problems. In addition to data shown above, this calculation requires the following:

Table 5.04. Data for Distributing Sediment Deposits Along the Reservoir

Type of Data	Source	Units
Cross sections	Topographic maps	ft. or m
Operating rule for the reservoir elevation	Calculations	
Hydrograph for inflowing water discharge	Direct measurements or calculations	cfs or cms
Size of sediment particles entering the reservoir	Direct measurements	mm
Concentration of sediment in inflowing water	Direct measurements	mg/l
Water temperature	Direct measurement or judgment	°F or °C

Data requirements for hydraulic model studies are not presented in this volume.

The first three study objectives do not require a great deal of calculations and can easily be accomplished by manual methods. On the other hand, determining the location of sediment deposits requires voluminous amounts of calculations and those studies are best conducted with automatic data processing equipment.

Section 5.03. Calculation of Reservoir Deposition Using Trap Efficiency

The term "trap efficiency" is defined as

$$T_e = (Q_{si} - Q_{so})/Q_{si} \tag{5-01}$$

where

T_e = trap efficiency expressed as a decimal

Q_{si} = inflowing sediment load

Q_{so} = outflowing sediment load

Methods which utilize trap efficiency to calculate the volume of sediment deposits are sometimes referred to as detention-time methods. This name stems from correlations which demonstrate a relationship between trap efficiency and the time required for water to flow through the reservoir. One such relationship, developed by Gunnar Brune, (3), is shown in fig. 5.01.

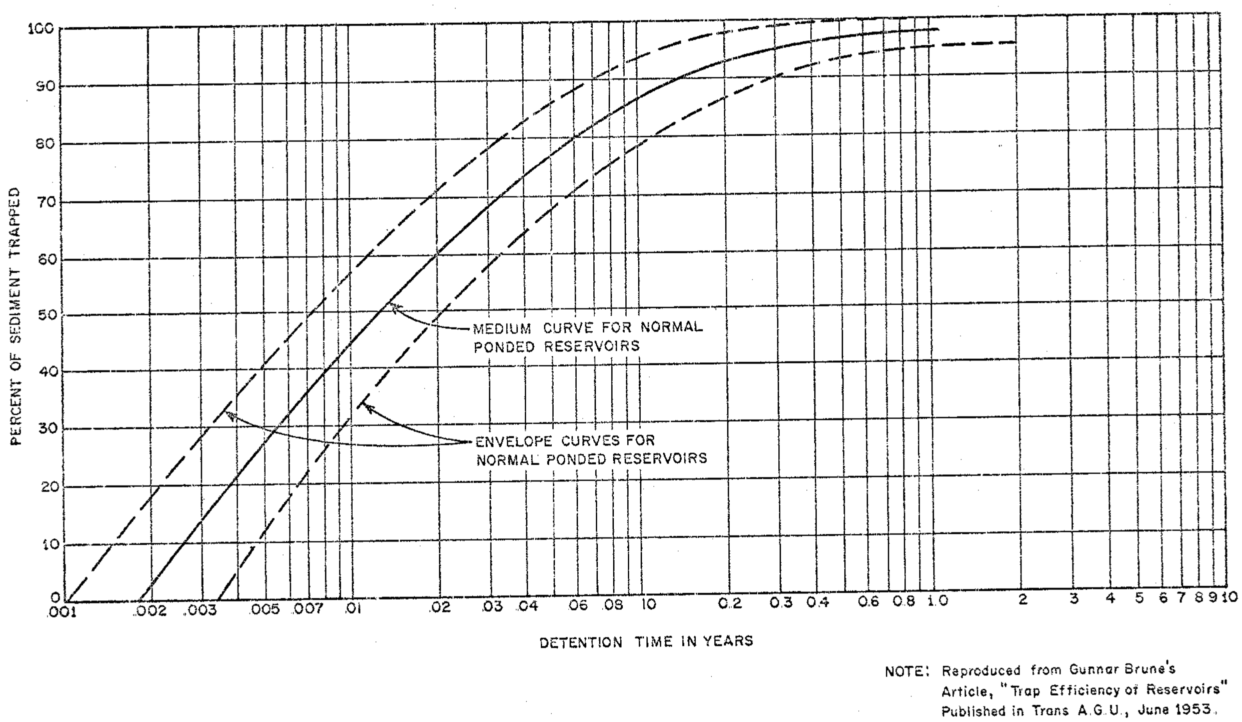


Fig. 5.01. Brune's Curve

In utilizing Brune's curve, flow through time is calculated as follows:

$$T_d = S/Y_w \tag{5-02}$$

where

S = Capacity of reservoir in ac. ft. or m^3

T_d = flow through time (or detention time) in years

Y_w = average annual water yield in units of volume/year

The following example, Lowsed Reservoir,1/ illustrates the calculation of total volume of sediment deposits using Brune's curve.

Given:

Design life of the reservoir (TIME)		=	100 years
Reservoir capacity, top of flood control pool (S)		=	3060 acre feet
Average annual water yield (Y)		=	36200 acre feet/year
Average annual sediment yield (Q_{si})		=	16000 tons/year
Composition of sediment material:	clay	=	25%
	silt	=	35%
	sand	=	40%
	total	=	100%

The unit dry weight for sediment deposits is not available for a proposed reservoir. Therefore, the values suggested in this volume, table 2.03, Unit Dry Weight for Sediment Deposits, are utilized along with equation 2-05 to calculate an average unit weight at the end of 100 years.

1/ This example was developed by Mr. Ernest L. Pemberton, United States Bureau of Reclamation, Denver, Colorado.

Table 5.05. Calculated Unit Dry Weight of Sediment Deposits

Sediment Material	γ_1 pcf	K	$\log_{10}(T)$	$\gamma_1+K\cdot\log_{10}(T)$	% 100	γ_T pcf
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Clay	30	16	2	62	0.25	15.5
Silt	65	5.7	2	76	0.35	26.6
Sand	93	0	-	93	0.40	37.2
						79.3

It is convenient to convert sediment inflow from the average annual amount in tons/year to the total volume delivered during the 100-year period of analysis in acre feet.

$$V_d = Q_{si}\ \frac{\text{tons}}{\text{year}} \cdot \frac{1}{\gamma_{100}}\ \frac{\text{ft}^3}{\text{lb}} \cdot 2000\ \frac{\text{lb}}{\text{ton}} \cdot \frac{1\ \text{ac. ft}}{43560\ \text{ft}^3} \cdot 100\ \text{years}$$

$$= \frac{Q_{si}}{\gamma_{100}} \cdot \frac{200000}{43560}$$

$$= \frac{16000}{79.3} \cdot \frac{200000}{43560}$$

$$V_d = 926\ \text{ac. ft.} \qquad (5\text{-}03)$$

The next step is the calculation of trap efficiency. Since this coefficient depends on the capacity of the reservoir and the capacity changes with time, it is customary to calculate a value for the beginning and one for the end of the design life of the project. These calculations are shown below, starting with initial conditions.

$$T_d = S/Y_w$$
$$= 3060/36200$$
$$T_d = 0.084 \text{ years} \qquad (5\text{-}04)$$

Entering fig. 5.01 with a detention time of 0.084 years, the trap efficiency is read directly as 85 percent. The resulting amount of sediment deposition, may be calculated with the volume equivalent of equation 5.01.

$$Q_{si} - Q_{so} = T_e \cdot V_d$$

$$\text{Total Volume Deposited} = T_e \cdot V_d = 0.85 \cdot 926 \text{ ac. ft.}$$
$$= 787 \text{ ac. ft.} \qquad (5\text{-}05)$$

The final step is to refine these calculations by assuming the reservoir storage capacity is decreased by 787 acre feet and recalculating the trap efficiency following the same computation procedure as before. The result is 81 percent. Utilizing the beginning and ending trap efficiencies it follows that the average trap efficiency for the 100 year project life is 83 percent which results in 769 acre feet of sediment deposits in the reservoir.

Grain size does not enter directly into these calculations for trap efficiency, although it is apparent, intuitively, that the larger grain sizes would deposit first and only the smallest grain sizes would be transported through the reservoir. The impact of grain size, then, is inherent in the empirical data used to develop the trap efficiency curve. On the other hand, approximating detention time by utilizing total reservoir capacity and annual water yield does not merit refinement of data to include particle size. Even so, the Brune's curves may be used to give a reasonable estimate of the total volume of sediment deposits to expect in a reservoir.

In making sedimentation studies for Dardanelle Reservoir on the Arkansas River, the U.S. Army Corps of Engineers District, Little Rock, Arkansas, USA, refined the trap efficiency calculations by establishing two trap efficiency curves. One of these curves was representative of the sand load and the other curve of the silt and clay load. The reservoir was subdivided into reaches and the storage in each reach determined so that for a given water discharge the detention time could be calculated for each reach and the sediment deposition could be calculated separately for sand, and silt and clay. The Little Rock District trap efficiency curve is presented in Appendix IV.

Section 5.04. Development of Trap Efficiency from Observed Data

The procedure which Little Rock District used in the development of their trap efficiency curve is contained in Appendix IV, entitled "Procedure for Development of LRD Trap Efficiency Curve."

Section 5.05. Calculation of Deposition in the Flood Control Pool

Fig. 5.02 shows an empirical relationship which can be used to determine how much of the total sediment deposition can be expected in the flood control pool (fig. 1.01). The "Flood Pool Index" is a measure

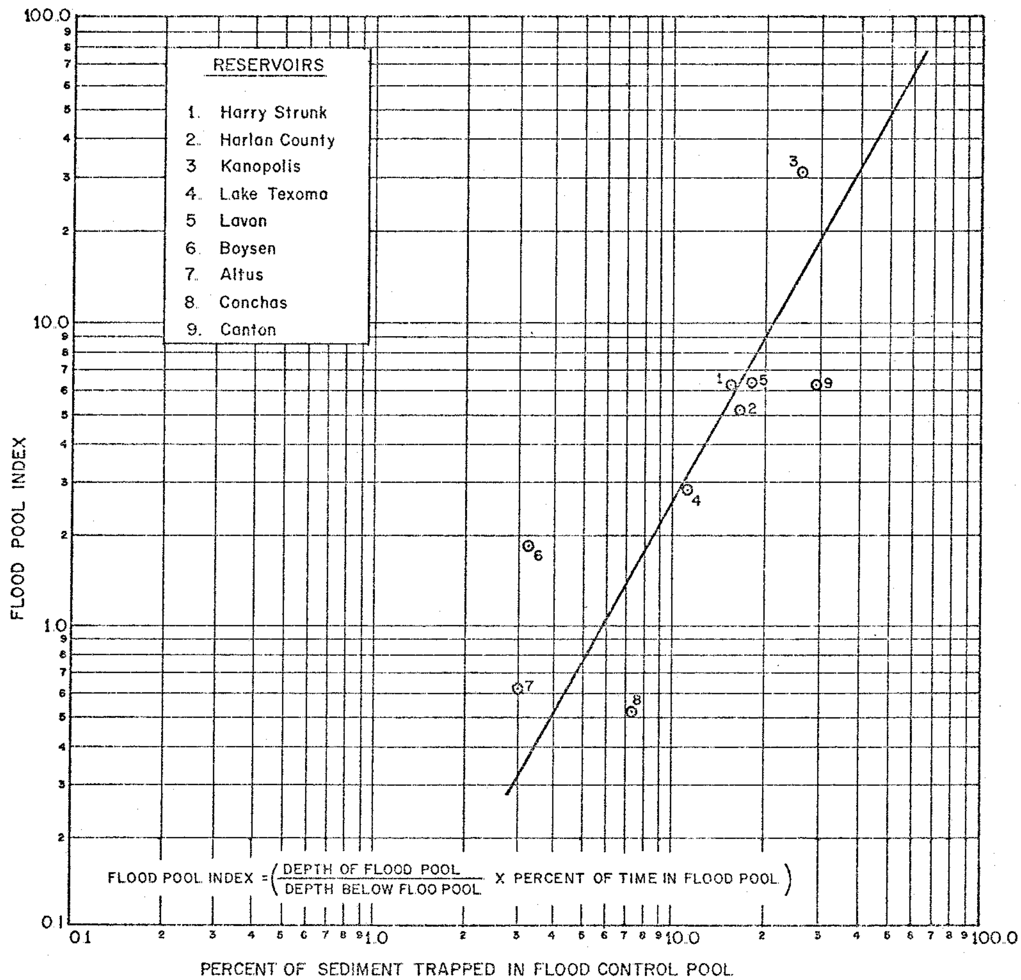


Fig. 5.02. Deposition in the Flood Control Pool

of the amount of time the reservoir remains in the flood pool and the relative depth of that pool. The index is defined by equation 5.06.

Necessary parameters for using this curve are listed in table 5.03, "Data for Calculating Deposition in Flood Control Pool." The calculations which require successive approximations, utilize the reservoir depth versus storage capacity curve as follows.

The required flood control storage at Lowsed is 650 ac. ft. The initial reservoir capacity at the top of flood control pool is 3060. Assuming no sediment deposits for the first approximation, the reservoir volume at the bottom of the flood control pool would be 2410 ac. ft. The corresponding pool elevation is 97 feet msl. Only 3 feet of depth is required in the flood control pool (i.e., 100.0 - 97.0) and the depth below flood control pool is 33.7 feet. The elevation-duration curve, fig. 5.03a, shows that the reservoir is in the flood control pool only 4.1 percent of the time, based upon average yearly conditions. A flood pool index is calculated as

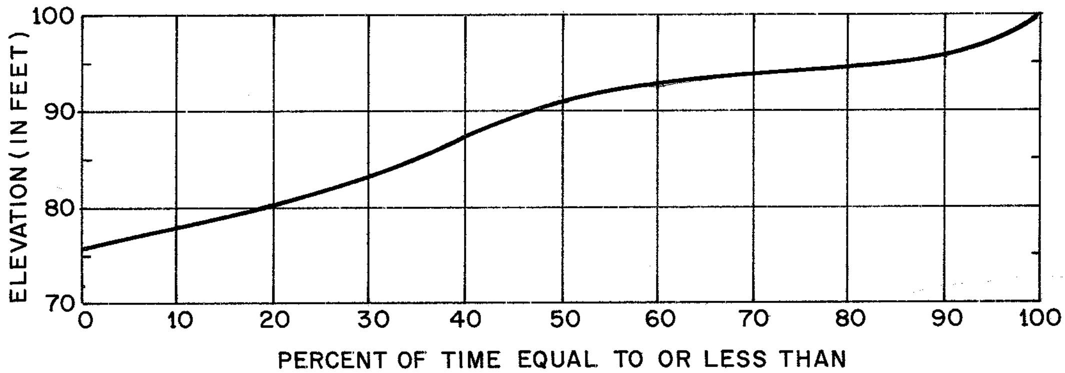
$$\text{Flood Pool Index} = \frac{\text{Depth of Flood Pool}}{\text{Depth Below Flood Pool}} \cdot \text{Percent of Time in Flood Pool}$$

$$= (3/33.7) \cdot 4.1$$

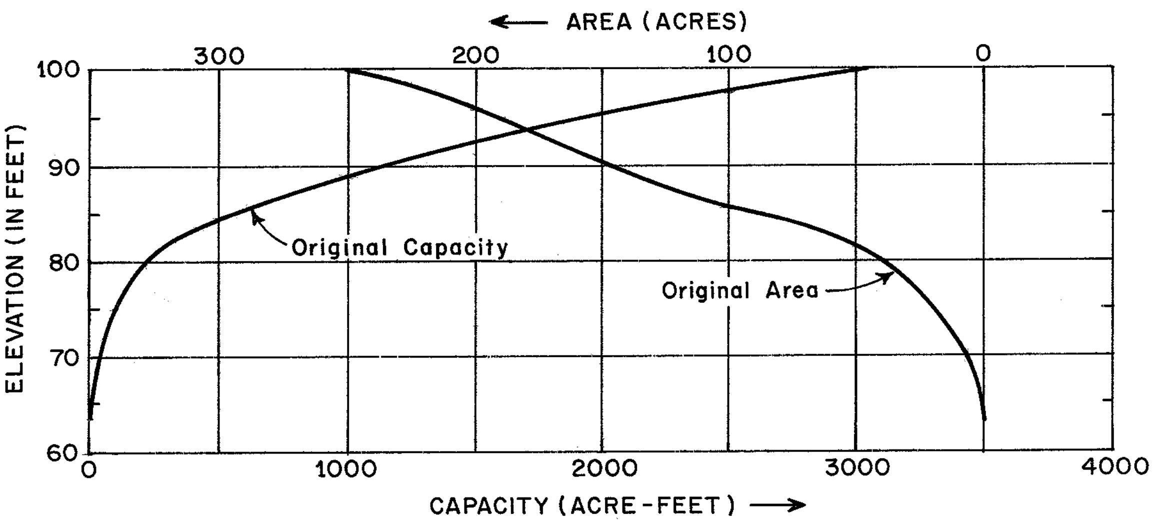
$$= 0.36 \qquad (5.06)$$

Entering fig. 5.02 with this index, the resulting amount of deposition in the flood control pool is read as 3 percent. The resulting 100 year volume is 3 percent of 787 ac. ft. which, rounded off, is 24 ac. ft. This additional storage for sediment does not change the flood pool depth on the second approximation and, therefore, it is adopted for planning purposes.

As a rough check, the available conservation storage at the end of 100 years may be determined as follows:



a. STAGE DURATION CURVE



b. AREA AND CAPACITY CURVES

Fig. 5.03. Duration and Capacity Curves for Lowsed Reservoir

Storage at top of conservation pool	= 3060 - (650 +24)
	= 2386 ac. ft.
Sediment deposition in conservation pool	= 787-24
	= 763 ac. ft.
Storage at bottom of conservation pool	= 1623 ac. ft.

Section 5.06. Distribution of Sediment Deposits Along the Reservoir

The planning or design of a reservoir requires an analysis to determine how sediment deposits will be distributed in the reservoir. This has been the most difficult aspect of reservoir sedimentation to deal with because of the complex interaction between hydraulics of flow, reservoir operating policy, inflowing sediment load, and changes in the reservoir bed elevation. The traditional approach to analyzing distribution of deposits has relied on empirical methods, all of which required a great deal of simplification from the actual physical problem.

Conceptually, deposition starts in the main channel. As flow enters a reservoir, the main channel fills at the upstream end until the elevation is at or above the former overbank elevations on either side. Flow then shifts laterally to one side or the other, but present theory does not predict the exact location. During periods of high water elevation, deposition will move upstream. As the reservoir is drawn down, a channel is cut into the delta deposits and subsequent deposition moves material farther into the reservoir. The lateral location of the channel may shift from year to year, but the hydraulic characteristics of it will be similar to those of the natural channel existing prior to impounding the reservoir. Vegetation will cover the exposed delta deposits and thus attract additional deposition until the delta takes on characteristics of a flood plain.

The diameter (size) of sediment particles commonly transported by streams ranges over five log cycles. As flow enters a reservoir, coarser material deposits first and the finest material is carried well into the reservoir, even to the point of passing the dam. In order to calculate the volume of material which will deposit as a function of distance, grain size must be included as well as the magnitude of the water discharge and the operating policy of the reservoir.

Reservoir shape is an important factor in calculating the deposition profile. For example, flow entering a wide reservoir spreads out, thus reducing transport capacity, but the path of expanding flow does not necessarily follow the reservoir boundaries. It becomes a 2-dimensional problem to calculate the flow distribution across the reservoir in order to approximate transport capacity and therefore the resulting deposition pattern. On the other hand, flow entering a reservoir that is narrow has a more uniform distribution across the section resulting in hydraulic conditions that are better approximated by one dimensional hydraulic theory.

Flood waves attenuate upon entering a reservoir. Therefore, their sediment transport capacity decreases from two considerations: (1) a decrease in velocity due to the increase in flow area and (2) a decrease in velocity due to a decrease in water discharge (attenuation) resulting from reservoir storage. As reservoir storage is depleted by the sediment deposits in the delta, the impact of attenuation on transport capacity diminishes. The resulting configuration, therefore, is assumed to depend upon the first consideration whereas the time for delta development is influenced somewhat by the second consideration.

A very useful technique for estimating the deposition of suspended sediment in deep reservoirs is presented in Appendix VI. This computer program does not actually change bed elevations; consequently the user should run two conditions before accepting the results: (1) initial bed elevation condition, and (2) calculated bed condition for end of reservoir life, determined from (1).

The Engineering Technical Letter, "Distribution of Reservoir Sediment Deposits," ETL 1110-2-64, dated 7 July 1969, Department of the Army, Office of the Chief of Engineers, Washington, DC 20314, by Mr. Brice L. Hobbs is included in Appendix V to give insight into reservoir sedimentation problems. In this ETL Mr. Hobbs points out several weaknesses in "present empirical methods" (1969) for distributing sediment deposits. These involve "total sediment loads," "average trap efficiencies," and "gross volumes of sediment trapped." The weaknesses have been overcome to a large extent by using analytical methods that can be applied with the aid of the electronic computer.

The final approach presented in this chapter is based on digital simulation, using the computer program "Scour and Deposition in Rivers and Reservoirs," described in Appendix VII. This approach eliminates the requirement of working with many of the averages and approximations of the reservoir behavior and increases the engineer's capability to approach sediment distribution problems from the standpoint of simulation, that is, from the standpoint of including a great deal of detail about reservoir operation, the inflowing sediment load, grain size of the material, the inflowing water discharge, hydrograph and reservoir shape, and changes in bed elevation with respect to time.

However, it is a one dimensional steady flow technique and does not attempt to locate the position of the channel through delta deposits. It does recognize, however, that ultimately the channel will exist and will be similar (in geometric size) to the natural channel that existed prior to impounding the reservoir. The results obtained enable prediction of an ultimate deposition profile through the delta deposits. Thus, the impact of deposition on the water surface profile and on the upstream limits of deposition can be determined.

Probably the most difficult problems involving the distribution of sediment deposits are associated with the flow through shallow reservoirs. Therefore, the example chosen to illustrate the aforementioned simulation techniques is a reservoir project which is sufficiently shallow so that during some inflow periods the deposits are actually entrained from the bed and moved further down into the reservoir.

The project is shown on fig. 5.04. This is a multipurpose project including hydroelectric power and navigation among other project purposes. The problem is complicated by the fact that levees are required for flood protection in the vicinity of the upstream

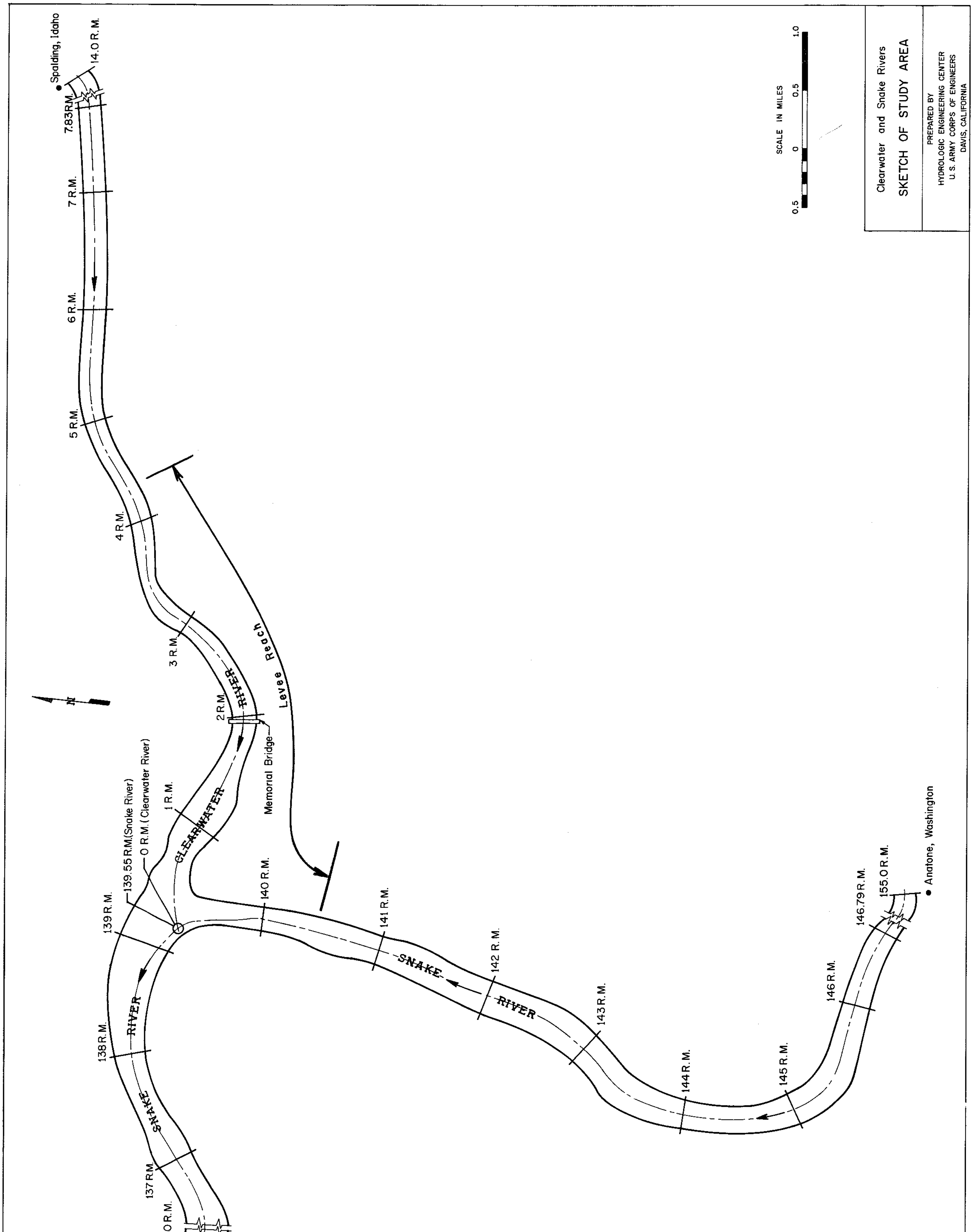


Fig. 5.04. Cross Section Locations, Lower Granite Reservoir, Sedimentation Study

Figure 1

limit of the reservoir project. Therefore, it is necessary to estimate the impact of future sediment deposits on levee heights.

Basically, the data required are cross sections and Manning n-values for use in backwater computations; the inflowing sediment load in tons per day as a function of the water discharge, the gradation of material in the stream bed; the operating rules at the dam, the water inflow hydrograph to the reservoir and the water temperature. Briefly, the sequence of events in the simulation study are as follows: The hydrograph of flows is converted to a histogram for which each discharge has an associated duration in days. The first discharge event is entered and a water surface profile calculated to determine the velocity, slope, depth and width at each cross section. The inflowing sediment load associated with that water discharge is entered at the upstream end and routed through the reservoir using the hydraulic parameters mentioned above. Deposition or scour is then calculated for each reach based on sediment inflow and outflow for that reach. Finally, the amount of change in the bed elevation is calculated for each cross section and cross section coordinates in the movable bed are changed. This completes the first pass through the calculations. A sample of the data involved is illustrated in the following figures and tables.

Fig. 5.05 shows a typical cross section with the limits of movable bed assigned. The user specifies the portion of the cross section over which deposition will occur.

Hydraulic roughness is assumed to be the same throughout the life of the project. This is a rather significant assumption since hydraulic

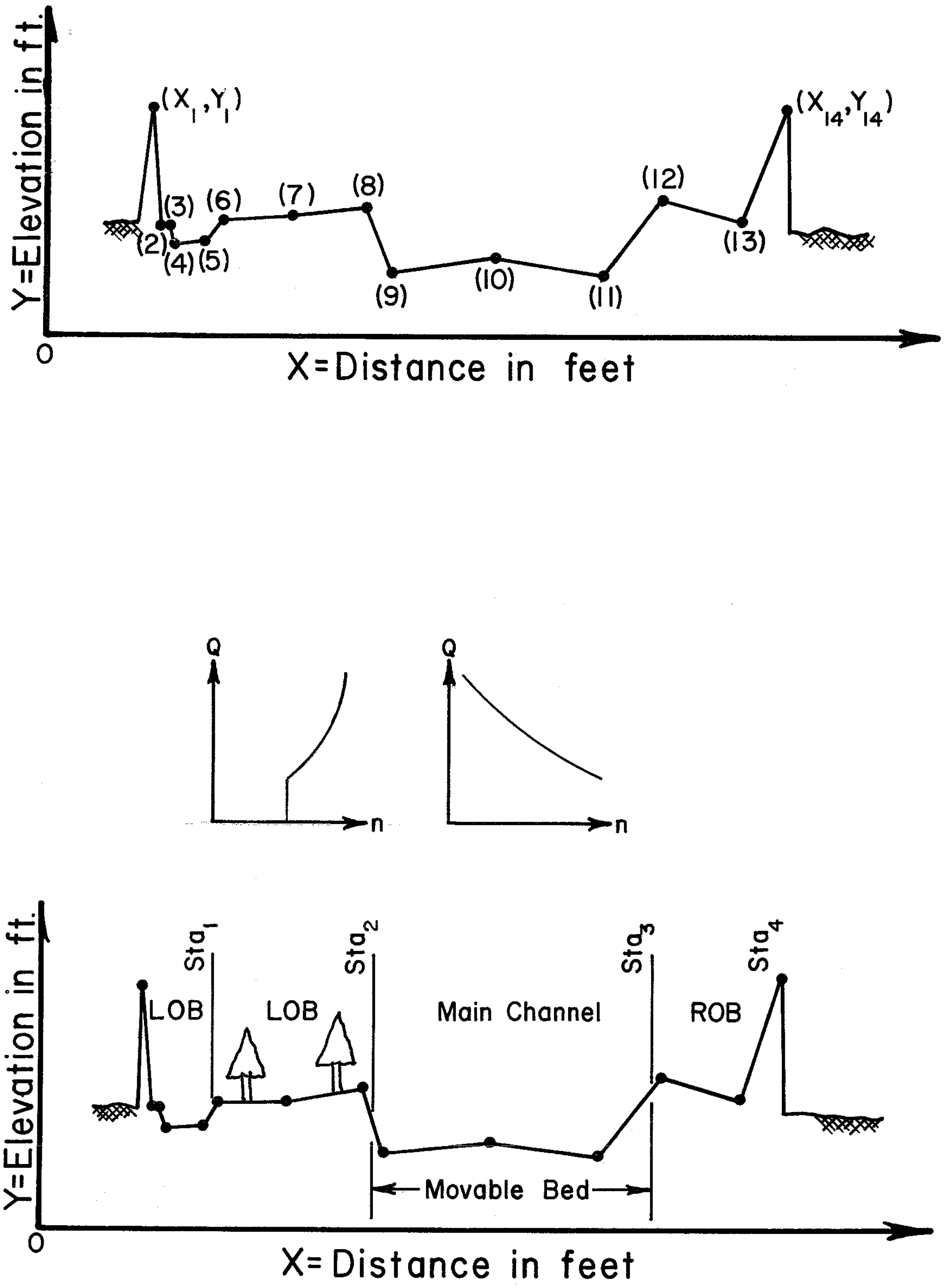


Fig. 5.05. Modeling Complex Cross Sections

roughness depends on both the grain size and bed form. The assumption is that, as the new equilibrium bed is approached, both grain size and bed form will return toward those existing in the natural state. One should evaluate the sensitivity of such an assumption by varying the n-value. Better hydraulic roughness theories, than are presently available are needed.

Table 5.06 shows the type and level of detail available for describing the inflowing sediment load. Both bed load and suspended load are considered. This table corresponds to a water discharge of 100,000 cfs. In the actual study similar information was developed for water discharges varying from 5000 to 200,000 cfs. Neither of the rivers entering the reservoir are high contributors of sediment. The Clearwater, for example, conveys only about 100 acre feet a year and the Snake produces only about 320 acre feet per year. Nevertheless, over the project life, both streams have the potential of depositing a sufficient depth of material to make a substantial impact on the water surface profile elevation for the levee design flood. Another point about the inflowing sediment load relates to the relative amounts of bed load and suspended load. Since the bed load comprises only about 2 percent of the total inflowing load, one is tempted to rely only on suspended load measurements and neglect the bed load altogether. However, for a water discharge of 100,000 cfs, calculations show that 90 percent of the gravel (bed load) deposits upstream from mile 2.6 and the sand does not deposit until the flow reaches about mile 2, fig. 5.06. This

Table 5.06. Distribution of Sediment Load by Grain Size Class

Clearwater River

Water Discharge, cfs 35,000

Total Bed Load, tons/day 130 (1)
Total Suspended Load, tons/day 1500 (1)
Total Sediment Load 1630

Grain Size (1) Diameter mm	Classification	Percent of Total Bed Load ÷ 100 (2)	Bed Load tons/day	Percent of Total Suspended Load ÷ 100(3)	Suspended Load tons/day	Total Load Col. (4) + (6) tons/day
(1)	(2)	(3)	(4)	(5)	(6)	(7)
< .0625	silt & clay	.04	.05	.54	810	810
.0625 - .125	VFS	.10	.13	.10	150	150
.125 - .250	FS	2.75	4.0	.13	195	199
.250 - .500	MS	16.15	21.0	.19	285	306
.500 - 1.000	CS	13.28	17.0	.04	60	77
1.000 - 2.000	VCS	1.19	2.0			2
2 - 4	VFG	1.00	1.0			1
4 - 8	FG	1.41	2.0			2
8 - 16	MG	2.34	3.0			3
16 - 32	CG	6.33	8.0			8
32 - 64	VCG	23.38	30.0			30
> 64	cobbles & larger	32.03	42.0			42
Total		1.0	130.18	1.0	1500	1630

Note: (1) Values were read from the "Sediment Load" curve, 1972-74 measurements.
(2) These values were calculated by analyzing measured hydraulic parameters and measured bed loads using the computer program "Total River Sand Discharge and Detailed Distribution" by F. B. Toffaleti.
(3) These are representative values determined graphically by plotting the results of sieve analyses and developing a single, percent finer curve from all samples analyzed.

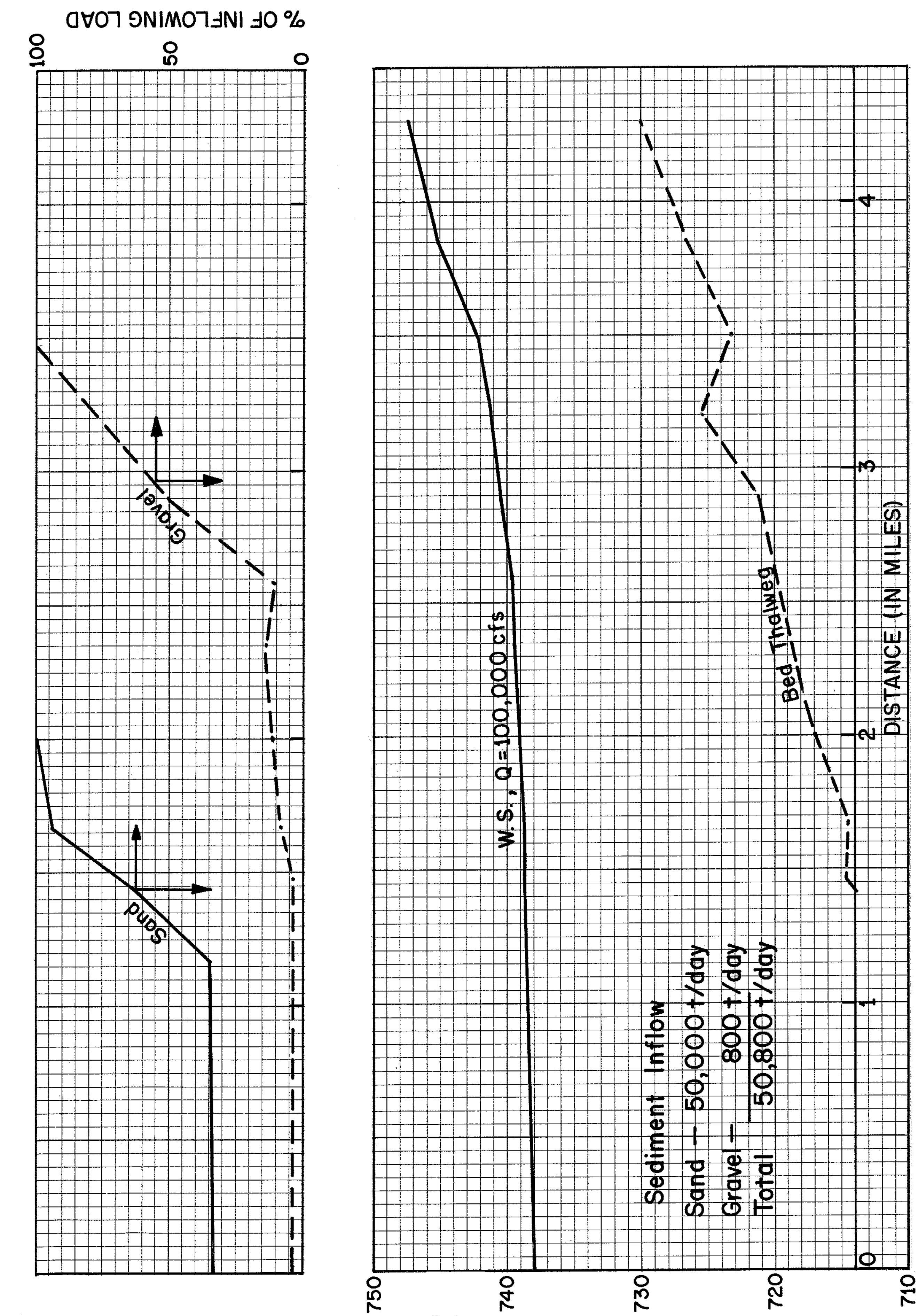


Fig. 5.06. Hydraulic Sorting as Flow Enters a Reservoir

sorting of grain sizes is particularly significant over the life of the project where the volume of bed load will be sufficient to make a substantial impact on the water surface profile and must therefore be identified separately.

The gradation of the stream bed is not particularly significant in deposition studies since that gradation is being continually changed by the material depositing. In fact, gradation of the stream bed and the detailed information on inflowing sediment load, shown in table 5.06, are redundant information. One is not free to specify both the gradation in the stream bed and the detailed information about the sediment inflow since the two data sources are linked together by sediment transport theory. Therefore, rely on measured bed material loads and not on values calculated from bed gradation curves.

In most studies, bed load measurements are not available and the bed load is calculated by measuring gradation of the stream bed. This technique, when attempted for this study, produced an amount of bed material load equal to twice the measured amount. However, because of the great variability in grain sizes deposited on the bed, this factor could have just as easily been 10 or 20. This problem is acute in armored streams such as the Clearwater and the Snake, because their capacity to transport sediment far exceeds the supply of sediment available. The computations become quite sensitive to the percentage of material in the bed, and it is extremely difficult to sample a bed for which the grain size ranges from very fine sand to cobbles and larger and have any assurance that the sample is representative of the entire bed. Therefore, in initial problem areas such as this involving levees in an urban area, measure all the data presented in table 5.06.

The inflowing water discharge hydrograph was analyzed in periods varying from one day during the peak flood season up to monthly values during the period of low flow. A sample period is shown in fig. 5.07. Water temperature was obtained from records at a nearby stream gaging station and the operating policy of the reservoir was specified, in this case, to be a constant pool elevation 738 for the entire 50 years of water discharge hydrograph.

The results of the analysis are shown on fig. 5.08, Deposition in Lower Granite Reservoir. In addition to calculating the average bed profile and the resulting impact on the levee design flood profile, the simulation technique calculated the trap efficiency over the 50 year life of the project to be 30 percent. Also, the amount of maintenance dredging required to support navigation up to mile 2 was calculated. Other simulation runs were made to test the impact of the maintenance dredging on both the sediment deposits and the water surface profile.

Section 5.07. Impact of Natural Aggradation Trends

Using a simulation technique, such as the Scour and Deposition program in Appendix VII, to calculate the distribution of sediment deposits

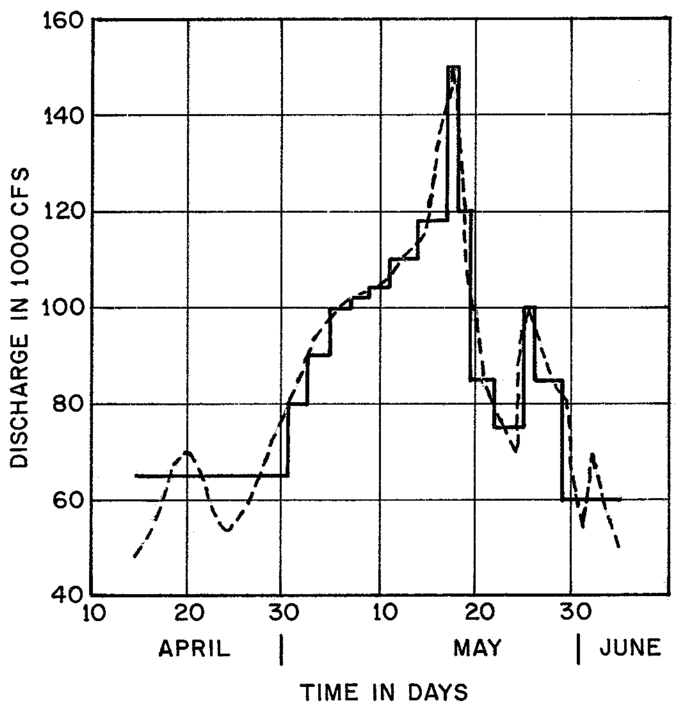


Fig. 5.07. Standard Project Flood

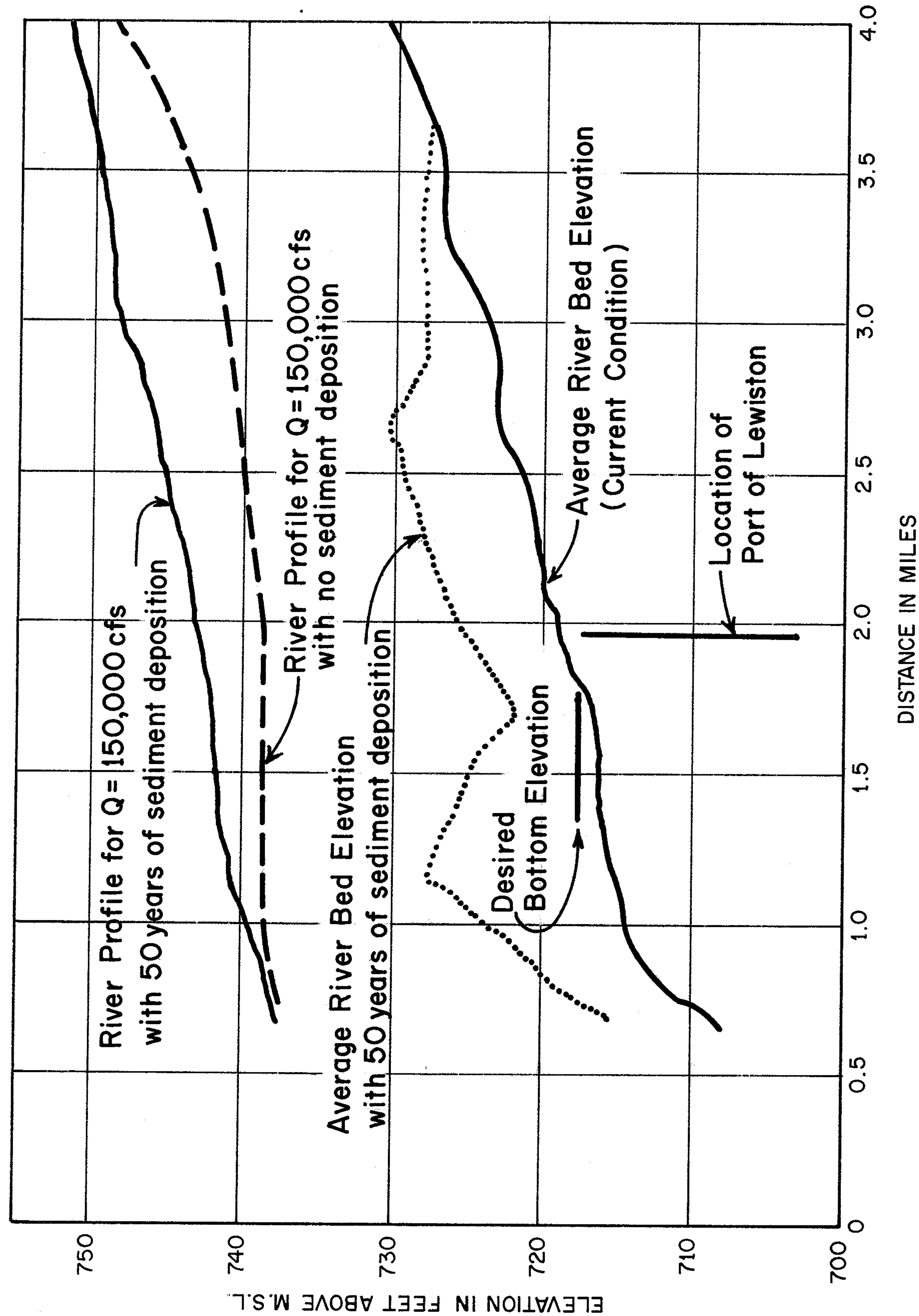


Fig. 5.08. Deposition in Lower Granite Reservoir

in a reservoir requires a three step procedure. The first step is to calibrate the model to the particular problem area. The second step is to perform a base test. This is a test which demonstrates that the simulation technique and the calibrated digital model can duplicate the behavior of the study reach during a historical period. The third step is to run the desired studies.

In performing the base test it often becomes apparent that the study area is a natural point of aggradation even without a reservoir project. This does not imply that the reservoir, when impounded, will trap an extraordinarily large amount of sediment. Two points should be made. In the first place, sediment yield from the watershed has the greatest impact on the amount and distribution of deposits in a reservoir. In the second place, aggradation trends in natural rivers should not be associated with geologic time. Reaches will tend to aggrade for a time and often the trend will reverse and they will degrade. Therefore, the analysis of sediment deposits for a potential reservoir site which demonstrates natural trends of aggradation may be made using the simulation techniques presented in the previous section and in the same manner. However, extra care should be taken to establish why such a trend exists. Perhaps it reflects a recent increase in sediment yield from the basin in which case historic yield curves should be modified accordingly.

Section 5.08. Impact of Upstream Reservoirs in the Basin

It is important to identify and locate any reservoirs in a basin where a sediment study is to be made. The projects upstream from the point of analysis potentially modify both the sediment yield and the water discharge duration curve. Both are very significant.

The date of impoundment is essential information. With this, one may coordinate observed inflowing sediment loads with whatever conditions existed in the basin during the periods selected for calibration and verification.

Useful information on the density of sediment deposits and the gradation of sediment deposits are often available from other reservoirs in the basin. Finally, other reservoirs offer a check on sediment yield.

Section 5.09. Erosion Control Measures

Erosion control measures refer to land use and farming practices in the basin. One is always a bit uncertain about how much credit to give erosion control measures when projecting sediment yield into the future. It is very likely that no credit should be given for the sand sizes and larger material. On the other hand, the silt and the clay sizes of material may undergo reduction by erosion control measures. Over the long run, it will be the management of those measures that insures they will continue to be effective.

Farming practices conducive to erosion control were implemented many years ago. Construction and industrial practices, on the other hand, are just now beginning to implement erosion control measures. Possible techniques are in the form of mulch, of seeding disturbed land surfaces, of stabilizing the soil with chemicals and of utilizing terraces and sediment traps to prevent material from entering the natural stream system. Any one construction project is going to be short lived compared to the life of a water resource project. However, many areas undergo continual construction activity and one cannot ignore the impact this has on sediment washing into the natural stream system. Potential increases of 50 to 100 times natural erosion rates can be associated with construction activities.

Section 5.10. Land Use Changes in the Basin

Land use can impact directly on sediment yield from the basin. For example, land being converted from pasture or forested area to row crop area can generate 10 to 20 times more sediment runoff. In most sediment studies it is customary to project existing land uses through the life of the project. That is, unless some explicit alternative future is being considered, the sediment yield from the watershed is considered to remain constant over the life of the project. A recent example where land use impacted substantially on sediment yield occurred when forested land was converted to strip mining. Because of the close proximity to the main channel, the impact of this land use change was manifest immediately by an increase in the sediment being deposited in a local reservoir.

Section 5.11. Reservoir Sedimentation Ranges for Post Project Surveys

Cross sections should be located as for water surface profile calculations. These define points of contraction and expansion and points where bed change is expected or is existing. Many, but not necessarily all, of the same points would be valuable for use in monitoring the rate of sediment deposition in the reservoir. Permanent ranges, called sediment ranges, are usually established for this purpose. It is essential that these ranges be periodically surveyed at the same location. Therefore, permanent range markers should be installed to insure the range can always be located. It is always feasible to discontinue ranges that prove to be non-descriptive, but beware of the tendency to establish too few. Simulation studies provide useful guidance in establishing sediment ranges.

The frequency of which reservoir ranges are resurveyed depends on how much sediment deposition is occurring. In the initial operation of a project, annual resurveys are essential. Later on, as the reservoir delta develops, the change in delta elevation from one year to the next is not substantial and five or perhaps even more years may lapse between resurveys.

The volume of sediment deposits is readily determined by analyzing successive surveys of the sediment ranges. However, it is essential to know the inflowing water discharge, temperature, the inflowing sediment load, gradation of material in the inflowing sediment load and in the deposits, and the operating levels of the reservoir in order to utilize data collected from sediment range surveys to verify or improve analytical techniques. This is an important step in a project and one which is usually omitted because study funds are not available once the project goes into operation. Those responsible for the operation and maintenance of projects are urged to establish a procedure by which the testing of analytical techniques can be accomplished as data becomes available during the life of the project.

Section 5.12. Channel Behavior Downstream from the Dam

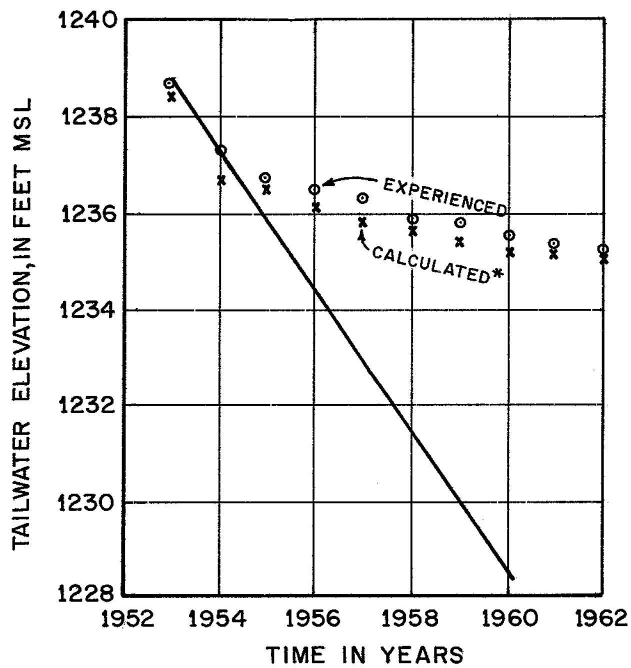
Degradation lowers the stream bed and, consequently, the tailwater rating curve at the dam. This is important from the standpoint of the dam foundation in the case of structures built on piling, and also with regard to impact on stilling basin performance. An important aspect of degradation studies is to locate the extent of degradation downstream from the dam. Rock outcrops or other hard bottom controls may reduce the vertical amount of degradation, but not the distance over which degradation problems exist. This distance is controlled by the modified flow duration curve and availability of bed material to replenish material removed by the reservoir.

The computer program, "Scour and Deposition in Rivers and Reservoirs," develops the armor layer by the selective removal of the finer grain sizes from the bed. Coarser sizes are removed at a much slower rate according to transport equations, and as a result the coarser sizes collect on the stream bed as degradation continues. The coarse particles shield the finer particles underneath and reduce the rate of degradation. The program may be used to calculate both the distribution of deposits in the reservoir and degradation of the channel downstream from the dam in one continuous analysis. This is particularly useful when some sediment passes the dam.

Degradation studies are more complicated than the calculation of deposition in reservoirs because degradation studies encompass both degradation and aggradation as flow passes from one reach to another in the natural river downstream from the dam. Nevertheless, the scour and deposition program provides a tool which is proving to be very useful for analyzing degradation problems as illustrated in fig. 5.09.

The degradation anticipated downstream from Ft. Randall Dam was arrested by armoring of the bed surface. The size of sediment in the armor layer composed less than five percent of the coarsest material sampled in the natural stream bed. Once established, flow regulation prevented the armor from being disturbed.

A rock outcrop or another reservoir is often suggested as a location for establishing the downstream end of a degradation study area.



* USING THE COMPUTER PROGRAM, " SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS."

NOTE: BASIC INFORMATION FROM U. S. DEPARTMENT OF AGRICULTURE, PROCEEDINGS OF THE FEDERAL INTER-AGENCY SEDIMENTATION CONFERENCE, MISCELLANEOUS PUBLICATION NO. 970, 1963.

Fig. 5.09. Degradation Downstream From Ft. Randall Dam

Certainly a reservoir is appropriate. However, a rock outcrop only limits the magnitude of degradation upstream from it and not the downstream migration of the degradation process. Two points are worthy of consideration relative to degradation studies.

The first is concerned with magnitude. A rock control does not stabilize the upstream bed at the elevation of the control. Bed material will be scoured upstream from the control until flow energy is in balance with resistance of the remaining bed material.

The second point concerns migration of channel degradation past the rock control. If other structures, such as bridge piers, water intakes, or diffusers, or if tributaries are present along the stream, the downstream extent of the degradation study area should include these. A sufficiently long reach should be established to include the transition from degradation to aggradation commonly observed downstream from existing projects.

It is possible that no degradation will occur. In fact, a reduction in channel capacity has been observed in numerous cases. This implies aggradation is occurring, and probably to narrow the channel in response to the modified flow duration curve. In other cases, the modified peak discharges lose transport capacity at major tributary junctions causing aggradation.

Chapter 6

Aggradation and Degradation in Free Flowing Streams

CHAPTER 6. AGGRADATION AND DEGRADATION IN FREE FLOWING STREAMS

Section 6.01. Introduction

The terms aggradation and degradation generally refer to trends in behavior of the stream bed profile. An aggrading stream is one on which the bed profile is tending to become steeper, whereas a degrading stream is one for which the bed profile is tending to become flatter.

Streams aggrade or degrade in discrete reaches. The process alternates between aggradation and degradation as the flow passes from one reach to the next. The fact that a reach of a river scours during the passing of a flood event does not make that a degrading reach. A degrading reach is one which projects a net lowering of the bed elevations with respect to time or, perhaps, a net widening of the river channel with respect to time. The rate at which aggradation proceeds depends on sediment yield, water yield, and grain size of sediment particles.

These discrete reaches are not fixed in space. They tend to shift back and forth with respect to time, with respect to the magnitude of water discharge and with respect to land use changes. Land use changes are important because they generally impact on sediment production from the basin. Other changes which are equally important are the construction of reservoir projects in the basin and modification of the water discharge duration curve (by interbasin transfer of flow or reservoirs).

Interbasin transfer of water is usually associated with large scale projects. However, this same concept is applicable, and the consequences more obvious, on small scale projects such as the construction of subdivisions, or other urban developments. Natural runoff patterns are altered, flow is collected into drains and other conveyances and degradation problems occur when these flows return to minor, natural conveyance channels.

In terms of Chapters 1 and 3 of this volume, the flow duration curve has been altered from that naturally forming the conveyance channel.

Section 6.02. Degrading Reaches

The obvious explanation as to why a reach degrades is that the inflowing sediment load is too small for the transport potential of the stream through this reach. The reach is providing a sediment supply for downstream points. Intensive meander is generally not associated with a degrading reach but rather the tendency is for the stream to become incised and perhaps to develop cutoffs.

The magnitude of degradation is arrested by several mechanisms. A rock outcrop or sill across the stream will tend to stabilize the bed. The development of an armor layer has the same effect. Oftentimes, the hydraulic conditions downstream from the degrading reach will change due to a downstream aggradation condition and this influence extends upstream. The classical examples of degrading reaches occur downstream from dams.

The stability of sediment material is often associated with tractive forces in accordance with the following figure. Tractive force is defined as

$$T = \gamma DS \tag{6-01}$$

where

D = water depth

S = energy slope

γ = unit weight of water

It should be pointed out that degradation is a function not only of the stability of material on the stream bed, but also the amount of the inflowing sediment load. A stream bed can be in equilibrium because material is being deposited as rapidly as it is being removed. The tractive force concept does not identify this type of equilibrium condition.

Section 6.03. Aggrading Reaches

The problem causing aggradation is just the opposite of that causing degradation. Reaches aggrade because the inflowing sediment load is greater than can be transported out of the reach by the hydraulics of flow. A tendency to meander is oftentimes associated with an aggrading reach, especially in streams having fine sediment with a non-cohesive bed and banks. Flow passing through an aggrading reach causes hydraulic sorting of grain sizes. Therefore, there is always

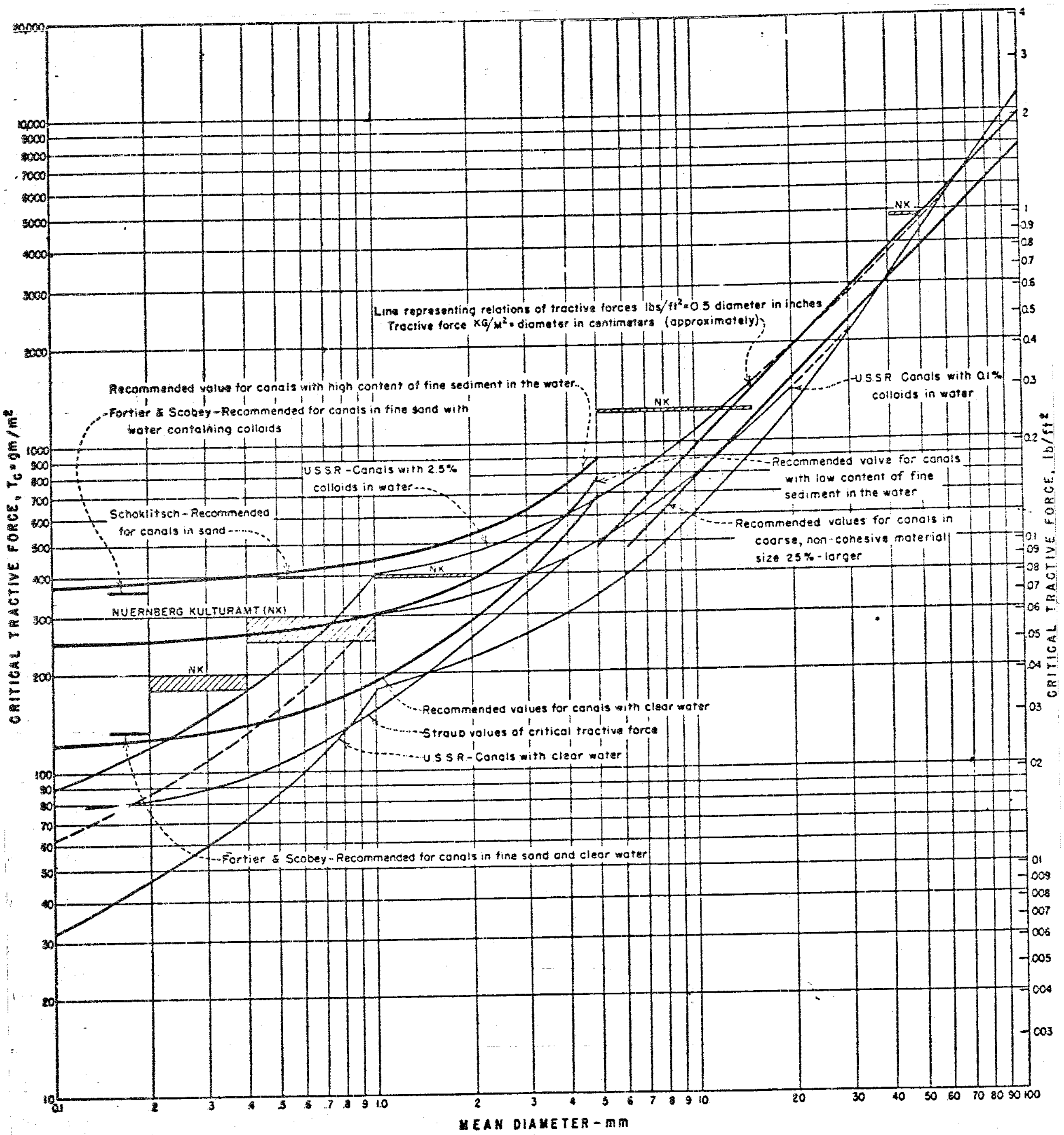


Fig. 6.01. LIMITING TRACTIVE FORCES RECOMMENDED FOR CANALS AND OBSERVED IN RIVERS

a deficiency of the coarser sizes as flow leaves the downstream end of the reach. The aggrading reach provides a temporary stopping place for sediment material moving downstream.

Aggradation is arrested by reducing the inflowing sediment load, by sorting to produce smaller particle sizes in the water-sediment mixture and by shifting in the downstream control due to a degrading condition at a downstream point.

Section 6.04. Shifts in the Stage-Discharge Rating Curve

Trends in the stage-discharge curve are good indicators of reach behavior. In alluvial streams, these curves typically exhibit a wide scatter of data which should not be construed as sample error. The range in scatter, between high and low data, is more appropriately attributed to aggradation, degradation, changing bed forms in the stream channel, or sediment transport rates produced by water temperature variances. The growth of natural levees will increase the discharge at which overbanks become effective. These factors should be considered in utilizing the stage discharge rating curves in the design of engineering projects, such as levees. It is not appropriate to develop an average line of best fit through the data, but rather an upper envelope curve is more appropriate for use in calculating the height of levees. Navigation depth and rip rap design, on the other hand, should utilize a lower envelope curve through the scatter of points. If the analysis of curves developed from successive years of stage-discharge data demonstrates a trend, then subsequent design studies must project the impact of this trend on project design.

Periodic measuring of profiles across the river will identify trends in lowering of the bed or enlargement of the channel. A meander does not represent an enlargement of the channel since both banks are shifting in the same direction. An enlargement of the channel would be represented when the two banks shift farther apart.

Section 6.05. Analysis of Aggradation and Degradation

The method for analyzing aggradation and degradation presented in Appendix VII of this volume is a movable bed, digital model. It can be compared with a fixed bed digital model as shown in figs. 6.02 and 6.03. Relative to fig. 6.02, if the topography of the river valley is known and the hydraulic roughness is known, the engineer may specify a water discharge and starting elevation, and he may then calculate the water surface profile. It is a direct calculation; there is no feedback such as that shown in fig. 6.03 by the double arrows. In fig. 6.03, sediment load has been added, and additional information on hydraulic roughness results. There is a great deal of uncertainty about how to predict the change in bed form and resulting impact on n-values, but it is at this point that the computer program presented in Appendix VII breaks into the loop for movable bed calculations. Basically, in utilizing that program, the assumption is made that n-values are either constant or they vary in the vertical with water discharge. The basic assumption, then, is that bed form can be related to water discharge.

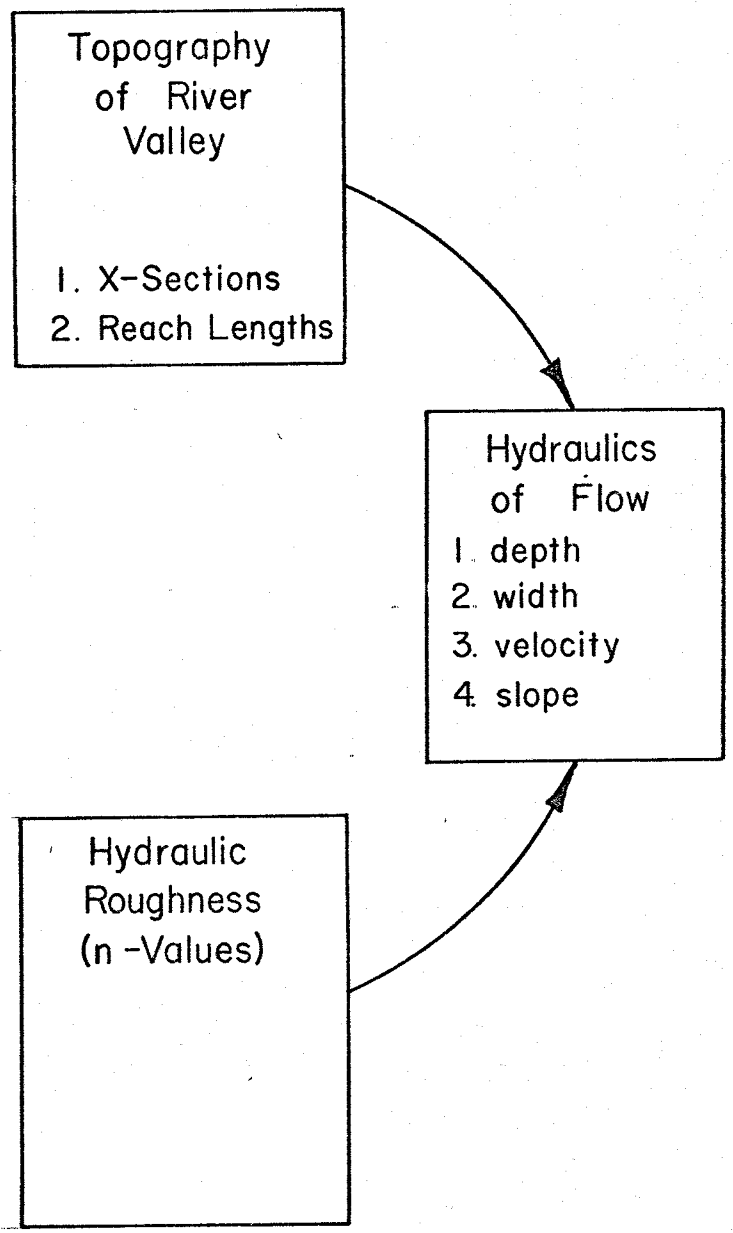


Fig. 6.02. FIXED BED MODEL

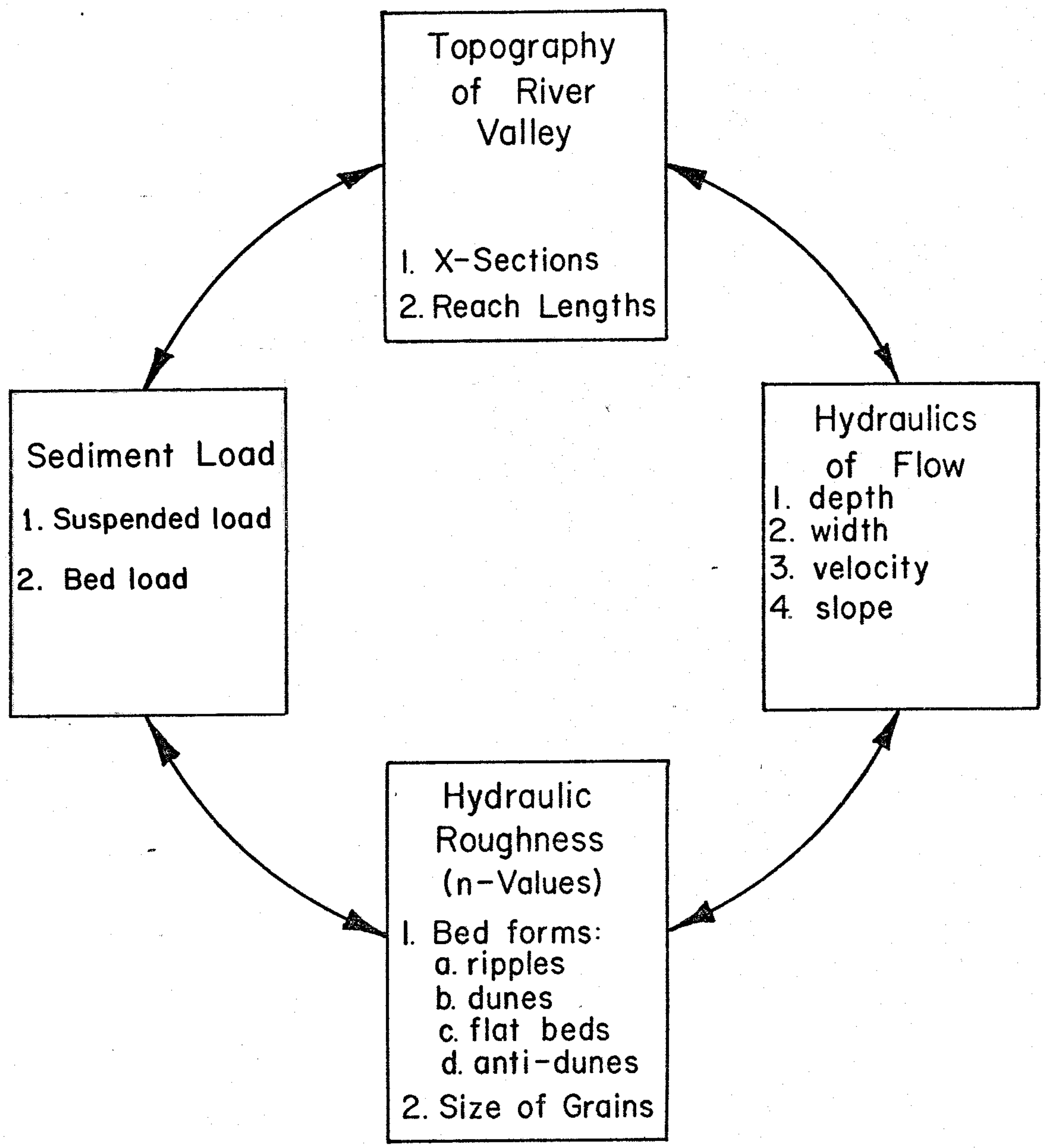


Fig. 6.03. MOVABLE BED MODEL

In proceeding with the analysis of aggradation or degradation, it is essential to follow the same guidelines given in Chapter 5.

1. Calibrate to an observed field condition
2. Verify that the calibrated digital model will reproduce the behavior of the river during a period of time, and
3. Analyze the degradation problem at hand.

Analysis of mobile boundary problems in free flowing streams adds a great deal of complexity to sedimentation studies. Input data is essentially the same as required for reservoir deposition studies; however, having the capability for aggrading and/or degrading complicates the calibration and base testing phase of studies. In summary, the required input data are as follows:

Initial channel geometry including a detailed description of natural levees along the channel

Water discharge hydrograph

Inflowing sediment load curve

Gradation of material in the stream bed

Water temperature

Sediment transport formula

a. Calibration of the Simulation Model

It is essential to calibrate the water surface profile calculations just as for a fixed bed study. The techniques are the same. A range of discharges varying from a low, in channel, discharge to the peak flood of interest should be analyzed to calibrate the n-values as the first step.

In fixed bed studies, one does not have to concern himself with the distribution of flow between the channel and the overbanks as long as the distribution is reasonable. In movable bed studies, it is a portion of the flow which travels in the channel that transports the bed material. For this reason, it is essential that the correct distribution of flow be known. Two parameters that may be evaluated are (1) cross section shape itself, especially the elevation at which water spills onto the flood plains and (2) the distribution of n-values between channel and overbank. This n-value information is seldom ever known; therefore, it becomes a matter of judgment to select the proper n-value for channel and for overbanks.

The third major item in the calibration is to determine and calibrate the inflowing sediment load. The amount and also the distribution with respect to grain size must be determined. The final type of data requiring calibration is the gradation of material in the stream bed.

The magnitude of water discharge selected for use during calibration is very important. If the flow is too low, the simulation model simulates a low water bed which often will have aggradation and degradation trends that do not appear to match the behavior measured in the prototype cross sections. If the water discharge is too large, aggradation and degradation trends may shift from those observed in the low water bed, but again they may persist in a manner that does not follow the overall behavior of the prototype. In order to simulate the behavior of the prototype over a period of time, one might consider using the dominant discharge as presented in Section 3.06.

It will be necessary to evaluate the water surface profile computations for discharges both higher and lower than this dominant discharge. However, primary emphasis may be placed on the dominant discharge to calibrate the inflowing sediment load, distribution by grain size in the inflowing load and the representative gradation of the bed surface itself.

The dominant discharge transports considerably more sediment material than the average daily volume, and therefore it is necessary to ratio the time scale to simulate the correct volume of sediment material moving during a year. This is quite straightforward once the total sediment yield and the sediment load associated with the dominant water discharge are known. It should be pointed out that sediment volume calculations are related to the total sediment load carried by the dominant discharge and not just the bed load when calculating a time scale.

By definition of dominant discharge one expects the calculated behavior of the river channel to follow the same trends as observed in the prototype. If this is not the case, one must re-evaluate analytical model calibration for n-values, the amount of material in the inflowing sediment load, the distribution by grain size of material in the inflowing sediment load, and the gradation of material in the stream bed.

These calculations assume the flow is distributed properly between the channel and overbanks. The dominant discharge itself is an inbanks flow. It will be a rather high flow, approximating that of bank full, oftentimes. Specifying cross section geometry such that natural levees are simulated is critical in this calibration study. If at one point or another the water discharge does flow into the overbanks, the correct distribution of n-values between the channel and the overbanks is essential. A representative geometry and the proper distribution of n-values must be developed before problems with sediment transport may be resolved.

The following performance criteria is suggested for use in determining when a model is properly calibrated. For a discharge equal to the dominant discharge, trends in stream bed elevation should approximate the behavior of the prototype. That is, degradation trends in the analytical model should correspond in magnitude and location to those in the prototype and, likewise, aggradation trends in the model should correspond in magnitude and location to those in the prototype. The sediment load moving from point to point in the model may vary a great deal. However, at points corresponding to gage locations, the sediment load passing should match that observed in the prototype. Once the model is calibrated for the dominant discharge, it is necessary to test performance at a high discharge and at a low discharge. One can only check n-values and distribution of flow since, for any single discharge other than the dominant discharge, the model will not necessarily respond to the trends observed in the prototype. Calibration is completed with this phase of testing.

b. Base Test

The next step in problem analysis is to verify that the calibrated model will reproduce behavioral trends observed in the prototype. This implies knowing a starting condition, calculating over a period of time, and comparing the results of the calculations with an ending condition in the prototype. Often, there are not enough data to identify a starting and an ending condition. In these cases, complete model verification is not possible. There are oftentimes trends that one can observe. For example, the magnitude of any scour or deposition should approximate that observed in the prototype and the calculated gradation of the bed surface should match that observed in the prototype.

The process of making small adjustments in the model data in order to achieve verification is often called fine tuning. It is in this phase of problem analysis that the engineer's understanding of river morphology is most essential. Any of the variables in the input data are susceptible to manipulation to some degree or another. However, adopted values must be reasonable and within the range of normal engineering experience. After the engineer has verified that the model can reproduce observed events, the study is ready to proceed to the third and final phase.

c. <u>Production Run</u>

It is most important that results from problem analysis be compared with the base test results established in the verification runs. This comparison will usually give a better response than absolute magnitudes of values calculated in the production run. The value of simulation is that any of the input data can be modified and the impact measured directly on either stream bed aggradation and degradation or the water surface profile elevations.

Section 6.06. Sediment Movement in Urban Conveyance Systems

Typically, urban conveyance systems for storm water runoff consist of storm drains in pipes interconnected with open channels. On the fringes of urban areas it is not unusual for flow to be collected into a well designed conveyance system in a subdivision only to pass out into a natural channel of limited capacity which becomes taxed with having to transport considerably more water than before the subdivision was constructed. Erosion of the natural channel is accelerated. These small conveyance channels obey the same regime concepts as those discussed earlier for larger rivers.

Deposition in the urban conveyance system itself is a common occurrence. Typical criteria for designing conveyance systems specify that velocities and/or bed shear stresses will be sufficiently high to prevent material from depositing in the section. Tractive force is a typical design criteria. As discussed in paragraph 6.02, tractive force alone is not sufficient to determine if sediment will deposit. Tractive force is a parameter for determining transport capacity; whereas deposition depends on both the transport capacity and the sediment yield from the basin.

Because of the large amount of construction activity in urban areas, there is always an abundance of sediment material available for washoff. When the rate of washoff exceeds the transport capacity of the conveyance system, deposition results, and the conveyance system takes on the characteristics of an alluvial stream in which the bed slope is in balance with sediment material in motion. Appropriate construction practices, including mulching, seeding, terracing, chemical applications and detention storage ponds, will help to reduce the deposition problem.

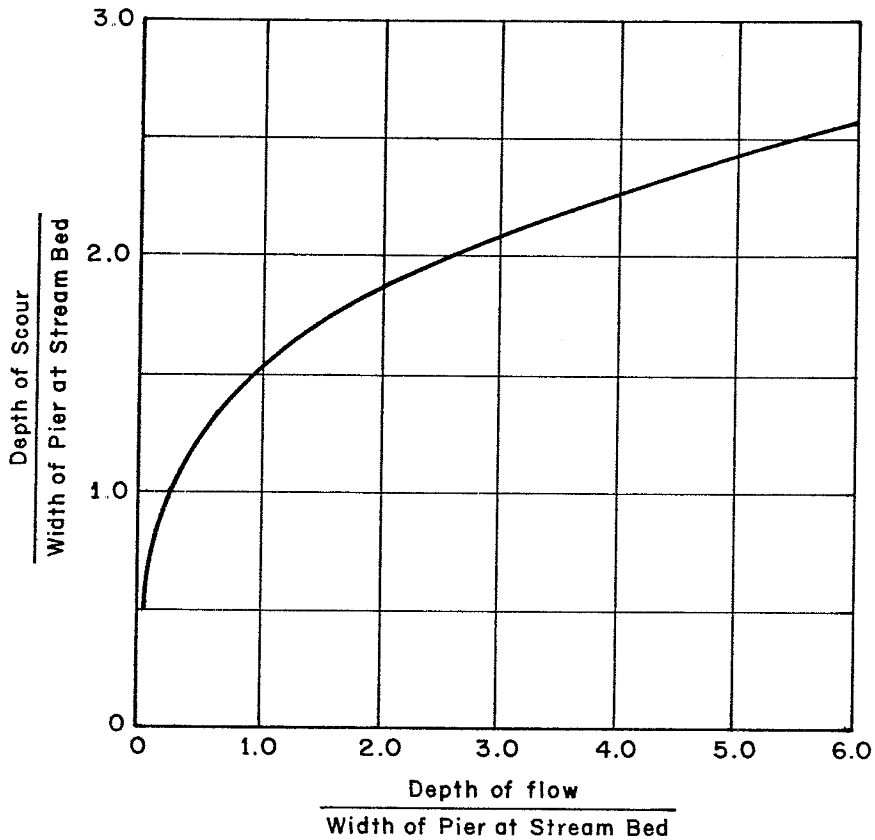
The analysis of sediment problems in urban drainage conveyance systems follows the same procedures discussed earlier for aggradation and degradation of free-flowing streams. Again, the two primary components of the problem are the determination of sediment yield and the calculation of sediment transport in the conveyance system. The sediment yield calculations are more complex than those for a major river because the conveyance system is much closer to the source of erosion and therefore the spatial distribution of sediment becomes an important consideration. Transport, on the other hand, follows the same physical laws as that in large rivers. Transport theory cannot be applied directly since there is usually no bed gradation. However, it can be calculated using procedures such as the Scour and Deposition program in Appendix VII.

One technique for calculating land surface erosion is the universal soils loss equation presented in Chapter 2 of this volume. The major disadvantage of this technique is that transport of the sediment material is not included in the formulation. Yet, one application of the equation quickly demonstrates that erosion of the land surface is not synonymous with sediment yield from the basin. Therefore, an additional factor called the sediment delivery ratio is necessary in order to convert from land surface erosion to sediment yield at the outflow point. All of the considerations of sediment transport are included in this sediment delivery ratio factor. A better procedure would be to couple this soil erosion equation with the sediment transport models and eliminate the need for the sediment delivery ratio factor.

The use of sediment detention basins requires analytical techniques that permit the design of the size of the basin to effect a prescribed trap efficiency. The detention-time trap efficiency concept is appropriate for deposition in the sediment basin, however, grain size of the sediment material is an important consideration, (reference 9).

Section 6.07. Local Scour at Structures

The difference between scour and degradation lies in the extent, and the trend with respect to time, of changes in the stream bed elevation. Laurson and Tock (reference 11) demonstrated that grain size was not a major factor in the magnitude of scour around bridge piers and abutments, but rather the dimensions of the pier, its alignment with respect to the flow and its shape were the important parameters. Their basic relationship is shown in the following figure, and their concept is presented in the next few paragraphs.



Feg. 6.04. Scour Around A Pier

In using this design curve, the following information on angle of attack is pertinent:

"Local scour at piers. All of the available data were adjusted to scour conditions at a zero angle of attack for a rectangular pier and plotted non-dimensionally as equilibrium depth of scour against depth of flow with the width of pier at stream bed used as the repeating variable. The design curve was drawn somewhat conservatively and represents the predicted local depth of scour for a rectangular pier, the sides of which are aligned with the current, as a function of the depth of flow and the width of the pier at stream bed.

In the laboratory investigation it was found that the angle between the axis of the pier and the direction of the current is more important than any other geometric detail of solid or webbed piers. If the pier is skewed to the current, the scour depth predicted must be multiplied by a factor greater than unity. Values of this factor K_{a1} are presented as a function of the angle of attack and the length-width ratio of the pier at stream bed." (Reference 11, p. 42)

Angle of attack and pier shape information are shown in the following figure and table.

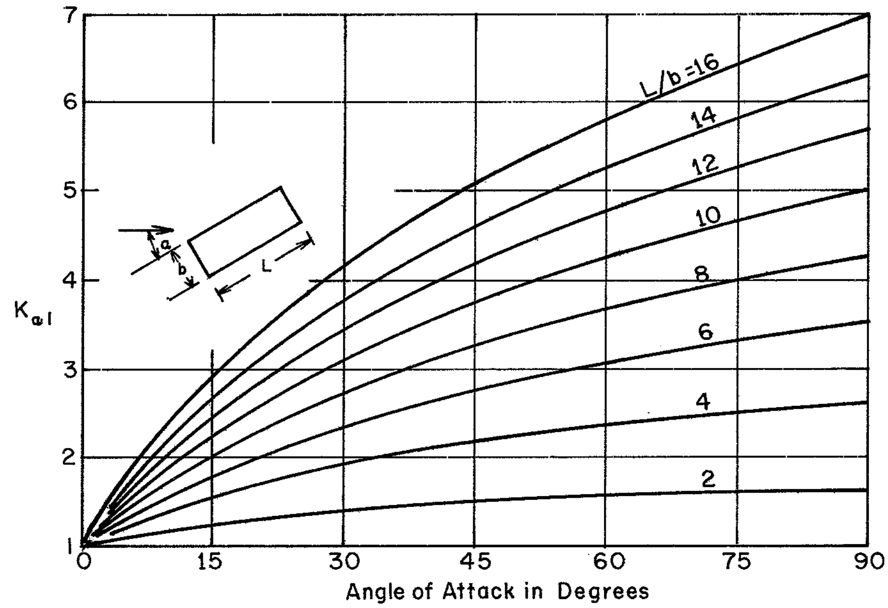


Fig. 6.05. Multiplying Factor for Angle of Attack

TABLE 6.01.

Shape coefficients K_s for nose forms

(To be used only for piers aligned with flow)

NOSE FORM	LENGTH-WIDTH RATIO	K_s
Rectangular		1.00
Semicircular		0.90
Elliptic	2:1	0.80
	3:1	0.75
Lenticular	2:1	0.80
	3:1	0.70

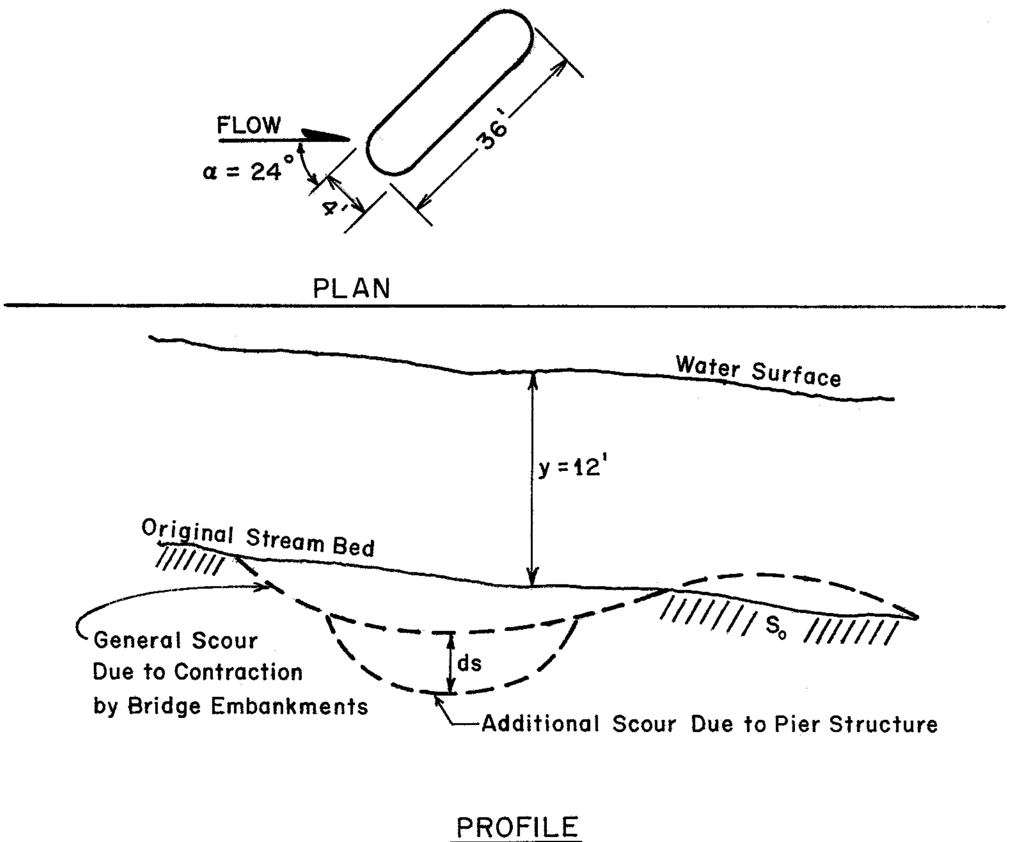


Fig. 6.06. Scour at Bridge Piers and Other Obstructions

Consider, as an example application, fig. 6.06 which shows a round nose pier having a width of four feet and located at an angle of 24° to the approaching flow. The pier is 36 feet long. The water depth, corresponding to a flood frequency of 25 years recurrence interval, is 12 feet.

Entering fig. 6.04 with y/b equal to 3.0 results in a ratio of d_s/b equal to 2.1. Adjusting for pier angle requires entering fig. 6.05 at 24° with a L/b ratio of 9. The resulting correction factor is 2.6.

The depth of scour can now be calculated as

$$\begin{aligned} d_s &= K_{a1} \cdot (d_s/b) \cdot b \\ &= 2.6 \cdot 2.1 \cdot 4 \\ &= 22 \text{ ft.} \end{aligned} \tag{6-02}$$

Note that the pier shape coefficient, K_s, is only utilized when the angle of attack is zero.

This water depth does not necessarily cause the most severe condition of scour. In fact, a range of depths should be tested. The following table presents the probability of at least 1 occurrence of the design flood during the design life of a structure. (Reference 11, page 46).

Table 6.02. Chance of 1-Occurrence of the Design Flood

Design Life, Years	Exceedance Frequency, Years 25	50	100
25	.64	.40	.22
50	.87	.64	.39
100	.98	.87	.63

These data are useful for interpreting the relative severity of the scour problem when a range of floods is utilized.

Turbulence in the flow has a major impact on scour. However, just the effect of the pier on concentration of flow is substantial. When the unit discharge increases due to deflection of flow around the pier, point velocities also increase. This redistribution of flow contributes substantially to the local scour problem. The design curves presented earlier contain the impact of both turbulence and the redistribution of flow on scour depth.

The Scour and Deposition model in Appendix VII is not appropriate for use in determining the scour around bridge piers. It is useful, however, for establishing the stream bed elevation between the bridge abutments. The magnitude of local scour due to the presence of the pier is in addition to and measured relative to this general bed elevation between the bridge abutments.

Appendix 1

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Appendix 2

Notation

a	Shortest axis of a sediment particle.
A_B	Cross sectional area of channel flow.
b	Intermediate length axis of a sediment particle or pier width or diameter for local scour calculations.
B	Top width.
c	Longest axis of a sediment particle.
C	Factor for converting ppm to mg/l.
C_d	Drag coefficient.
C_f	Cropping factor in the Universal Soil Loss equation.
C_s	Concentration of suspended sediment, mg/l.
d	Sieve diameter of a sediment particle.
D	Water depth.
d_{90}	The particle diameter for which 90 percent of particles, by weight, in the sample are finer.
D_s	Depth of local scour at a bridge pier.
DW	Dominant water depth calculated for obtaining the dominant water discharge.
D50	The grain size at which 50 percent, by weight, of the sediment grains are smaller.
g	Acceleration of gravity.
G	Bed load transport in tons/day, dry weight.
G'	Total bed load transport in metric tons/sec, or lbs/sec, submerged weight.
G''	Bed load transport in metric tons/sec/meter of width, submerged weight.
h	Gage height.
k	Coefficient for converting volume per second to weight per day.
K	Sediment load weighted by flow depth and class interval in dominant discharge calculations.

K'	Consolidation coefficient for silt deposits.
K''	Consolidation coefficient for clay deposits.
K_{a1}	Coefficient for angle of attack between flow and bridge pier for analyzing local scour.
K_B	Strickler roughness coefficient, $m^{1/3}/sec$.
K_e	Soils erodability in the Universal Soil Loss equation.
K_G	The grain roughness, $m^{1/3}/sec$.
K_s	Coefficient for pier shape for analysis of local scour.
L	Length term specifically defined where used.
m	Time interval in days during which the stage was within class interval Δh in the dominant discharge calculations.
n_B	Manning n-value for grain and form roughness in channel.
n_G	Grain roughness.
p	A dimensionless coefficient defined by equation 3-08.
P_e	Erosion control factor in the Universal Soil Loss equation.
ppm	Parts per million.
Q	Water discharge.
Q_B	That portion of the total water discharge which is responsible for bed load transport.
Q_D	Dominant discharge.
Q_K	A dimensionless coefficient in the Meyer-Peter and Muller equation, defined by equation 3-13.
Q_s	Sediment load.
Q_{si}	Inflowing sediment load.
Q_{so}	Outflowing sediment load.
$\mathbb{R}$	Reynolds number.

R_B	Hydraulic radius of flow on channel bed.
R_e	Rainfall energy in the Universal Soil Loss equation.
S	Energy slope or storage capacity.
T_d	Detention time or flow through time.
T_e	Trap efficiency.
V	Average velocity of flow.
V_d	Total sediment delivered to a reservoir during the project life (50 or 100 years).
w	Fall velocity of a sediment particle.
Y_e	Potential sediment yield from land surface erosion of a test plot.
Y_w	Average annual water yield.
γ	Specific weight of fluid.
γ'	Initial, submerged unit weight of a silt deposit.
γ''	Initial, submerged unit weight of a clay deposit.
γ_s	Specific weight of a sediment particle.
γ_s''	Submerged specific weight of sediment particles $(\gamma_s-\gamma)$.
γ_{sand}	Submerged unit weight of a sand deposit.
γ_T	Representative unit weight of a sand/silt/clay deposit T years after deposition occurred.
Δh	The class interval assigned to water stage in the dominant discharge calculations.
ν	Kinematic viscosity of fluid.
ρ	Density of the fluid.
ρ_s	Density of a sediment particle.
σ	$(\rho_s-\rho)/\rho$.
τ	Tractive force on stream bed.

App2

Appendix 3

Corps of Engineers Methods for Predicting Sediment Yields

APPENDIX 3

CORPS OF ENGINEERS METHODS FOR PREDICTING SEDIMENT YIELDS

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Oxford, Mississippi on
28 - 30 November 1972

COVER PAGE

CORPS OF ENGINEER METHODS FOR PREDICTING SEDIMENT YIELDS

By Robert H. Livesey 1/

INTRODUCTION

The methods used by the Corps of Engineers for predicting sediment yields are, in general, based upon empirical relationships but vary in scope and procedure depending upon the complexity of the individual water resource project plan or design. Due to the diverse nature of these projects, both in design magnitude and geographic location, a standard method approach for design application is not employed throughout the Corps. Instead, the individual District Offices make a sensitivity appraisal to evaluate the impact of all sedimentation influences on a specific project plan. From this first approximation analysis, the scope of the sedimentation problem is defined. This definition then becomes the basis for selection of feasible methods to be used in establishing the true magnitude of the problem components and design solution criteria. Where it is apparent that modification of a method might be practical to produce an improvement in design evaluation, such modification is encouraged. For this reason, a variety of procedures are developed and employed throughout the Corps but they all relate closely to one of the three basic empirical approaches for predicting sediment yield; namely (1) measuring the yield rate directly by sediment sampling or reservoir surveys, (2) extrapolation of such measured data to unmeasured drainages by various correlation and probability techniques, or (3) establishment of identifiable physiographic watershed or stream

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flow characteristics that permit development of predictive equations. Theoretical approaches to the prediction of sediment yields have been occasionally employed for special circumstances where empirical relationships were weak or confidence lacking but such procedures are not common.

DEVELOPMENT OF PREDICTION METHODS

The earliest record of sediment sampling in the United States dates back to 1838 when the Corps of Engineers was engaged in navigation channel work on the lower Mississippi River. During the next 100 years, the need for sediment predictions related almost entirely to river navigation or estuary maintenance work. It was not until after passage of the Flood Control Acts of 1928 and 1936, when the Corps started the planning, design and construction of multiple purpose reservoirs, that the need for sediment yield predictions developed. Typical of this initial phase of sediment yield investigations was STRAUB'S work that is well documented in the 1933 Missouri River Basin 308 Report. His development of the sediment rating curve method was later amplified by CAMPBELL and BAUAER in the 1940's, and MILLER in the 1950's, into the popular rating curve-flow duration method. After STRAUB'S 308 work the emphasis on documenting sediment yield rates shifted in the 1940's to reservoir survey measurements and the relation of sediment yield to contributing drainage areas, reservoir capacities, stream density or slope, and runoff. The early work of BROWN and GOTTSCHALK is typical of this period. But this work, like STRAUB'S, was considered professionally weak because it related sediment yield to only a few of the many contributing factors. Next, during the early 1950's, efforts were concentrated on the expansion of MUSGRAVE'S definition of quantitative factors for small land units to the drainage increments of large river control projects. These evaluations attempted, without much success, to relate many of MUSGRAVE'S factors on a regional or annual basis in lieu of local or seasonal definitions. During this same period, sediment sampling and reservoir survey measurement techniques were enhanced. Long term basin runoff characteristics were also identified to improve confidence in the sediment rating curve - flow duration method. However, by the late 1950's, a shift in project planning to smaller drainage areas started. The definition of local drainage controls and urban runoff assumed greater importance; the "big dam" criteria for yield predictions was no longer vogue. This change required a downward extrapolation toward the upper limits of SCS criteria. To meet this need, the number of Corps sediment load stations were doubled, plans were implemented to document urban runoff characteristics and correlation techniques concentrated on qualifying the adequacy of short term records. As the environmental issues of the late 1960's developed their impetus, design criteria and needs mushroomed into the broad fields of water quality control, biological reproduction, eutrophication acceleration and most recently wastewater management. The proper prediction methods for most of these latter aspects remain unqualified at the present time.

PREDICTION CRITERION

Corps' study investigation or design criterion for individual projects dictates that alternative methods for sediment yield prediction be considered and evaluated. These empirical methods generally fall into two basic categories: (1) the extrapolation of measured records and (2) the use of predictive equations. Most work related to the planning, design and operation of reservoirs is based upon the former method while channel alignment and stabilization aspects relate to the latter method. Although the Corps has no standard method, the use of the sediment rating curve - flow duration technique, or some ramification, has had the widest application. Prior to discussing the characteristics of various methods, some comment must be focused on the appraisal techniques which precede the selecting of the alternative methods to be considered. The following are common project evaluation criteria:

1) Sensitivity Evaluation. This appraisal attempts to bring the scope of sedimentation influences into focus with the over-all project purpose and plan. Later detailed analyses define the real magnitude and occasionally dictate a shift in study emphasis; but, early in both the planning and design phases, all potential problems are identified and priorities established regarding their importance to the various design features. When considering current environmental aspects, it is not uncommon to schedule a later, second sensitivity evaluation in case a re-orientation of project priorities or efforts is necessary.

2) Identifying Basic Data. This operation consists of a records and literature search to identify available streamflow or sediment measurement records, previous related study data or pertinent research activity work.

3) Hydrology. This analysis usually constitutes the initial design effort. Early in this work preliminary sediment yield predictions are made to satisfy first approximation storage and flow routing requirements. Later, as alternate project operation schemes are developed, the design yield rates are incorporated into the final hydrologic analysis. The development of long-term flow-duration data is another important contribution.

4) Geomorphic Characteristics. The factors considered in this analysis are quite varied and broad; the degree of investigation depends upon need. General needs include such items as geologic variations, soil classifications and characteristics, channel dimensions, composition of stream bank and bed materials and stream slopes.

5) Basin Reconnaissance. At least one field reconnaissance of the contributing drainage is made early in the preliminary design phase. Usually it is a "wind shield" type survey of sufficient scope to identify major or contrasting features of the drainage and permit judgment comparison of variations in yield rates and channel dimensions.

PREDICTION METHODS

The following discussion of the various sediment yield prediction methods used in Corps of Engineer studies and designs will be divided into the two basic categories previously mentioned. Descriptive comments will be limited to a summary nature but a study or design memorandum reference is given for each method. Most references can provide complete details on one or more methods. An attempt was made to include with each discussion a reference plate which identified the salient features of the method or the output results.

The first category involves the extrapolation of measured records and is divided into the three major measurement classifications: sediment loads, reservoir surveys and reconnaissance inspections. Relevant methods for each include:

1) Sediment Load Measurements

a) Sediment Rating Curve Method. This basic, older method is usually associated with a flow-duration analysis but occasionally special circumstances still require its use. An example would involve instantaneous units of flow and concentration rather than mean daily values. These applications usually relate to a near constant or limited range of flows, such as for seasonal or monthly variations between run-of-river reservoirs within a large system. In such instances the minor incremental flow and sediment contributions, including their duration and frequency, are usually obscured by the large base flow. The method involves the plotting of measured suspended sediment load values versus equivalent units of discharge for desired time periods and defining the mean curve. An example is shown in Figure 1. The original use of this method was developed for the 1933 Missouri Basin 308 report with further enhancement by CAMPBELL and BAUDER in their paper, A Rating-Curve Method for Determining Silt-Discharge of Streams as published in Transactions American Geophysical Union, Volume 30, August 1949.

b) Sediment Rating Curve-Flow Duration Method. This popular method combines the above rating curve principle with the measured stream-flow record to develop a probability correlation between the sediment and water discharge of a stream. The method consists of a determination of suspended sediment load values from the rating curve for corresponding increments of discharge from a flow duration curve. Multiplication of the suspended sediment load and discharge increments by the time percentage interval gives a daily occurrence value. Totaling these daily average values produces the mean daily discharge and suspended sediment load for the year. Further multiplication of these mean daily values by the number of days in the year gives average annual rates. Addition of unmeasured suspended or bed load estimates results in a total average annual sediment load value. Variations in this method permit development of long-term rate estimates based upon seasonal or short periods of record. Figures 1, 2 and 3 record the principal details of this method. For more complete details, including an evaluation of the techniques of this method, see An Analysis of the Flow-Duration, Sediment-Rating Curve Method of Computing Sediment Yield by Carl R. Miller as published by the Bureau of Reclamation in April 1951.

c) Sediment Discharge-Soil Type Relationships. This method relies upon a runoff-sediment load record to obtain a correlation of sediment yield according to soil classification and cultivated areas. River basins are divided by soil types and annual surface runoff-sediment discharge curves developed for each classification according to the degree of cultivated acreages. An example of the relationship developed for 13 drainages of mixed loess and glacial soils is shown in Figure 4. A comparable correlation was possible for residual limestone, sandstone and shale soils but in loessial terrain the results were indeterminate. For further information refer to an unpublished report on Rates of Sediment Production in The Kansas City District by A. L. Hill.

d) Dominant Basin Characteristics. The similarity of the dominant physical characteristics of a drainage basin versus the measured sediment production is the basis for this method. The dominant characteristics included land use, relief and topography, climate, water and soil types. Land resource areas are used to group the defined individual sediment yield rates into comparable area categories. Both suspended sediment load and reservoir sedimentation survey records are used to establish yield rates by drainage area or time increments for a given base period. The flow-duration principle is applied to adjust short-term records to the base period. Such adjustments require establishment of sediment discharge to streamflow relationships for the period of measurements and then correlating this data to the long-term flow regimen of the stream. The method has produced indications of sediment yield trends with time in several instances. Figures 5, 6 and 7 depict the general features of this method. For details see Sediment Yields in the Upper Mississippi River Basin by Frank J. Mack as published in Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs in April 1970 by the Hydrologic Engineering Center, Corps of Engineers at Davis, California.

e) Sediment Yield by Isogram Intervals. Except for the degree of individual basin analysis, a similarity exists between this and the preceding method. This method recognizes the dominant physical characteristics and measured sediment production records of the basin, but, in addition, relies upon personal knowledge and engineering judgment to evaluate the sediment yield characteristics of a basin. The method was developed for use as a task force expedient by a group of inter-agency sedimentation specialists to document sediment yield rates for large river basins. Yield rates for standard periods of time are derived by extrapolation of shorter period records by one of three procedures; comparing sediment load-water discharge relations between periods of record and the standard period, derivation of sediment-water regression curves for increments of drainage area or evaluating relations between intermittent sediment measurements made over short-time periods. The final delineation of isogram lines are based upon group experience and judgment. A typical end-product of this method is shown on Figure 8. Examples of this method can be found in any one of the seven sub-basin sedimentation reports prepared by the Task Force on Sedimentation for the Missouri River Basin Comprehensive Framework Study, as submitted to the Missouri Basin Inter-Agency Committee in 1968 and 1969.

f) Sediment Yield During Urban Expansion. The techniques of this method are still in the developmental stage. The basic premise concerns transition of rural lands to urban usage over given time periods. It assumes that sediment yield rates accelerate from agricultural values to a high peak during landscaping or construction, then decline to a lower plateau as the land "heals" and finally level off at some low stable rate representative of business or residential lands. A projection of urban expansion limits, as provided by the local metro planning authority, serves as a base for converting contributing drainages from rural use to single family, multi-family or commercial usage. Integration of varying yield rates for area increments under various stages of development permits a continuous assessment over the design life of the project. Judgment extrapolation of limited urban runoff and sediment yield measurements is currently necessary but data collection programs that concentrate on storm runoff measurements can quickly improve this limitation. A generalized schematic outline of this method, as being developed by the Omaha District, is shown in Figures 9 and 10.

2) Reservoir Sedimentation Surveys

a) Sediment Yield Per Unit of Drainage. The application of this method is common because of its simplicity in relating measured rates of sediment yield to the contributing drainage area increment. Numerous correlations are possible within certain ranges of drainage area by soil types, runoff volumes, watershed-capacity ratios, dominant discharge, land use, physiographic areas and many other parameters. Most Corps applications of these yield rates pertain to contributing drainages greater than 100 square miles so correlation with the conventional soil loss parameters is not common. The principle source of reference data is ARS Misc Publication No. 1143, Summary of Reservoir Sediment Deposition Surveys Made in the United States through 1965, or related reporting Form 1787. A typical example of this method can be noted in Figure 11.

b) Yield Production for Debris Basins. This is a special application used to determine the sediment yield into flood control debris basins in mountainous type terrain. The method was developed from observed debris volumes that reflect ground conditions influenced by prior rain runoff and areas subjected to partial or complete "burns." Influencing factors include size and shape of drainage area; steepness of canyons and side slopes; geological characteristics; type and density of plant cover; recency of burns; and frequency, duration and intensity of storms. Measured debris volumes are adjusted to a common base and curves developed for separate corrections of the major factors affecting debris production. Figure 12 summarizes the details of this method. Further information is available in A New Method of Estimating Debris-Storage Requirements for Debris Basins by Fred E. Tatum as published in the Proceedings of the 1963 Federal Inter-Agency Sedimentation Conference, ARS Misc. Pub. No. 970.

3) Reconnaissance Inspections. The following methods are directed toward establishing preliminary estimates of sediment yield for large drainage areas. On occasion, the investigation details have been expanded to cover studies of design scope for small to moderate drainages. Their basic premise consists of a quick but detailed reconnaissance type inspection of the contributing drainage area by two or more Sedimentation Specialists who, by experience, are capable of making judgment estimates of sediment yield rates. During the field reconnaissance they collectively establish representative point rates for incremental portions of major drainages within the over-all study basin. This technique is particularly applicable for a degree assessment of contributing versus non-contributing drainage as influenced by soil

management practices, smaller reservoirs or ponds or irrigation diversion projects. If the basin is relatively small, perhaps less than 1000 square miles, the estimates for even third or fourth order streams can become quite detailed. For larger basins, selected streams might be covered in more detail and the remainder left to a random choice of inspection. The end product is usually similar to that shown in Figure 8.

a) Interpolation of Rates Within a Basin. This method requires several points of measured sediment yield, by either sediment sampling or reservoir surveys, within the basin drainage. One of these points should be located near the mouth of the basin to reflect the total measured yield from the drainage. During the field reconnaissance these measured rates are used as a comparative guide for estimating yield rates for small increments of the unmeasured drainages. When sufficient point estimates are established, a yield contour map is developed. Using digitizing or planimetering processes, drainage area increments of equal yield rates are totaled for the major drainages within the basin. A summation of these totals and division by the contributing drainage area value gives an average sediment yield rate for the subject increment. These increment rates are checked against the measured increment rates for verification. If they are not comparable within reason, adjustments to selected point estimates are justified to bring the integrated total into balance with measured data.

b) Extrapolation to Unmeasured Watersheds. The basic procedure is similar to that above except that a comparison between the total estimated and measured rates for a basin is not possible. Prior to the field inspection of the unmeasured drainage, the reconnaissance team usually makes a preliminary inspection of the measured drainages being used as the extrapolation base. This visual inspection requires additional time and effort but serves as an effective means for comparative extrapolation. The validity of this method is dependent upon the degree of extrapolation but apparent satisfactory results have been produced within a restricted time period.

The second category involves predictive equation methods. Most of the individual methods discussed below apply to the solution of specific problems. They differ from the preceding methods in that the predicted sediment yield relates primarily to channel contributions rather than from a watershed drainage. The Corps use of predictive equations for determining watershed yields is very limited.

1) Sediment Transport Relationships. There are a variety of methods in this classification but the most common is the EINSTEIN approach, with one of its many modifications, or the more recent TOFFALETI procedure. Their connection with sediment yield predictions usually relate to channel stabilization projects involving aggradation or degradation problems. But their application is also common in establishing the magnitude or rate of unmeasured suspended or bed sediment load values. Estimates of such values are extremely important in certain instances when establishing yield rates from measured suspended sediment load records, such as is required in the

rating curve-flow duration method. An excellent discussion of the EINSTEIN and TOFFALETI methods, plus others, and a listing of complete references can be found in the Journal of the Hydraulics Division, ASCE, April 1971, under Paper 8076 titled Sediment Transportation Mechanics: Sediment Discharge Formulas

2) Detention-Time Method. This method is used to predict the volume of sediment passing through a series of run-of-the-river type reservoir projects. It is based upon empirical relationships between the detention time of flows passing through the reservoir system and the percentage of sediment deposited. Detention time is defined as the ratio of reservoir storage to the inflow discharge at any given time. Curves of detention time versus percent of wash load and bed material load deposited are developed to determine deposition-flow through volumes for incremental reaches. As the reservoir volume is depleted by deposition, the detention time is reduced and the yield rate per unit of flow increases. Figure 13 shows a typical relationship between detention time in hours and percent of load deposited for a series of reservoirs. Reference details for this method can be found in Dardanelle Reservoir Design Memorandum No. 6, Part IV Sedimentation prepared in October 1957 by the Little Rock District.

3) Hydraulic Elements. This is another method for determining run-of-the-river reservoir yield rates. Individual reservoirs are divided into reaches and hydraulic elements are determined for various discharges by back-water computations. The sediment load is then related to the velocity, depth and slope, or a combination of such elements. The inflow-outflow sediment loads are computed on a step procedure from reach

to reach with backwater computations repeated as necessary to obtain new hydraulic element values as deposits accumulated with time. The method is time consuming but permits recognition of the individual element changes or trends, an example is shown in Figures 14 and 15. (Note: These figures could not be reduced in size and consequently are not included. The method depicted is embodied in the computer program presented in Appendix VII of this volume. W. A. Thomas) The reference for this method is the same as given above for the detention-time method.

4) Bank Caving-Wash Load Yields. This is another special application method used to estimate the excess rate of bank-caving over bank building relative to an increase in the wash load being transported. It applies, again, to run-of-river reservoirs where the erosion of concave banks in bends may continue at the natural high flow rates due to the duration of artificial bank full stages under operating conditions. The change in bank caving-bank building equilibrium produces an additional supply of wash load due to channel widening. The method is admittedly over-simplified for the complex phenomena of bank caving but it offers a systematic method of recognizing the increase in wash load due to bank caving. An example of this method is given in Figures 16 and 17. Reference details can be found in a Supplement To Dardanelle Reservoir Design Memorandum No. 6-4 prepared by the Little Rock District in January 1959.

5) Sediment Delivery Ratio. This category covers both the sediment delivery and sheet erosion prediction methods developed by the Department of Agriculture. The application of these methods to Corps projects is generally limited to small watersheds of less than 25 to 50 square miles. Adoption of the MUSGRAVE equation is probably still preferred over the Universal Soil Loss equation for smaller drainages. However, more useful are the various empirical equations developed by such authors as ANDERSON, BARNES, BRUNE, GLYMPH, GOTTSCHALK, HEINEMANN, KOHLER, MANER, PIEST and others. Due to the limited application of these methods, reference is made to the following sources for precedural details: Studies of Sediment Yields From Watersheds by Louis Glymph or Sediment Sources and Sediment Yields prepared by Robert F. Piest as Chapter IV of the ASCE Manual on Sedimentation Engineering and published as paper 7337 in the Journal of the Hydraulics Division, June 1970.

6) Tailwater Degradation. Several methods are included in this grouping. Their principal function is to predict degradation trends; but, as part of the computational procedure, sediment yield values for the degrading reach are developed. Factors considered in their application include composition of the bed material and its coarsening with time, the magnitude of future flows and changes in flow characteristics such as channel shape, depths, velocity and slope. Three common methods include use of the EINSTEIN bed load function for sediment transport; use of the KALINSKE formula to compute bed load plus

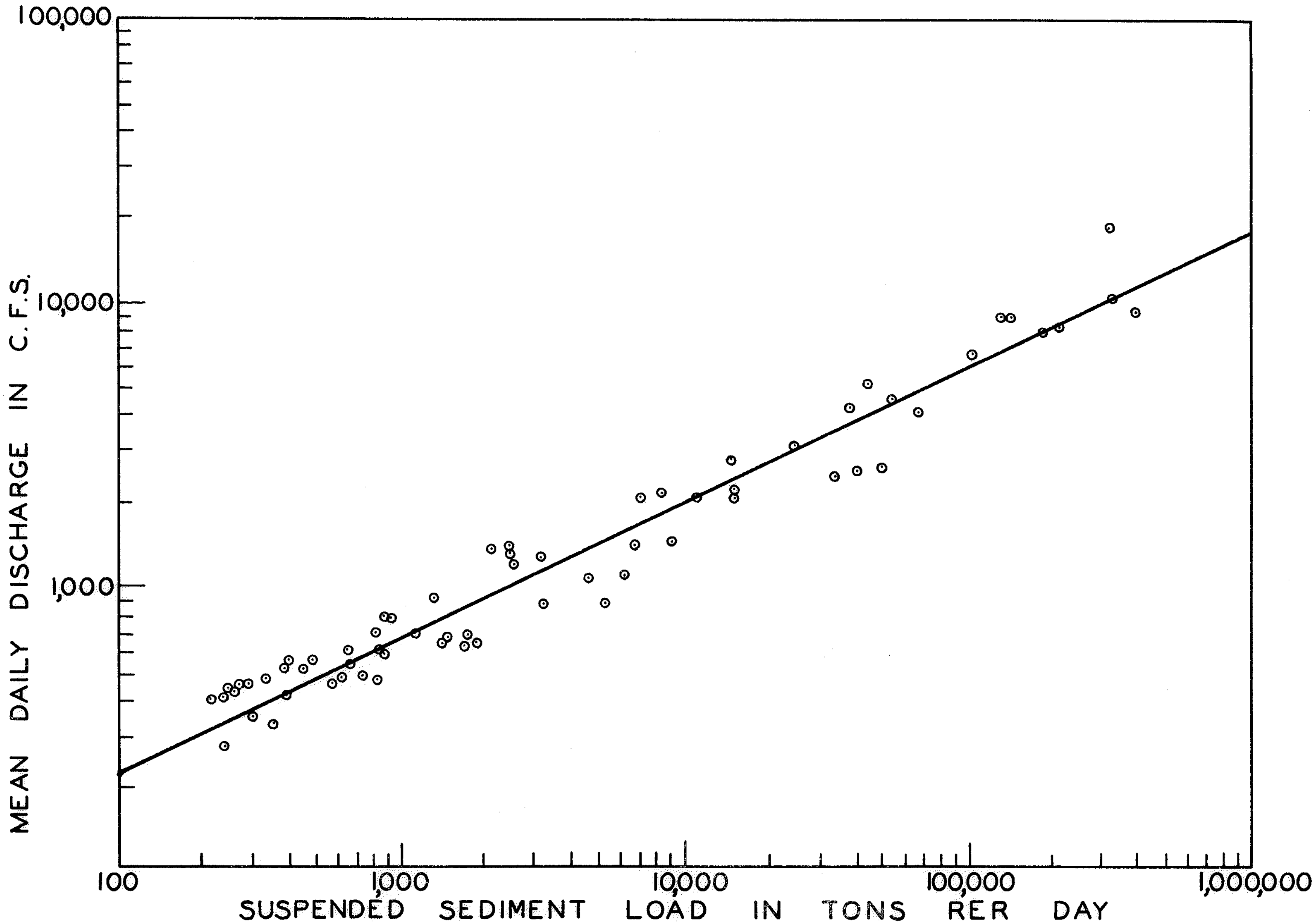
the development of relationships between natural and modified bed material load transport as degradation progresses; and determination of the thickness of an armor layer and the depth of scour at which this layer would form. This latter technique assumes degradation would cease when a layer of "non-moving" particles forms a sufficient armor to prevent the effective leaching of finer particles from the underlying bed material. Procedural details on these methods can be found in a paper on Sedimentation Studies for Robert S. Kerr Lock and Dam, Arkansas River Basin by Howard O. Reese as published in the Hydrologic Engineering Center's Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs, April 1970.

FUTURE NEEDS

During the past decade a shift in emphasis has taken place within the Corps regarding the need for sediment yield predictions. Prior to the mid-1950's, sediment was viewed primarily as a malignant growth that reduced the effectiveness of reservoirs, floodways, navigation channels and harbors. This was also the period of "big dam" planning and construction where sediment depletion rates played a relatively minor role in design because of the voluminous storage allotted for multiple purpose use. The need for sediment yield predictions for large drainage areas has essentially vanished. As an indication, about 15 years ago the Corps was operating 135 sediment load stations with 43% having drainage areas greater than 5000 square miles, 27% in the 500-5000 range and 30% less than 500 square miles. Presently this number of stations has doubled with a comparative shift in percentage ratio of 25:37:38. Almost half of the current stations are operated for planning or design purposes. For example, during 1969 the Corps had under construction 23 reservoir projects for hydro-electric power and flood control, 64 reservoir projects for flood control and multi-purpose use and 84 local flood control protection projects. Now the Corps emphasis seems to be focused on projects with sediment contributing drainages that generally vary within the 500 to 2500 square mile range. But if our prediction approach is to continue on an empirical basis, long-term data records for drainage areas within this bracket are inadequate, particularly for reservoir survey data. It is estimated that there are some 28,000 reservoirs in the United States yet we have sediment yield records on only 4%. But more significant is the fact that of the 1200 individual reservoirs listed in the 1965 summary of reservoir survey data, 80% of the documented record ranges below 50 square miles and 90% below 500 square miles. It is apparent that, figuratively speaking, a scarcity of data exists in the no-man's land that is bracketed with voluminous SCS records on the low side and adequate Corps, USBR and TVA experience on the high side. In essence, the basis for future Corps yield predictions by empirical methods will be somewhat handicapped until data records within this bracket are expanded by measurements or enhanced by correlation techniques.

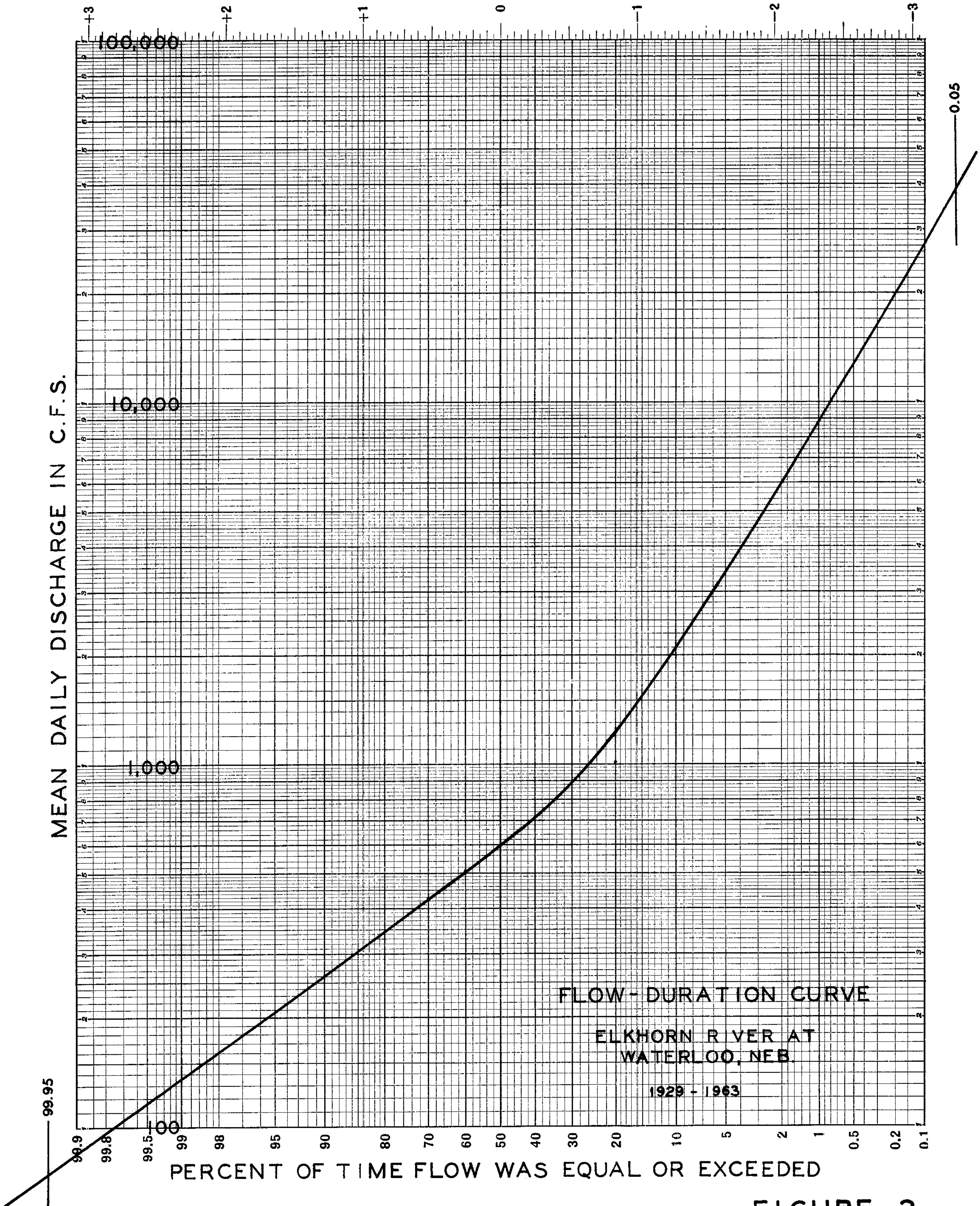
Today, the dirty word "sediment" has dual connotations; it must now be recognized from both a beneficial and detrimental point of view. On one hand sediments rank as a major cause of water pollution, but on the other hand they play a dominating role in water quality control due to their assimilation capabilities. Apparently they also serve similar dual roles as catalytic or transporting agents in physical, chemical or biological processes. With the current focus of Corps activities in areas of environmental control, urban development or expansion and wastewater management, the recognition of such aspects is receiving prime attention in planning and design. But unanswered questions continue to outnumber even qualified answers. There is an unquestionable need for further amplification of key sedimentation influences in certain environmental processes before proceeding with detailed planning or design applications.

The immediate needs of the Corps of Engineers in expansion of sediment yield prediction methods will probably be focused along these two major channels: 1) definition of empirical relationships for drainage areas of moderate size, and 2) establishment of the role sediments play in the complex environmental processes. The application of computer-oriented methods for mathematical simulations or modeling will undoubtedly play a key role in the solution of some of these problems. Past experience however, has clearly demonstrated that one or two standard methods or universal equations, regardless of their complexity, will not meet the diverse needs of modern day engineering, planning or design. For this reason, our efforts will continue to concentrate along the lines of practical needs to resolve particular problems. But in doing so, we intend to also continue our policy of improving available methods or techniques by modification, regardless of their degree of sophistication, as the needs of the problem warrant.



SEDIMENT RATING CURVE
ELKHORN RIVER
WATERLOO, NEBR.

FIGURE 1



MEAN DAILY DISCHARGE IN C.F.S.
100,000
10,000
1,000
100
+3
+2
+1
0
-1
-2
-3
0.05
99.95
99.9
99.8
99.5
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
PERCENT OF TIME FLOW WAS EQUAL OR EXCEEDED
FLOW-DURATION CURVE
ELKHORN RIVER AT
WATERLOO, NEB.
1929 - 1963

FIGURE 2

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RATING CURVE - FLOW DURATION METHOD

LONG TERM TOTAL SEDIMENT LOAD ESTIMATE FOR
ELKHORN RIVER AT WATERLOO, NEBRASKA

STREAMFLOW RECORD - 1929 TO 1963
SUSPENDED SEDIMENT SAMPLING RECORD - AUG. 1948 TO NOV. 1950

Percent Mid Ord.	Percent Increment	Water Discharge Q_w (cfs)	Suspended Sediment Load Q_s (tons)	Daily Average Q_w (cfs)	Daily Average Q_s (tons)
0.05	0.1	37,000	4,500,000	37.0	4500
0.3	0.4	15,000	680,000	60.0	2720
1.0	1.0	9,000	230,000	90.0	2300
3.25	3.5	4,500	55,000	157.5	1925
10	10	2,100	11,000	210.0	1100
20	10	1,200	3,500	120.0	350
30	10	880	1,800	88.0	180
40	10	710	1,150	71.0	115
50	10	600	800	60.0	80
60	10	510	580	51.0	58
70	10	425	390	42.5	39
80	10	345	250	34.5	25
90	10	260	140	26.0	14
96.75	3.5	180	64	6.3	2
99.0	1.0	135	35	1.4	1
99.7	0.4	105	20	0.4	0
99.95	0.1	74	13	0.1	0
		Totals		1055.7	13,409

Annual Q_w = 1055.7 x 365 x 1.98 = 762,950 AF/Yr

Annual Q_s = 13,409 x 365 = 4,894,000 tons/yr

Unmeasured & bed load = 10% Qs = 489,000 tons/yr

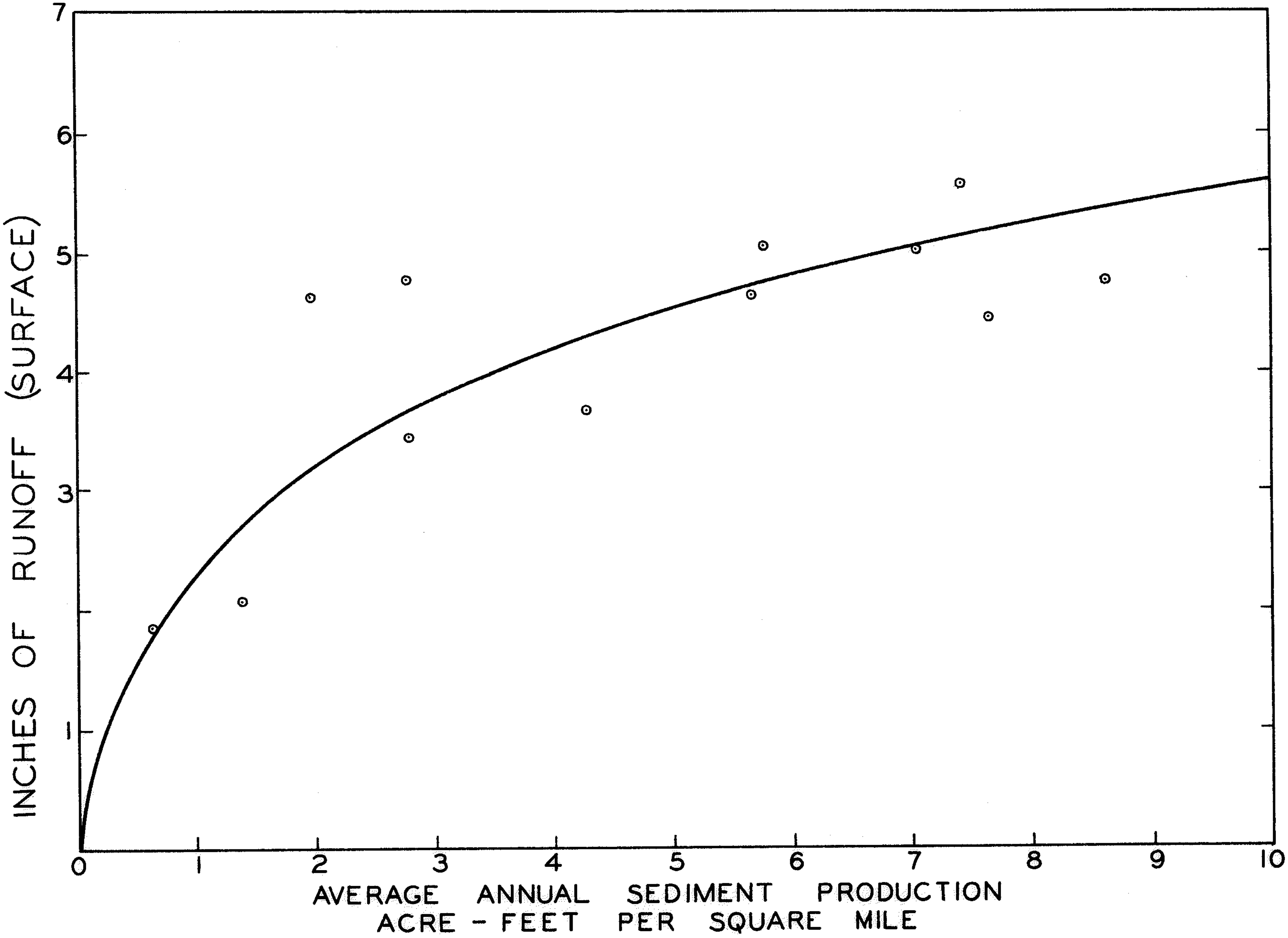
Total sediment load = 5,383,000 tons/yr

Total Drainage Area = 6,900 square miles

Sediment Contributing D.A. = 5,900 square miles

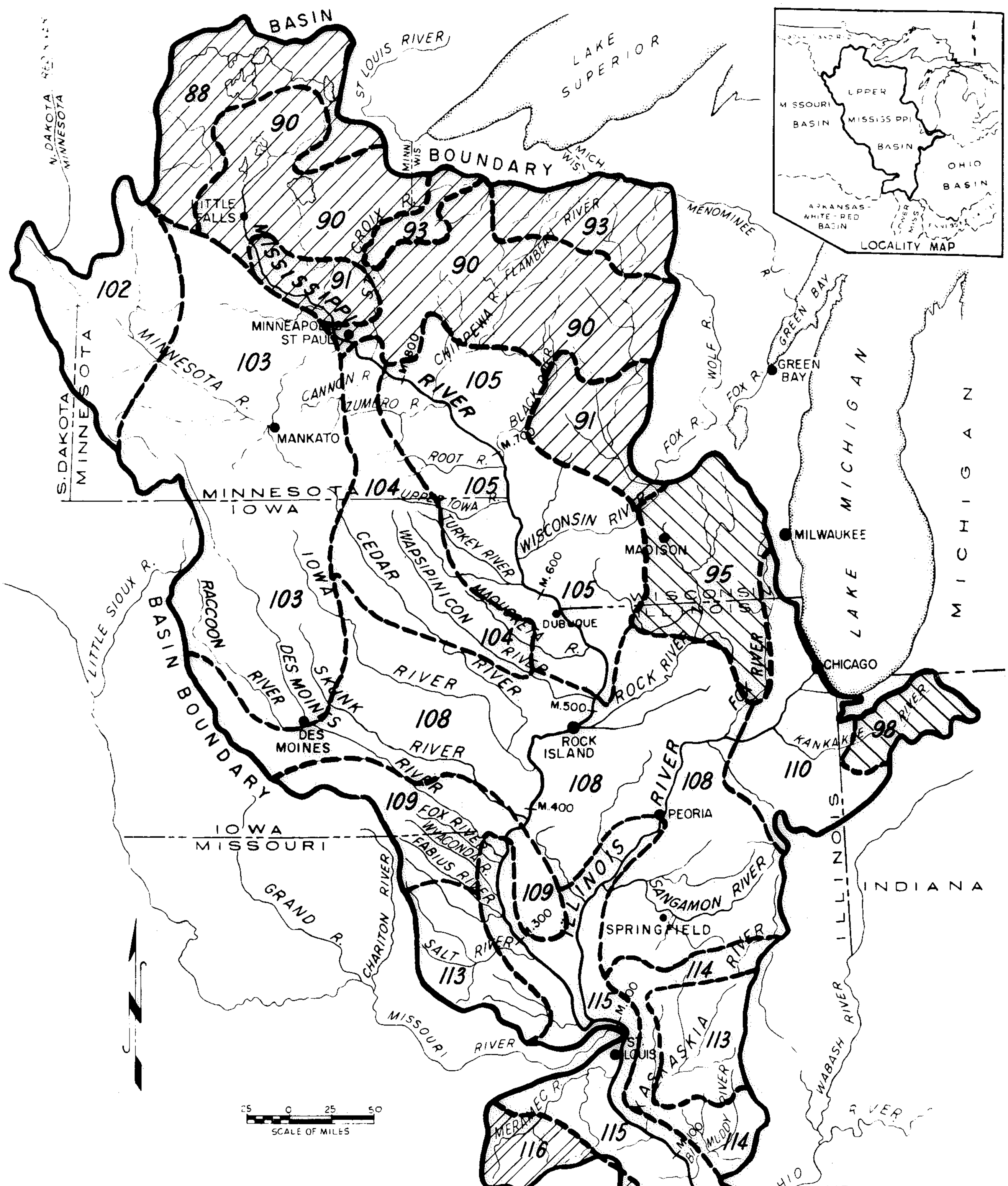
Average Annual Sediment Yield = 912 tons/square mile

FIGURE 3



AVERAGE ANNUAL RUNOFF FOR
MIXED LOESS & GLACIAL SOILS

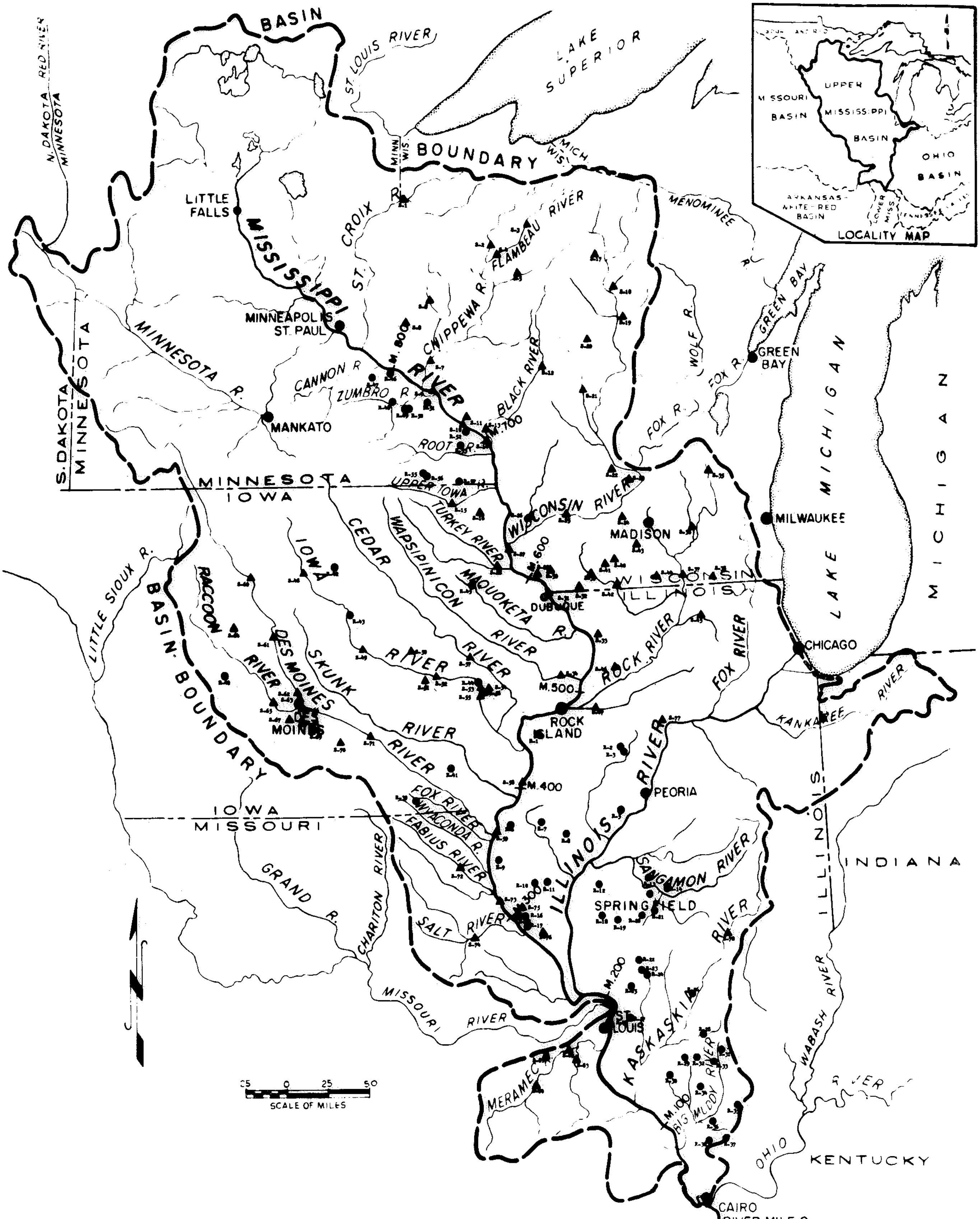
FIGURE 4



- NORTHERN LAKE STATES FOREST AND FORAGE REGION
- LAKE STATES FRUIT, TRUCK, AND DAIRY REGION
- CENTRAL FEED GRAINS AND LIVESTOCK REGION
- EAST AND CENTRAL GENERAL FARMING AND FOREST REGION

LAND RESOURCE REGIONS AND MAJOR LAND RESOURCE AREAS

FIGURE 5

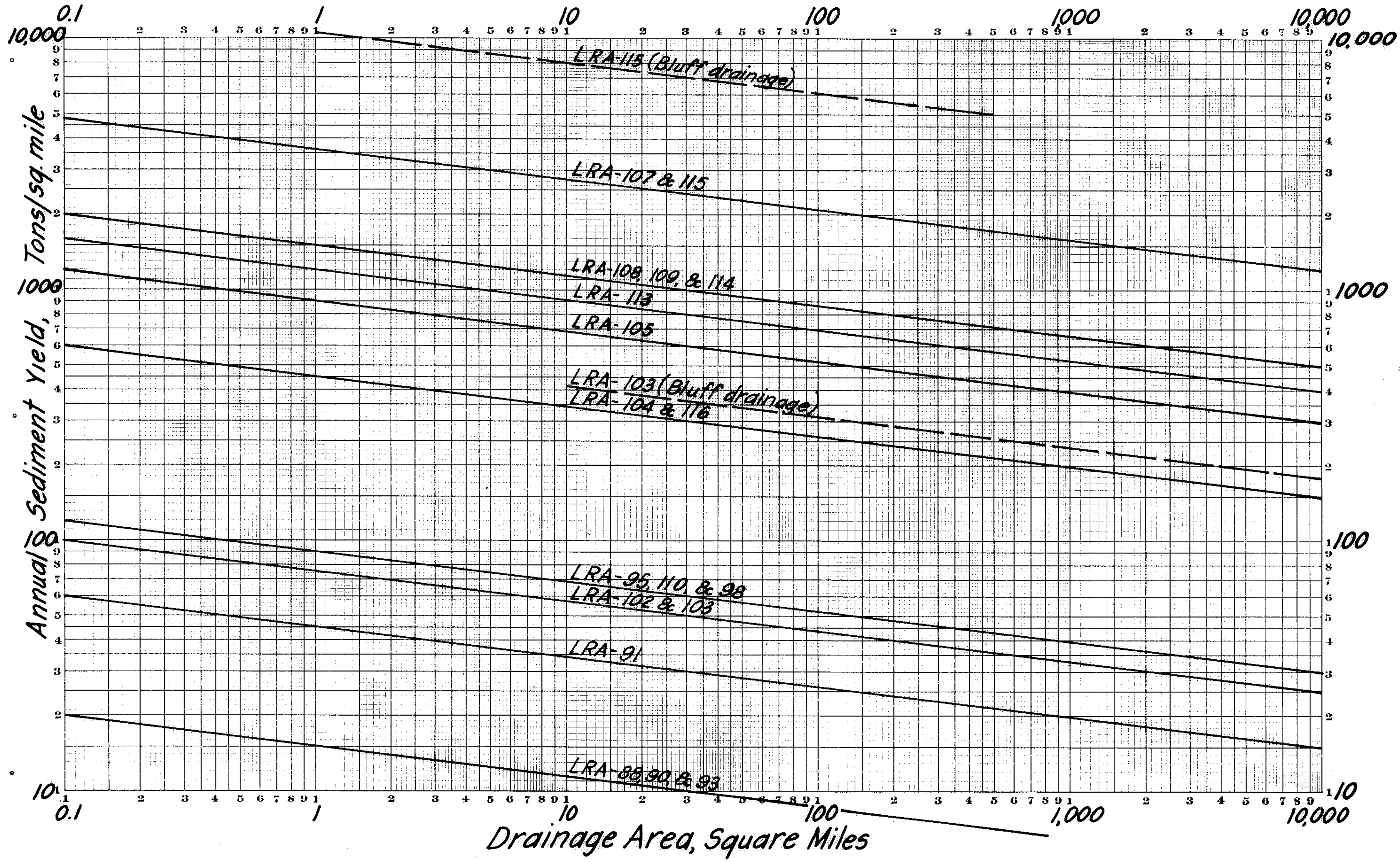


▲ SUSPENDED SEDIMENT STATIONS

● RESERVOIR SEDIMENTATION SURVEY SITES

LOCATION OF BASIC DATA

FIGURE 6



Observed Sediment Yields
All Land Resource Areas

FIGURE 7

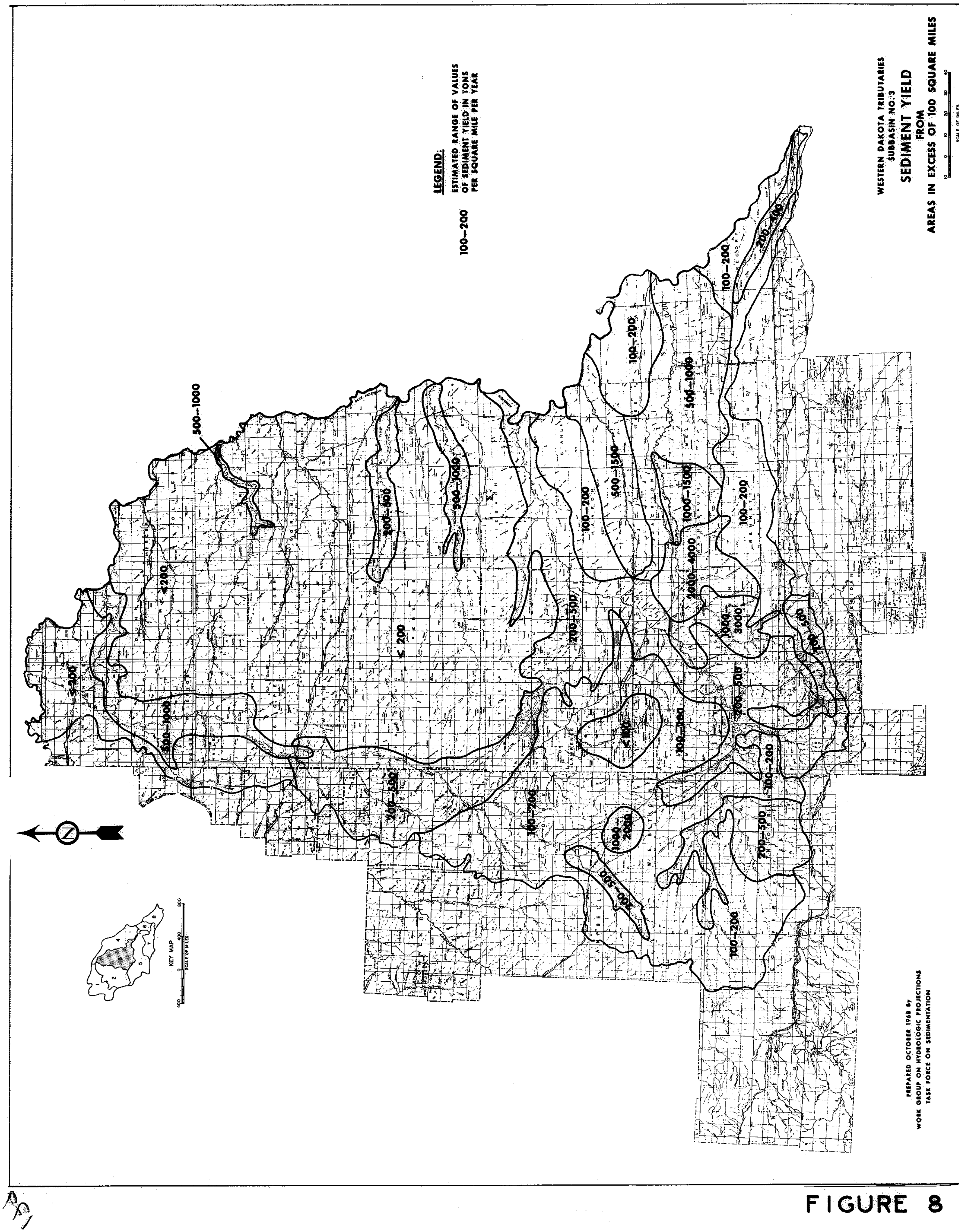
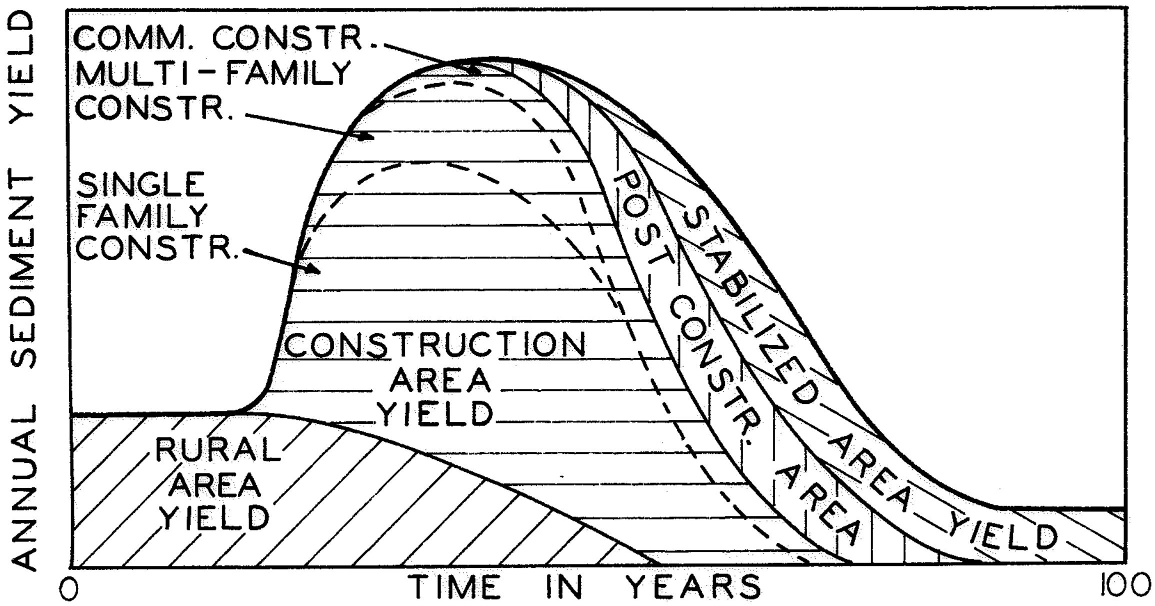
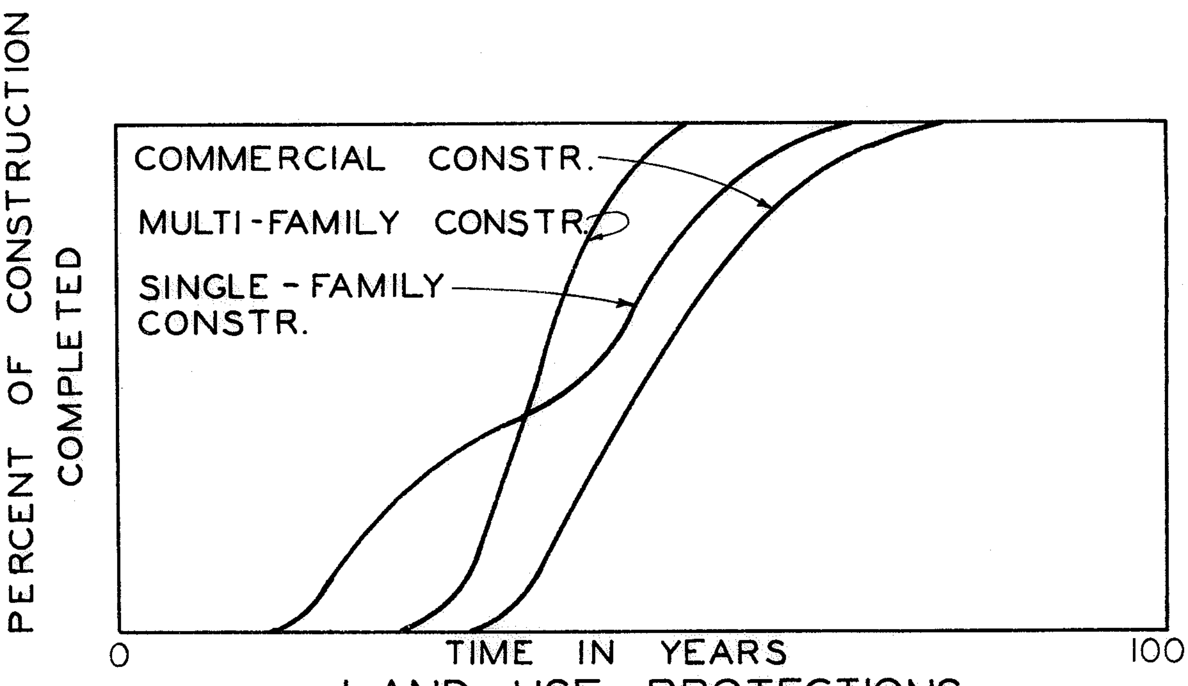

WESTERN DAKOTA TRIBUTARIES
SUBBASIN NO. 3
SEDIMENT YIELD
FROM
AREAS IN EXCESS OF 100 SQUARE MILES
SCALE OF MILES
LEGEND:
100—200 ESTIMATED RANGE OF VALUES OF SEDIMENT YIELD IN TONS PER SQUARE MILE PER YEAR
KEY MAP
SCALE OF MILES
PREPARED OCTOBER 1968 By
WORK GROUP ON HYDROLOGIC PROJECTIONS
TASK FORCE ON SEDIMENTATION

FIGURE 8



ACCUMULATIVE SEDIMENT YIELD



LAND USE PROJECTIONS
(FURNISHED BY METRO. PLANNING AUTHORITY)

SEDIMENT YIELDS DURING URBAN EXPANSION

FIGURE 9

SUMMATION OF TOTAL SEDIMENT YIELD DURING CONVERSION FROM RURAL TO URBAN LAND USE

ANNUAL SEDIMENT YIELD FROM SOURCE AREAS					
YEAR	RURAL	CONSTRUCTION	POST CONSTR.	STABILIZED	TOTAL
1	X				X
2	X				X
3	X				X
4	X	Y			X+Y
5	X	Y			X+Y
6	X	Y	Z		X+Y+Z
7	X	Y	Z		X+Y+Z
8	X	Y	Z	W	X+Y+Z+W
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
n − 8	X	Y	Z	W	X+Y+Z+W
n − 7		Y	Z	W	Y+Z+W
n − 6		Y	Z	W	Y+Z+W
n − 5			Z	W	Z+W
n − 4			Z	W	Z+W
n − 3			Z	W	Z+W
n − 2				W	W
n − 1				W	W
n				W	W
TOTAL	$\sum X$	$\sum Y$	$\sum Z$	$\sum W$	$\sum(X+Y+Z+W)$

FIGURE 10

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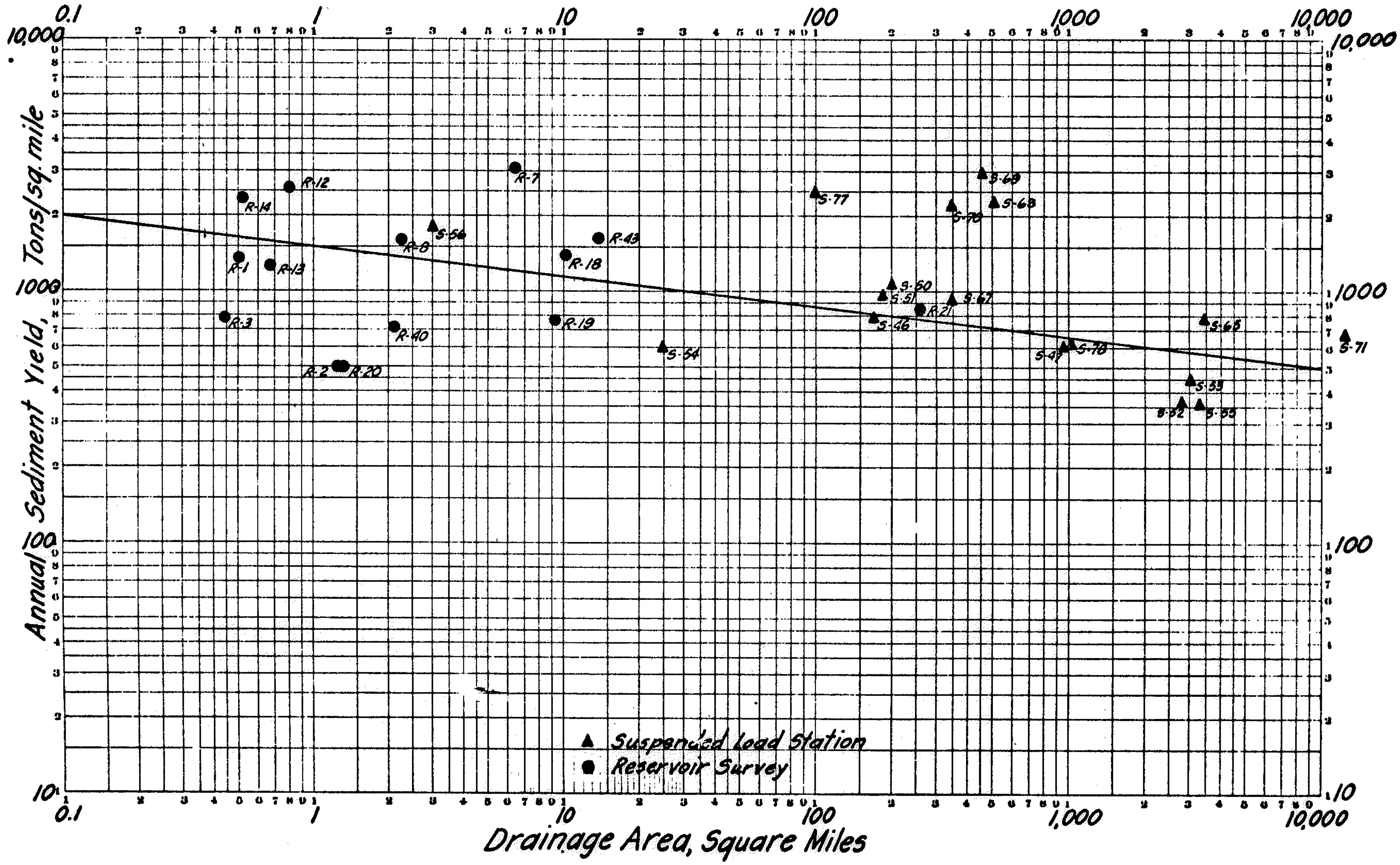


Observed Sediment Yields
Land Resource Area 108

FIGURE 11

Observed data and computed debris production for selected debris basins in the Los Angeles area[1]

Debris basin[2]			Burn in drainage area		Debris-producing flood		Observed debris production during flood		Observed debris rate adjusted to 100 percent burn 1st year[2]	Debris production factors for—				Correction factors					Computed debris production	
No.	Name	Drainage area	Year	Area	Year	Years after burn	Total	Rate		Slope	Drainage density	Hypsometric index	3-hour rainfall	Slope	Drainage density	Hypsometric index	3-hour rainfall	Total	For maximum 1 square mile with 100 percent burn 1st year[3]	For year of observed flood and actual area burned[2]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
	La Cresenta Area:	*Square miles*		*Square miles*			*Cubic yards*	*Cubic yards per square mile*	*Cubic yards per square mile*	*Feet per mile*	*Miles per square mile*		*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Cubic yards*	*Cubic yards*
1	Dunsmuir	0.84	1933	0.78	1938	5	58,800	70,000	695,000	1,390	1.7	0.54	2.94	99	97	98	67	64	1,220,000	106,000
2	Eagle-Goss	.61	1933	.46	1938	5	40,900	67,050	767,000	1,480	3.3	.25	2.89	100	84	33	64	18	342,000	19,400
3	Haines	1.53	1933	1.01	1938	5	52,000	33,990	423,000	1,040	2.4	.46	2.85	92	95	98	62	52	1,010,000	117,000
4	Hall-Beckley	.83	1933	.63	1938	5	86,300	103,980	1,185,000	930	2.2	.50	2.82	88	96	100	61	59	990,000	73,000
5	Hay	.20	1933	.06	1938	5	12,600	63,000	1,190,000	1,290	.6	.65	2.72	97	99	76	36	40	760,000	9,700
6	Pickens	1.84	1933	1.75	1938	5	122,200	66,410	650,000	940	3.4	.47	2.93	88	82	99	67	48	910,000	160,000
7	Shields	.27	1933	.24	1938	5	33,500	124,000	1,320,000	1,570	2.5	.51	2.90	100	94	100	65	61	1,160,000	34,400
8	Snover	.23	1933	.11	1938	5	16,800	73,040	1,110,000	1,280	3.5	.54	2.82	97	81	98	61	46	874,000	15,500
	Pasadena Area:																			
9	Fair Oaks	.21	1935	.21	1938	3	12,000	57,140	257,000	1,180	0	.21	2.34	95	100	25	36	9	171,000	9,600
10	Fern	.30	1935	.30	1938	3	20,700	69,000	310,000	1,180	4.8	.41	2.42	95	51	92	39	17	323,000	24,600
11	Las Flores	.45	1935	.31	1938	3	36,000	80,000	495,000	1,610	3.2	.58	2.62	100	85	94	49	39	741,000	60,000
12	Lincoln	.50	1935	.50	1938	3	8,000	16,000	72,000	780	4.6	.31	2.39	81	57	60	38	11	209,000	25,600
13	West Ravine	.25	1935	.24	1938	3	29,800	119,200	555,000	1,290	0	.40	2.40	97	100	90	38	33	627,000	39,500
14	Bailey	.58	1953	.46	1954	1	65,000	112,070	140,000	1,520	2.6	.50	1.70	100	93	100	12	11	209,000	104,000
	Burbank Area:																			
15	Brand	1.03	1927	.77	1943	[4]10	3,100	3,010	99,000	910	3.0	.50	1.70	87	88	100	12	9	171,000	5,300
16	Sunset	.44	1927	.42	1938	[4]10	6,600	15,000	495,000	1,610	2.0	.48	1.93	100	97	99	18	17	323,000	4,800
17	Stough	1.65	([4])	([4])	1943	([4])	33,500	20,300	670,000	1,020	4.4	.62	2.64	91	63	85	52	25	475,000	20,000
	Beverley Hills Area:																			
18	Nichols	.94	([4])	([4])	1938	([4])	17,900	19,040	626,000	480	.9	.56	2.48	57	99	96	42	23	437,000	12,600

[1] See fig. 3 for location.
[2] Computed by use of equation 5 (see text) and adjusted for size of drainage area.
[3] 1,900,000 times total percent from column 19.
[4] 10 years or more assumed to have no effect on debris production.

FIGURE 12

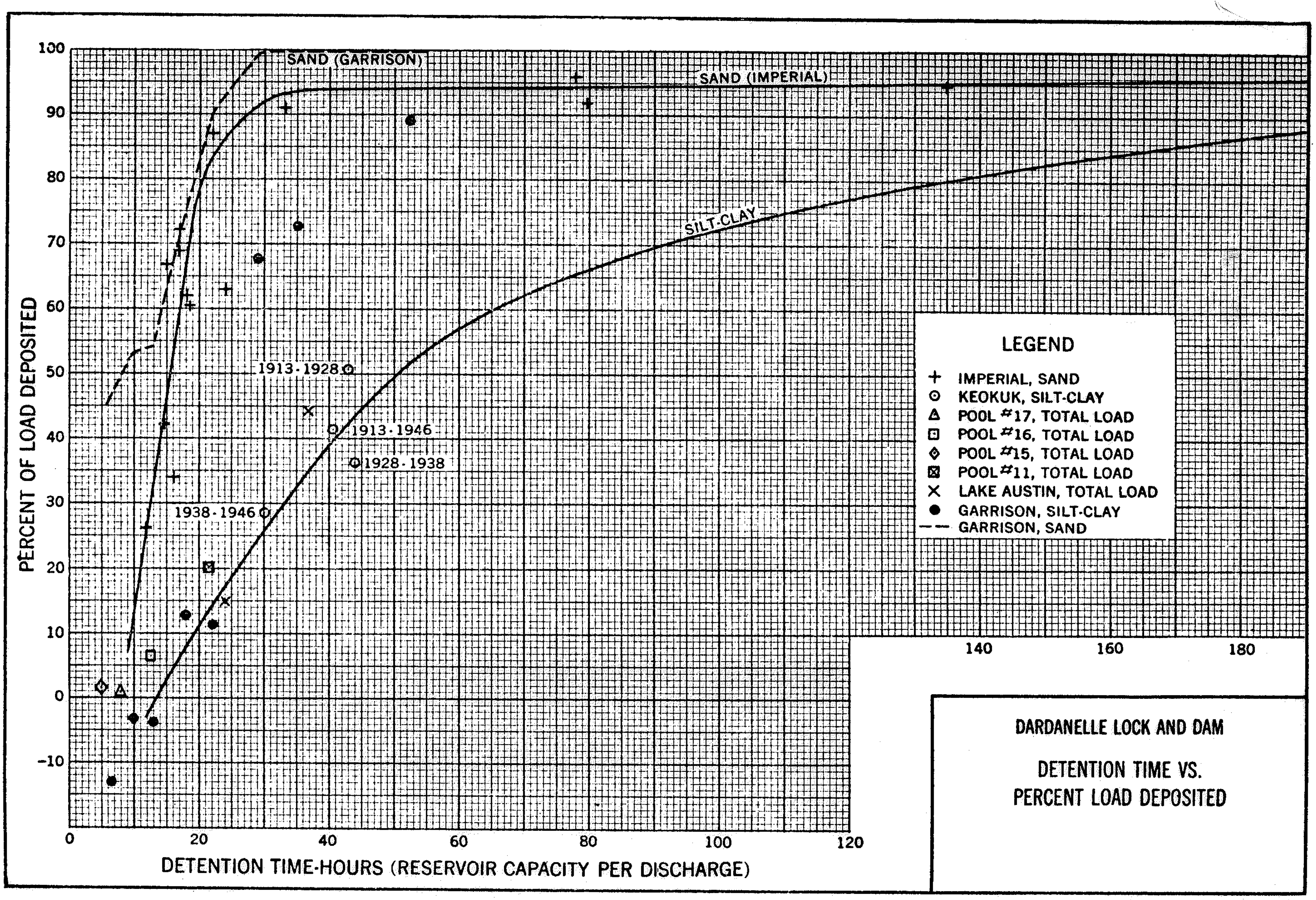

DARDANELLE LOCK AND DAM
DETENTION TIME VS.
PERCENT LOAD DEPOSITED
LEGEND
IMPERIAL, SAND
KEOKUK, SILT-CLAY
POOL #17, TOTAL LOAD
POOL #16, TOTAL LOAD
POOL #15, TOTAL LOAD
POOL #11, TOTAL LOAD
LAKE AUSTIN, TOTAL LOAD
GARRISON, SILT-CLAY
GARRISON, SAND
SAND (GARRISON)
SAND (IMPERIAL)
SILT-CLAY
1913-1928
1913-1946
1928-1938
1938-1946
PERCENT OF LOAD DEPOSITED
DETENTION TIME-HOURS (RESERVOIR CAPACITY PER DISCHARGE)
100
90
80
70
60
50
40
30
20
10
0
-10
0
20
40
60
80
100
120
140
160
180

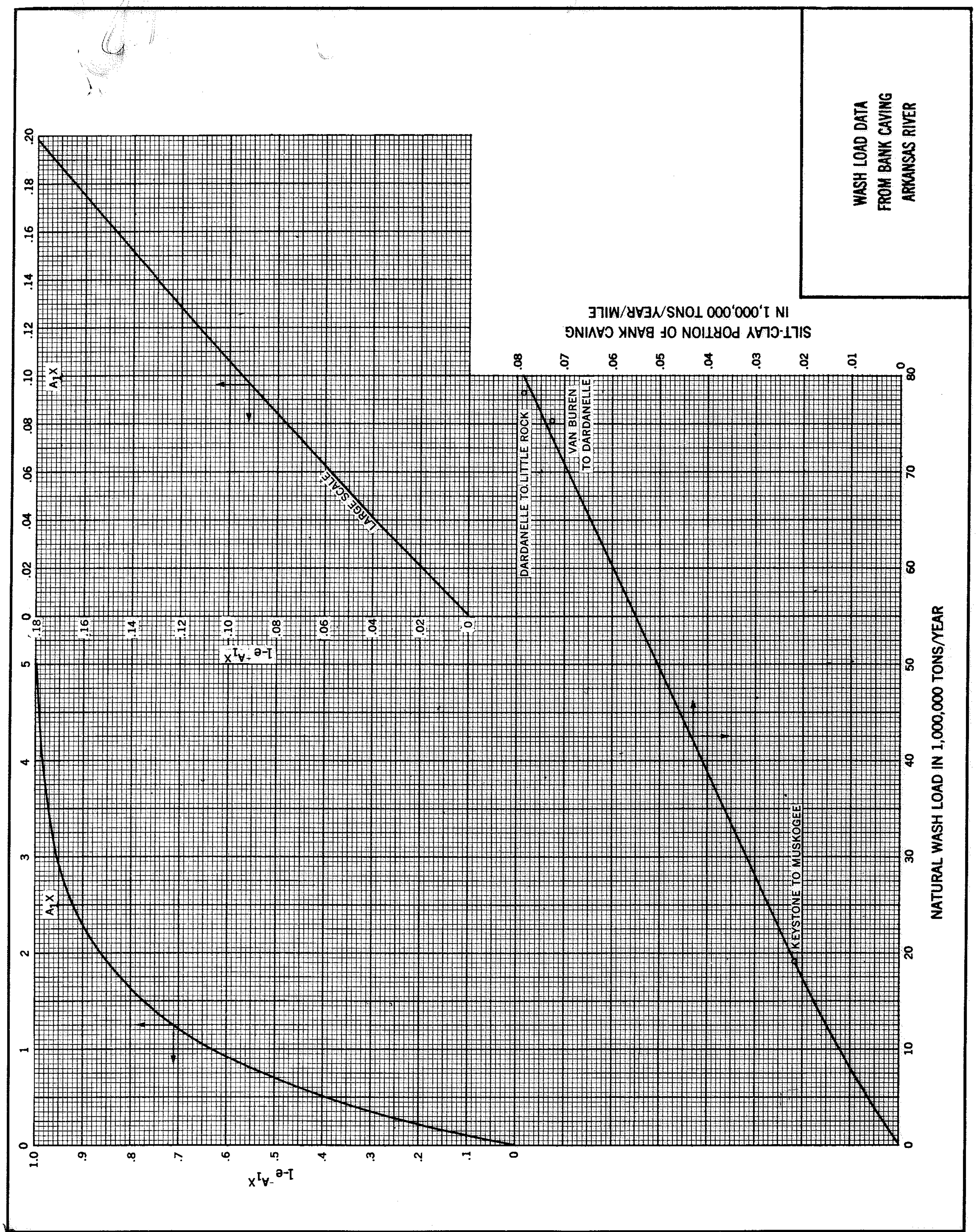
FIGURE 13

FIGURES 14 and 15 OMITTED

WASH LOAD FROM BANK CAVING

Project (1)	Un-protected bank length (miles) x (2)	Wash load portion of bank caving (1,000,000 t/yr./mi.) A_2 (3)	Gross wash load from bank caving (1,000,000 t/yr.) A_2x (4)	Natural wash load at projects (1,000,000 t/yr.) A_2/A_1 (5)	$A_1x = \frac{A_2x}{A_2/A_1}$ (6)	$1-e^{-A_1x}$ (7)	Net wash load at lower end of reach from bank caving (1,000,000 t/yr.) L (8)
		Years 1 and 2 after closure of Dardanelle					
		(Keystone to Verdigris River)					
Keystone	79	.0209	1.65	18.1	.091	.087	1.57
Total			1.65				1.57
		(Verdigris River to Webbers Falls)					
Keystone	112	.0209	2.34	18.1	.129	.121	2.19
Oologah	60	.0036	.22	2.8	.079	.075	.21
Ft. Gibson	41	.0105	.43	8.5	.051	.049	.42
Total			2.99				2.82
		(Eufaula to Arkansas River)					
Eufaula	27	.0375	1.01	36.2	.028	.027	.98
Total			1.01				.98
		(Webbers Falls to Van Buren.)					
Keystone	144	.0209	3.01	18.1	.166	.153	2.77
Oologah	92	.0036	.33	2.8	.118	.111	.31
Ft. Gibson	73	.0105	.77	8.5	.091	.087	.74
Tenkiller	45	.0010	.04	.7	.057	.055	.04
Eufaula	59	.0375	2.21	36.2	.061	.059	2.14
Wister	61	.0007	.04	.5	.080	.076	.04
Total			6.40				6.04
		(Van Buren. to Dardanelle)					
Keystone	171	.0209	3.57	18.1	.197	.179	3.24
Oologah	119	.0036	.43	2.8	.154	.142	.40
Ft. Gibson	100	.0105	1.05	8.5	.123	.116	.99
Tenkiller	72	.0010	.07	.7	.100	.095	.07
Eufaula	86	.0375	3.22	36.2	.089	.085	3.08
Wister	88	.0007	.06	.5	.120	.113	.06
			8.40				7.84

FIGURE 16



WASH LOAD DATA
FROM BANK CAVING
ARKANSAS RIVER
SILT-CLAY PORTION OF BANK CAVING
IN 1,000,000 TONS/YEAR/MILE
NATURAL WASH LOAD IN 1,000,000 TONS/YEAR
LARGE SCALE
DARDANELLE TO LITTLE ROCK
VAN BUREN
TO DARDANELLE
KEYSTONE TO MUSKOGEE
A_1X
$1-e^{-A_1X}$

FIGURE 17

Appendix 4

Procedure for Developing a Trap Efficiency Curve

NOTE: This information was presented in Project Design Memorandum No. 6, Sedimentation-Part IV, Section II. Deposition in Dardanelle Reservoir, Arkansas River and Tributaries, Multiple-Purpose Plan, Arkansas and Oklahoma, U.S. Army Engineer District, Little Rock, Corps of Engineers, Little Rock, Arkansas, October 1957.

GREEN App H Disclaimer

SECTION II

DEPOSITION IN DARDANELLE RESERVOIR

36. Procedures. When sediment loads enter the slack water of a reservoir the sand fraction is deposited first followed by the silt and clay sizes. The rate and location of the deposits depend on the discharge at the time, the sediment sizes, and the changes in velocity and depths of water across the flowway. Also, flocculation of the fine particles in suspension and density currents formed by differences in temperatures or sediment concentration are sometimes important both with respect to the amount and location of the deposits. It appears doubtful that density currents will be significant in increasing the passage of sediment through the Dardanelle Reservoir because as discussed previously the modified wash load is expected to be composed mainly of silt or sediment sizes too large for the formation of density currents. There are a number of possible approaches in estimating the deposition in a reservoir, each method varying in the detailed steps followed and depending on the basic data available and practical considerations of time and extent of the investigation. Owing to the uncertainty of obtaining conclusive results by following any single method, the results of several methods are shown herein for Dardanelle Reservoir.

37. Detention time method. This method is based on relationships between the detention time of flow through existing reservoirs and the percentage of sediment deposited. It is a means of approximately comparing one reservoir with another provided they have similar capacity-streamflow ratios and are regulated in the same manner.

Detention time as used herein is the ratio of the storage capacity to the discharge at any time. As a reservoir fills with sediment the detention time is reduced for a given discharge and less of the sediment load is deposited.

38. The following data are needed at existing run-of-river type projects for comparison with Dardanelle.

a. Capacity of reservoir for the time period under study, preferably including the storage under the backwater curve.

b. Volume of sediment deposited from resurvey of the ranges.

c. Average dry weight of the deposits in place for the period.

d. Representative grain size distribution of deposits.

e. Flow-duration curves of inflow and outflow for period.

f. Suspended load samples of inflow and outflow.

g. Size distribution of inflowing and outflowing load.

h. Estimate of bed load.

There are only a few existing reservoirs of a run-of-river type for which sufficient data are available for comparison with conditions at Dardanelle. Data for these projects are described in the following paragraphs. Supplemental estimates of missing data have been made where feasible.

39. Keokuk (Pool No. 19). Keokuk on the Mississippi is rather similar to Dardanelle, being a run-of-river type power and navigation project with an original capacity of 479,600 acre-feet and average flow of 57,000 c.f.s. compared to Dardanelle with 500,000 acre-feet of storage and an average flow of 41,000 c.f.s Keokuk was closed in 1913

TABLE 12

SEDIMENT DATA FOR KEOKUK (POOL NO. 19)

Date of range survey	Storage capacity acre-feet	Years between surveys	Lost capacity: Acre-feet	Lost capacity: Acre-feet per year	Dry weight Lb/cu.ft.
June 1913	479,600				
Average	425,000	15	109,300	7,300	50
June 1928	370,300				
Average	353,000	10	33,300	3,300	52
June 1938	337,000				
Average	325,000	8	25,000	3,100	54
June 1946	312,000				
Total		33	167,600		

Date	Deposits t/yr: Total	Deposits t/yr: Silt-clay	Sediment Inflow t/yr: Total	Sediment Inflow t/yr: Silt-clay	% Deposited: silt-clay	Average flow (c.f.s.)	Flow, 10% time (c.f.s.)	Detention time (hours)
1913-28	7,940,000	7,146,000	15,560,000	14,000,000	51.0	58,700	118,000	43
1928-38	4,200,000	3,780,000	11,515,000	10,400,000	36.4	48,000	97,000	44
1938-46	4,450,000	4,005,000	15,430,000	13,900,000	28.8	65,000	131,000	30
1913-46	5,950,000	5,355,000	14,300,000	12,900,000	41.6	57,000	118,000	40.5
Computed deposits from silt-clay curve on Plate 22.								
1913-28		6,601,000						
1928-38		4,939,000						
1938-46		4,518,000						
1913-46		5,705,000						

and sediment range resurveys were made in 1928, 1938, and 1946. By 1946, after 33 years of operation, the reservoir had lost 167,600 acre-feet, or 35 percent of its capacity. The results of these surveys are shown in "Reservoir Sedimentation Data Summary" and in Table 12 herein with the average inflow for the periods between surveys.

40. In 1956 the Rock Island District spudded at eight locations spaced throughout the reservoir and obtained unit weights and grain size distribution of the deposits. From those data an average dry weight of 55 pounds per cubic foot was computed. The deposits in a reservoir become denser with age. Using the terminal unit weight of 55 pounds per cubic foot and the formula listed below by Lane and Koelzer (2) as a guide, unit dry weights of 50 to 54 pounds were assumed for the periods as shown in Table 12. The formula is:

Weight of sand = 93 pounds/cu. ft.

Weight of silt = 65 + 5.7 log (No. of years of deposit)

Weight of clay = 30 + 16 log (No. of years of deposit)

The size distribution of the deposits used were 10 percent sand, 53 percent silt, and 37 percent clay. The volumes of deposits were then converted to weight in tons as shown in Table 12. Conversion of the deposits to weight was necessary to compare with the sediment load inflow which was of course sampled in terms of percent of sediment by weight of water mixture.

41. The next step was to estimate the sediment inflow to Keokuk for the different periods. The flow-duration curves were determined for the periods as shown on plate 20. The Rock Island District has sampled the

suspended load at Burlington, Iowa, near the head of the Keokuk pool during the years 1944 to 1950 and determined the average annual suspended load. The Soil Conservation Service has also made similar estimates. An average load curve is shown on Plate 21 which is intended to include both suspended and bed load. By applying the flow-duration curves on Plate 20 to the average load curve on Plate 21, the average annual inflowing load for each period between range surveys was computed. As the load curve on Plate 21 is based on sediment measurements after construction of the upstream pools Nos. 11 to 17, it was necessary to correct the loads for the periods 1913-28, 1928-38, and 1938-46 to allow for the sediment which was trapped in those pools (deposits in those pools are described in par. 43). Finally, the silt-clay loads for the respective periods were separated from the total load as shown in Table 12. Grain-size analysis of samples by the Rock Island District indicate that the load is composed of about 10 percent sand and 90 percent silt-clay. The primary interest in Keokuk herein is the silt-clay fraction. The percentages of inflowing silt-clay load deposited in the reservoir for the four periods are shown in Table 12.

42. In order to develop a relationship between detention time and percent of sediment deposited for the respective periods between resurveys it is necessary to know the representative detention time to plot since it varies with each discharge. It was found that the best trial-plotting position was for a discharge corresponding to the percent of time when about half the load was transported, or 10 percent of the time for Keokuk. The detention times for flows occurring 10 percent of the time are shown in Table 12. The plotted points of detention time versus percent of

TABLE 13

SEDIMENT DEPOSITS - KEOKUK (POOL NO. 19)
1913-1928

Increment of time %	Inflow 1,000 c.f.s.	Silt-clay load 1,000 t/day (1)	Days/yr.	Silt-clay wtd. by time t/day	Detention time hours (2)	% Silt-clay deposits (3)	Silt-clay deposit 1,000 t/day (4)
2.5	13.7	1.4	9.12	40	375	98	39
5.0	17.7	2.5	18.25	125	291	96	120
5.0	20.8	3.4	18.25	171	247	94	161
5.0	23.0	4.2	18.25	211	224	92	194
5.0	25.4	5.1	18.25	257	202	90	231
5.0	27.8	6.0	18.25	302	185	87	263
5.0	30.5	7.3	18.25	365	169	85	310
5.0	33.0	8.6	18.25	428	156	83	355
5.0	36.0	10.1	18.25	507	143	81	411
5.0	39.2	12.0	18.25	599	131	79	473
5.0	43.1	14.6	18.25	730	119	77	562
5.0	47.5	17.7	18.25	884	108	75	663
5.0	50.3	19.8	18.25	992	102	73	724
5.0	59.6	27.5	18.25	1,374	86	68	934
5.0	67.5	35.0	18.25	1,750	76	65	1,138
5.0	76.9	45.6	18.25	2,280	67	61	1,391
5.0	87.5	58.7	18.25	2,936	59	57	1,674
5.0	100.5	77.5	18.25	3,876	51	51	1,977
5.0	118.0	106.0	18.25	5,301	44	44	2,332
3.75	143.4	156.3	13.69	5,857	36	34	1,991
2.5	168.0	213.0	9.13	5,330	31	27	1,439
1.25	210.0	331.0	4.56	4,133	24	17	703
Tons/day				38,356			18,085
1,000 tons/yr.				14,000			6,601
				From range surveys, Table 12			7,146

(1) Without upstream pools.

(2) $\frac{12.1 \times \text{av. capacity}}{\text{Flow}} = \frac{425{,}000}{\text{Flow}}$

(3) From silt-clay curve of detention times vs. percent deposited, Plate ~~21~~. 22

(4) Column 7 x column 5.

the silt-clay load deposited are shown on Plate 22 with a curve drawn approximately through the points. An example of the trial computations to check the curve is shown in Table 13 for the 1913-28 period. The percent of time and corresponding discharges, sediment load, and detention times are listed in the table. The detention time is the ratio of the average available level storage for the period divided by the discharges as noted by footnote. The corresponding percentages of sediment deposited are obtained from the silt-clay curve on Plate 22 and multiplied by the loads to obtain the deposits. The sum of these deposits is 6,601,000 tons per year compared to the estimated value of 7,146,000 tons from the range survey, or a discrepancy of about 8 percent for the 1913-28 period. Similarly, the other three periods were tested and the computed deposits are shown in the lower part of Table 12. They may be compared with the silt-clay deposits from the range surveys shown immediately above. It will be noted that the silt-clay curve on Plate 22 is poorly defined for detention times greater than about 50 hours. However, that part of the curve corresponds to the smaller discharges and therefore the smaller sediment loads, so that this part of the curve is relatively insensitive to error.

50. Garrison Reservoir. Garrison is a large multiple-purpose project on the middle Missouri River. On 7-9 July 1954 the suspended load was sampled and the hydraulic elements were measured at a number of ranges starting at the head of backwater and terminating in the lake where most of the load had been deposited. The discharge at the time was about 30,000 cubic feet per second. The results of this survey are

given in reference (29). Similar surveys were made at Fort Peck and Fort Randall. The differences in the concentration at successive ranges indicate the sediment load deposited. The percent deposited upstream from any range may be computed from the data as well as the storages and detention times.

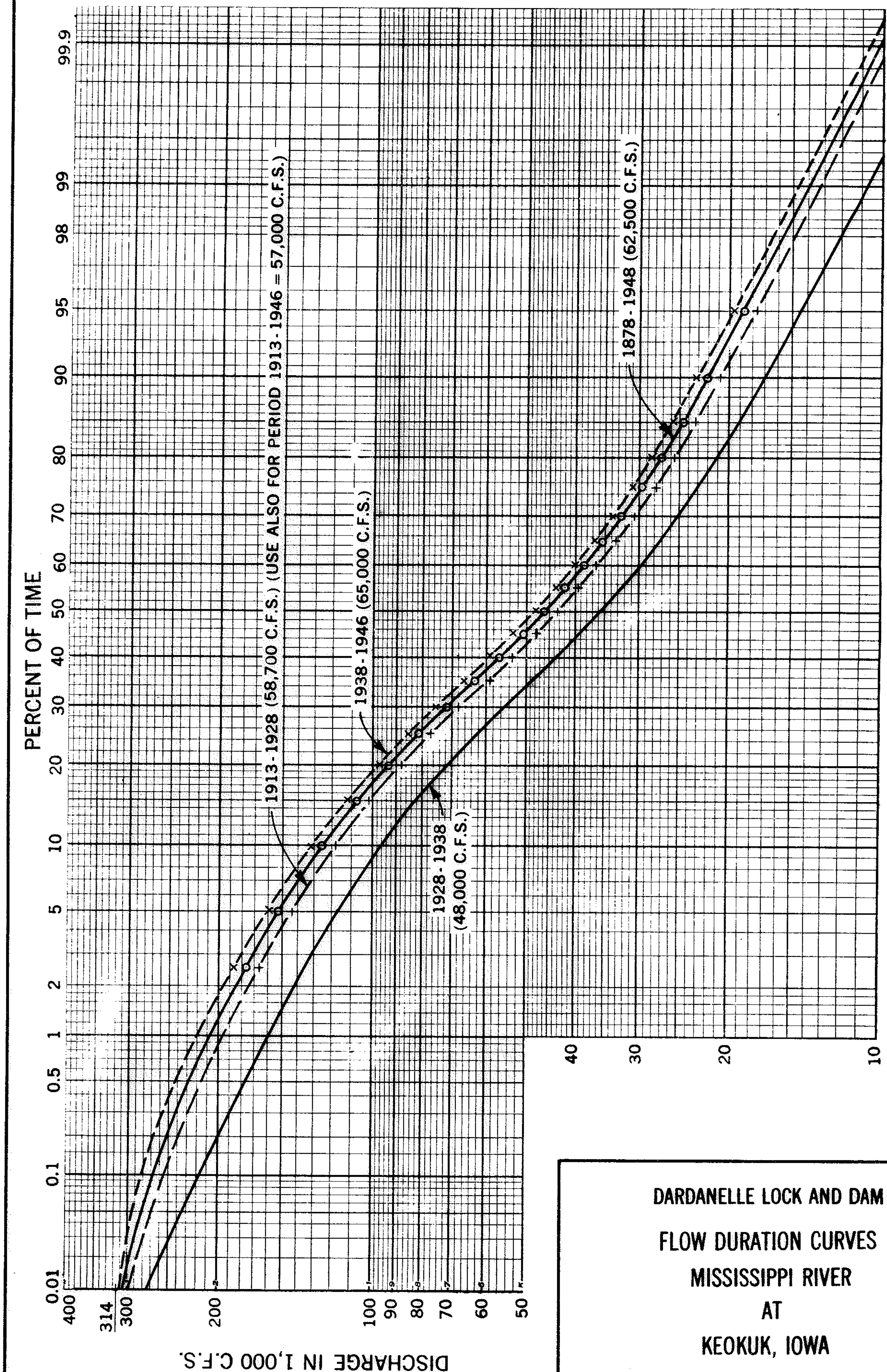
51. A summary of this information for Garrison Reservoir is shown in Table 17. The percent deposits of sand and silt-clay are shown separately. The detention times versus percent of deposits for these two size fractions are shown on Plate 22, representing accumulated values above the respective ranges. The plot of the sand fraction follows the trend of the data shown for Imperial Dam. The silt-clay fraction checks the silt-clay curve shown for short detention times, but indicates a generally steeper curve as will be noted from the points for detention times of 29 to 52 hours. The plotted values showing minus deposits, or scour, may be the result of error in measuring the concentration, although scour will sometimes occur with short detention times. The data are not fully comparable to the other information shown. Storages under the backwater curve were included in computing the detention time and the cross sections used omitted dead water areas. Also, Garrison is a large storage reservoir and the velocities decrease rapidly as the flow reaches the deeper part of the lake. This may account in part for the steep trend of the plotted points, or the more rapid fall out of the suspended load. The data for Fort Peck and Fort Randall indicate a similar trend and are not shown. While this type of information is limited, it is of considerable interest and contributes to the available

records. Further reference is made to the report on these projects in connection with another method considered herein for estimated sediment deposits in Dardanelle Reservoir.

TABLE 17

SEDIMENT DATA FOR GARRISON RESERVOIR, MISSOURI RIVER

Range	Mile and distance	Accumulated storage acre-feet	Discharge c.f.s.	Detention time hours	Suspended sediment concentration: Sand: Concentration p.p.m.	Sand: Accumulated deposits p.p.m.	Sand: Percent deposited	Silt-clay: Concentration p.p.m.	Silt-clay: Accumulated deposits p.p.m.	Silt-clay: Percent deposited
Sanish Bridge	1,558		29,800		392			1,085		
	13	16,000		6.5		176	45		-137	-13
22	1,545		29,800		216			1,222		
	7	24,500		10		208	53		-35	-3
23	1,538		29,800		184			1,120		
	6	31,800		13		212	54		-47	-4
23A	1,532		29,800		180			1,132		
	9	44,500		18		289	74		143	13
23D	1,523		29,800		103			942		
	6	53,600		22		354	90		121	11
23E	1,517		29,800		38			964		
	6	70,500		29		389.6	99.5		741	68
24	1,511		29,800		2.4			344		
	4	87,200		35		390.4	99.6		796	73
25	1,507		29,800		1.6			289		
	8	127,200		52		391.4	99.8		963	89
26	1,499				0.6			[illegible]		

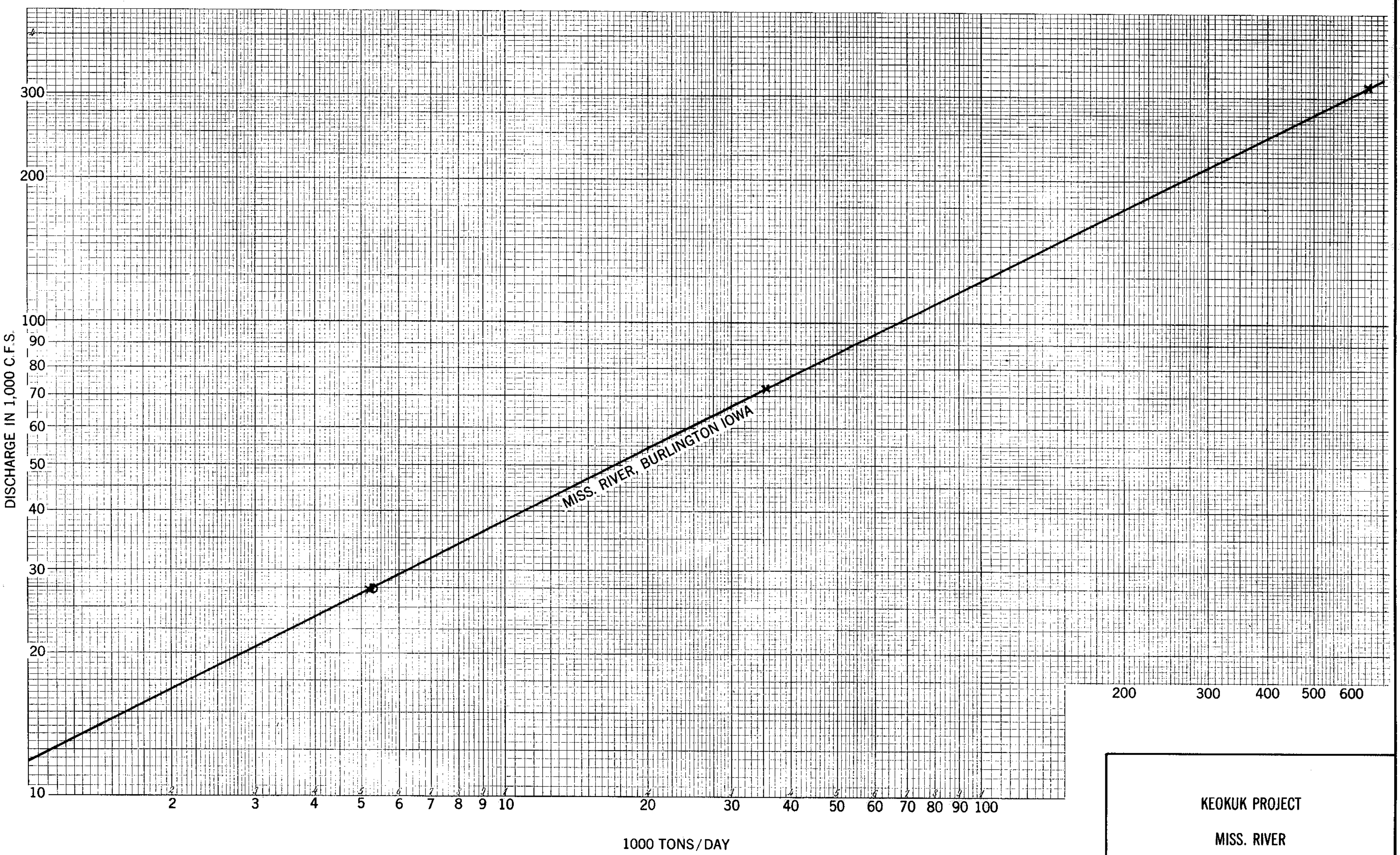


DARDANELLE LOCK AND DAM

FLOW DURATION CURVES
MISSISSIPPI RIVER
AT
KEOKUK, IOWA

CORPS OF ENGINEERS

U. S. ARMY



KEOKUK PROJECT

MISS. RIVER

SUSPENDED INFLOW LOAD

PLATE 21

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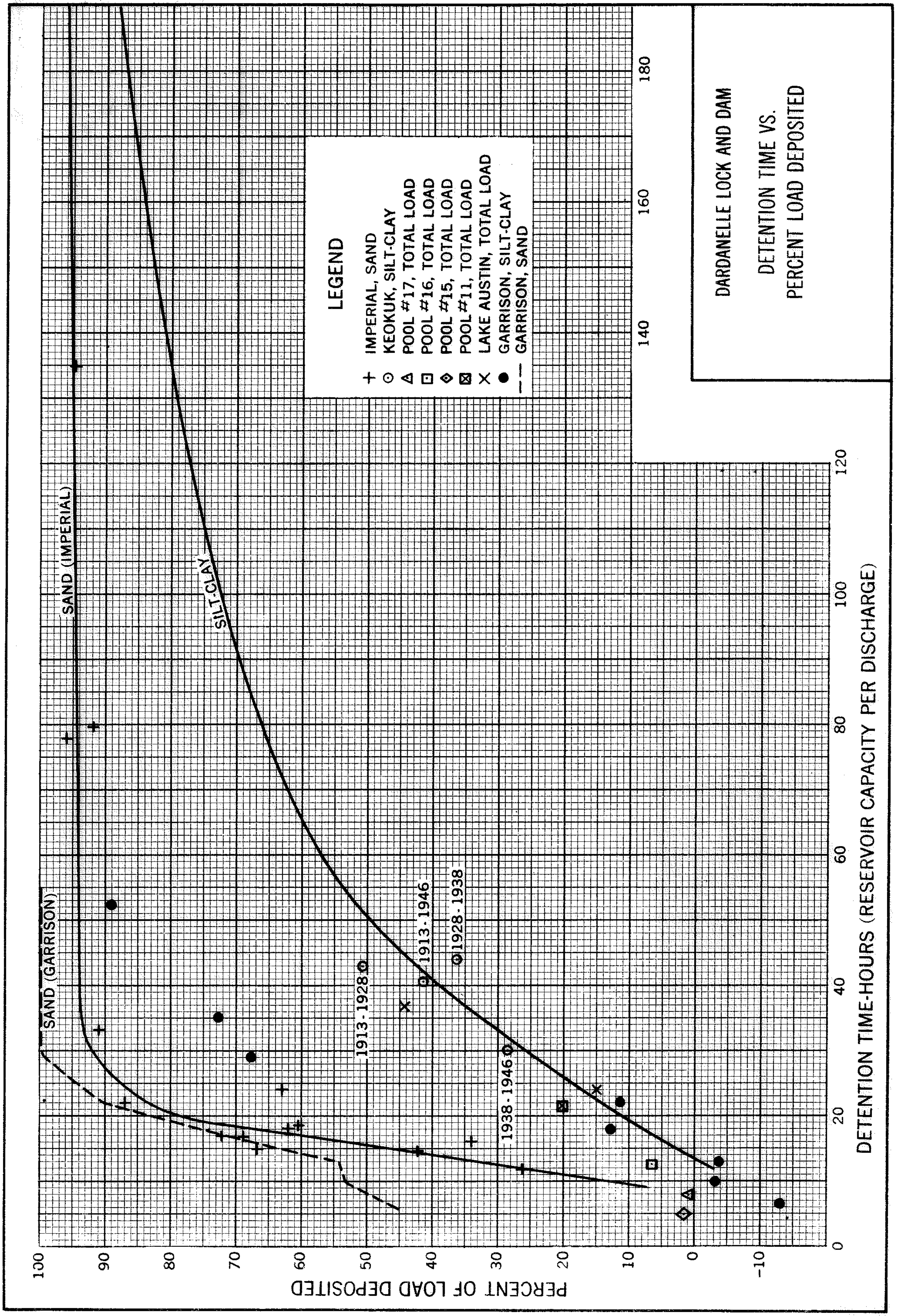
DARDANELLE LOCK AND DAM
DETENTION TIME VS. PERCENT LOAD DEPOSITED
LEGEND
+ IMPERIAL, SAND
⊙ KEOKUK, SILT-CLAY
△ POOL #17, TOTAL LOAD
□ POOL #16, TOTAL LOAD
◇ POOL #15, TOTAL LOAD
⊠ POOL #11, TOTAL LOAD
× LAKE AUSTIN, TOTAL LOAD
● GARRISON, SILT-CLAY
— — GARRISON, SAND
SAND (IMPERIAL)
SAND (GARRISON)
SILT-CLAY
1913-1928
1913-1946
1928-1938
1938-1946
DETENTION TIME-HOURS (RESERVOIR CAPACITY PER DISCHARGE)
PERCENT OF LOAD DEPOSITED

Appendix 5

Forecasting Distribution of Sediment Deposits in Large Reservoirs

DEPARTMENT OF THE ARMY
Office of the Chief of Engineers
Washington, D.C. 20315

ETL 1110-2-64

ENGCW-EY

Engineer Technical
Letter No. 1110-2-64

7 July 1969

ENGINEERING AND DESIGN

Distribution of Reservoir Sediment Deposits

1. Purpose and Scope. The purpose of this ETL is to present a discussion of problems associated with reservoir sediment accumulations and to review pertinent planning and design considerations relating to anticipated distributions of reservoir deposits. This letter is applicable to all Divisions and Districts concerned with civil works activities.

2. References: a. Paper entitled "Forecasting Distribution of Sediment Deposits in Large Reservoirs," by Brice L. Hobbs (Appendix I).

b. EM 1110-2-4000, "Reservoir Sedimentation Investigations Program," 15 November 1961.

3. Discussion: a. The importance of forecasting the probable distribution of reservoir sediment deposits is often overlooked in planning and design investigations. Many recent project design reports present only one or two brief paragraphs concerning the gross volume of storage space depletion anticipated during the period considered for economic investigation and make no reference to possible serious problems that might be created by adverse distributions of sediment deposits in particular areas or elevation zones. Conditions at certain reservoirs which have been in operation for long periods point up the need for making sediment distribution studies in connection with most reservoir design investigations; this is particularly true of all projects on streams which transport substantial quantities of sediment.

b. In most of the check computations made in the Office of the Chief of Engineers in reviewing the methodology and results of field measurements, the results obtained by the "Pool-Elevation Duration Method," presented with Appendix I, have been found to give results comparing favorably with the measured values. However, there are a few instances where the values estimated for certain elevation zones depart appreciably from the measured values reported in the "Reservoir Sediment Data Summaries" submitted in accordance with EM 1110-2-4000 (ref 2b). This is also true of estimates obtained by other methods. The reasons for some of these discrepancies are obscure while in others, examination of the records yield logical explanations. For example, it is doubtful that conditions of deposition in Jemez Canyon Reservoir in New Mexico could have been accurately predicted by any of the currently available empirical methods, since substantial quantities of material have accumulated in reservoir-elevation zones high above the maximum experienced pool elevation, and it appears likely that some of the deposition is wholly unrelated to reservoir effects.

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1 of 8

4. <u>Action to be Taken</u>. The information presented in Appendix I discusses various types of upstream sedimentation problems that may be induced by the construction and operation of a dam and reservoir. The computational procedures outlined in the report, and those described in references therein, are representative of methods available for estimating the locations of future sediment deposits in reservoirs. The practices and techniques described in Appendix I have been found by long experience to give generally satisfactory results in estimating future sediment conditions. Accordingly, it is suggested that Corps representatives utilize the methods and techniques outlined in the inclosed report, where feasible, in connection with sediment investigations.

FOR THE CHIEF OF ENGINEERS:

Wendell E. Johnson

WENDELL E. JOHNSON
Chief, Engineering Division
Civil Works

I Appendix
Forecasting Distribution of
Sediment Deposits in Large
Reservoirs, 10 Feb 69

APPENDIX I

FORECASTING DISTRIBUTION OF SEDIMENT DEPOSITS IN LARGE RESERVOIRS

by Brice L. Hobbs 1/

Reservoir impoundments disrupt the natural order of the processes of sediment transportation in streams and the results range from those that are relatively insignificant to those where undesirable deposition is expected to seriously affect the utility of the project within a relatively short period of time. It is the purpose of this discussion to characterize some of the problems, discuss certain practical considerations regarding the importance of forecast estimates and to present some approaches for approximating future distributions of sediment deposits in large artificial reservoirs.

RESERVOIR CLASSIFICATION ACCORDING TO SIZE

Usually there is a considerable degree of ambiguity in designation of a reservoir as "large" or "small". The capacities of the reservoirs considered herein range from about 60,000 to 20,000,000 acre-feet at elevations of the spillway crests. Perhaps the descriptive terms "large" or "small" should not be emphasized in discussions of reservoir sedimentation; comparisons of relationships such as capacity-inflow ratios are more meaningful. However, the size of a reservoir (and therefore, the areal changes associated with pool fluctuations) is one of the more important influences affecting the distribution of sediment deposits. Accordingly, the vague demarcation between large and small reservoirs is likely to persist.

DISTRIBUTION PROBLEMS

General - Information on sedimentation contained in many reservoir planning and design reports suggest that those responsible attach little importance to the possible affects of adverse distribution of the sediment. Often times the only information presented consists of a brief statement to the effect that estimated depletion for 50 or 100 years will represent only a small fraction of the gross storage. In this connection it should be mentioned that there have been some important problems associated with local deposits where depletion of gross storage is not expected to be serious for 1000 years or longer.

Depletion of Storage Space - If volumetric reductions of reservoir storage space allocated for various purposes represented the only problems associated with reservoir sedimentation, forecast information of fractional distributions of total deposits would not serve any particularly useful purpose even where rapid gross depletion is anticipated. If such were the case it would only be necessary to make appropriate reallocations as would be indicated by periodic resurveys. However, the significance

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of storage depletion and other related problems depend generally upon the average sedimentation rates and progressive distribution of deposits. On alluvial streams, it is usually important to have forecast estimates of the probable distributions of deposits both with respect to areal location and volumetric accumulations in various elevation zones. Such information is useful in connection with planning and design considerations to assure that serious encroachments upon space allocated for purposes other than sediment retention will not occur during the period used for economic analysis of the project. Some important sediment distribution problems are discussed further in the following subparagraphs.

Aggradation of Tributary Channels - A reservoir on an alluvial stream is one of the more important manmade influences which may affect channel conditions. The aggradation of channels which sometimes occurs above reservoirs is an extension of the reservoir sedimentation processes which may adversely affect drainage conditions and aggravate flooding problems on adjacent lands. Relatively small fractions of the total accumulations are usually involved in the aggradation of channels in the reaches of reservoir-backwater influences above established pool levels and future dimensions of aggraded channels cannot be accurately forecast by known methods.

Aesthetic Effects - Regardless of the need for sediment distribution estimates for other purposes, it is occasionally important to foresee future conditions which might be unsightly and therefore objectionable to people residing nearby.

Depletion of Storage Space in Single-Purpose Reservoirs - Normally a reasonable estimate of the total volume of sediment anticipated during the period used for economic considerations is all that is necessary for establishing storage requirements in single-purpose reservoirs, and advance information regarding the locations of the deposits is usually not needed. Exceptions may be found in cases where substantial inactive storage is required in reservoirs operated primarily for power production.

Depletion of Storage Space in Multiple-Purpose Reservoirs - In cases where sediment yields are appreciable, advance information of probable future distributions of sediment deposits is important in connection with planning and design considerations of storage depletion regardless of the project purposes. Misjudgments involved in the initial allocations of storage space cannot always be satisfactorily rectified by reallocations of space remaining at some future date. For example, head limitations might preclude lowering the elevation of the minimum power pool.

Depletion of Space Where Water is Stored for Recreational Purposes - Recently, there has been a rapid increase in demands for storage of water for recreational activities in artificial lakes. The needs are usually satisfied by: use of water stored primarily for other purposes; provisions for perpetual storage of a given volume of water regardless of pool elevation; specific allocations of storage below a given pool elevation; or arrangement for regulation so as to provide for a minimum pool having storage not exceeding that provided for conservation and the undepleted space initially reserved for sediment. There is general agreement regarding the importance of recreational needs, therefore, the problems that may be expected to result from unfavorable sediment distributions should be recognized. For example, a plan to continuously provide a small pool of fixed volume in the lowest elevation zone of remaining space may become completely unsatisfactory for the planned activity relatively early in the life of the project. Also, decisions are often made, after completion of the design stage and without benefit of additional engineering study, to regulate a reservoir so as to utilize space reserved for sediment deposits for recreational or other conservation purposes. In such cases there is no opportunity for changing the total storage, therefore, the effects of the change on sediment distribution expected to result from the change in regulation procedures should be carefully examined.

Shore Erosion - Shore erosion and bank caving processes frequently create beach and boat harbor problems. Movement of material by these processes may cause an exchange of storage space between elevation-zones or a net storage loss or both.

Utilization of Delta and Backswamp Areas - Interests opposing the construction of reservoirs frequently cite sedimentation as one of the horrible consequences of these developments and the general public is led to believe that the results are always entirely bad. Actually, the program for wildlife propogation, by the U. S. Fish and Wildlife Service, in the delta areas of Denison Reservoir is reported to be quite successful. This represents a type of planning problem that has not had proper consideration in the past.

FACTORS AFFECTING DEPOSIT ACCUMULATIONS

General - The factors involved in reservoir sedimentation processes are numerous. The influences most frequently mentioned in qualitative discussions[1/] are: (1) Reservoir size and shape; (2) Sediment quantities and characteristics; (3) Sediment sources; (4) Progressive vegetative growth on frequently exposed deposits; (5) Consolidation of deposits; (6) Magnitudes, frequency and sequences of hydrologic events; and (7) Reservoir regulation practices. These factors and other influences comingle in ever changing combinations to produce the distribution of deposits at any given time.

Dominant Factors - As indicated above, the distribution as well as the quantities of sediment involved, are sensitive to numerous factor combinations which include unpredictable sequences of flood events and pool elevations coincident with high sediment inflows. Regulation is one of the dominant influences affecting deposition in reservoirs. In fact, the first five factors listed above are governed in some degree by pool fluctuations. The charts and diagrams shown on Incls 1 and 2 illustrate the effects of regulation on sediment deposition in a large multiple-purpose reservoir.

Incl. No. 1 shows estimated sand loads delivered by a design flood which was developed for a large reservoir on an alluvial stream. The flood was assumed to have started at a time when the pool level was at the bottom of the flood control pool. Attention is directed to the cumulative sand curve which shows that 97 percent of the sand transported by the flood would be delivered to the reservoir before the maximum pool elevation was reached. The sand load graph is based upon an average rating curve and therefore, has the same shape and peak time as the discharge hydrograph; actually maximum suspended sediment concentrations quite often precede peak discharge rates and under such conditions, the cumulative sand curve would be in a position to the left of that shown on Incl 1.

Coincidental values of inflow and pool elevations from graphs on Incl 1 were used to develop the general illustration shown on Incl 2. The locus of the upstream limits of backwater effects in this hypothetical situation further demonstrates why most of the sediment delivered to a large flood-control reservoir, by any given flood, is transported to areas below the higher pool elevations attained. Also, it affords some insight to tendencies for material previously deposited to be redistributed. Reference Nos. 1/ through 5/ contain considerable additional information regarding the manner in which sediment is transported into and deposited in a reservoir.

METHODS FOR ESTIMATING DISTRIBUTION OF SEDIMENT DEPOSITS

General - There are several methods described in the literature for estimating future distributions of sediment deposits. For purposes of this discussion, it is considered satisfactory to classify these methods as: (1) analytical methods[2/], [3/], [4/] which utilize procedures based upon theoretical concepts of hydraulics and sediment transport and (2) purely empirical methods[5/]. All methods are subject to limitations imposed by necessary simplifications involving uncertain assumptions regarding sequences of significant hydrologic events and lack of accountability for other dominant influences which help to produce individual deposition patterns. For example, large tributaries occasionally transport 5 to 10 times the average annual sediment load in a 10-day period and the range of extremes in "low-order" tributaries is often much greater. There is no way of predicting when during the project life, extreme events may occur. The uncertainties and difficulties not withstanding it is important to make the best possible distribution determination commensurate with probable seriousness of anticipated problems and practical considerations of the purpose of the estimate, available data and time allowed for the study.

Choice of Methods - Where sediment deposition is expected to have a major effect upon the design and operation of a reservoir project, it is prudent to use more than one approach so that the results of somewhat independent determinations can be used as guidance for judgment in allowances for conservatism. In many project investigations it is impracticable to attempt detailed analyses, to consider the probable effects of many individual influences, because of insufficient data and a number of other limitations. With present knowledge, the writer believes that in most cases the results obtained by empirical methods are sufficiently reliable for engineering purposes. However, there are many cases where thoroughly rigorous sedimentation analyses are imperative. Dardanelle Reservoir[4/] is one example. Also, there are cases where serious tributary channel and flood-plain aggradation may be expected to accompany delta developments. In some of these situations, it may be found reasonable to use empirical methods to establish the initial condition assumed for the starting point in an analytical study of patterns of continued deposition.

Empirical Methods - In practice, empirical methods are being used in most instances where sediment distribution estimates are required. These methods have the advantage of simplicity but sacrifice consideration of some important influences and when followed implicitly, these methods often produce misleading results. This is true of the method presented herewith as well as all of those described in literature known to the writer. All depend upon the same basic requirements for estimates of total sediment loads, average trap efficiencies and gross volumes of sediment trapped during the period under consideration. None delineate developments at individual tributaries. The methods described by Borland and Miller[5/] are probably most widely used in the United States; it is believed that the principal weakness of these methods is that no particular consideration is given to the sediment characteristics or the operational effects of the reservoirs. The method presented in Incl 3 also has obvious weaknesses but consideration is given to sediment characteristics and regulatory influences.

Pool-Elevation Duration Method - This empirical method attempts to account for the influences of reservoir regulation inherent in a pool-elevation duration curve, general effects of the fraction of sand materials involved and the size and shape of the reservoir. The approach is based upon the idea that pool elevation and the size characteristics of the sediment are two of the most important factors influencing deposition in given elevation zones. It also embodies the thesis that: (1) over a long period of time, sediment delivered by medium and moderate floods will establish some statistical order of coincidence with pool elevations between the maximum and minimum and (2) that regulation of the rare floods (and therefore, the distribution of sediment deposited in the higher elevation zones) will be similar. This suggests that there may be some reasonably definable relationships between duration of a given pool and the amount of sediment that will be deposited above and below the elevation of that pool. Step procedures for one simple approach are presented in Incl 3. This index method is based upon limited data and its reliability for general application will require much more testing. There are several refinements that appear worthy of further study.

Apps 7 & 8

CONCLUDING OBSERVATIONS

1. The Reservoir Sediment Data Summaries assembled and published by the Committee on Sedimentation, Water Resources Council, represent the most complete source of available information on sediment distribution but relatively few of these data summaries contain information regarding the sediment size characteristics. Also, many of the formal sediment survey reports, which present these summaries and other information, contain little useful data on particle sizes.

2. Some thought might well be given to the utility of certain information presented in accordance with the instructions issued for preparing certain items of the Reservoir Sediment Data Summaries. For example, in some large reservoirs the capacity at the elevation of the spillway crest elevation may bear little or no relationship to the trap-efficiency; some other capacity value would often be more meaningful in capacity-inflow ratios.

3. A great mass of reservoir sediment data has been collected on a routine basis according to somewhat arbitrary observation schedules. Analytical studies of these data to establish useful relationships for general application and to identify data collection deficiencies have lagged far behind the data collection programs. It is believed that some of the money being used for surveys should be diverted for funding some intensive analytical studies of the information now available.

4. Without the aid of electronic computers, it would generally be impracticable to attempt rigorous analytical investigations aimed at predicting future distributions of sediment deposits in large reservoirs having a large number of tributaries. Important advances have been made in computer applications in hydrologic analyses relating to flood inflows and regulation of reservoirs. Also, considerable progress has been made in the use of electronic computers in sediment discharge determinations.[6/] The possibilities for integrating these techniques appears to offer the greatest promise for development of improved analytical procedures for investigating reservoir sediment distributions.

Incls
1. Illustration-Coincidental Sand Inflows & Reservoir Pool Elevations
2. Illustration-Locus of Upstream Limits of Reservoir Effects
3. Paper-"Forecasting Sediment Distribution in Large Reservoirs"

References on subject of Sediment Distribution in Large Reservoirs

1/ E. W. Lane, "Some Aspects of Reservoir Sedimentation," India Central Board of Irrigation and Power Journal, V. 10, No. 2-3 (Apr-July 1953).

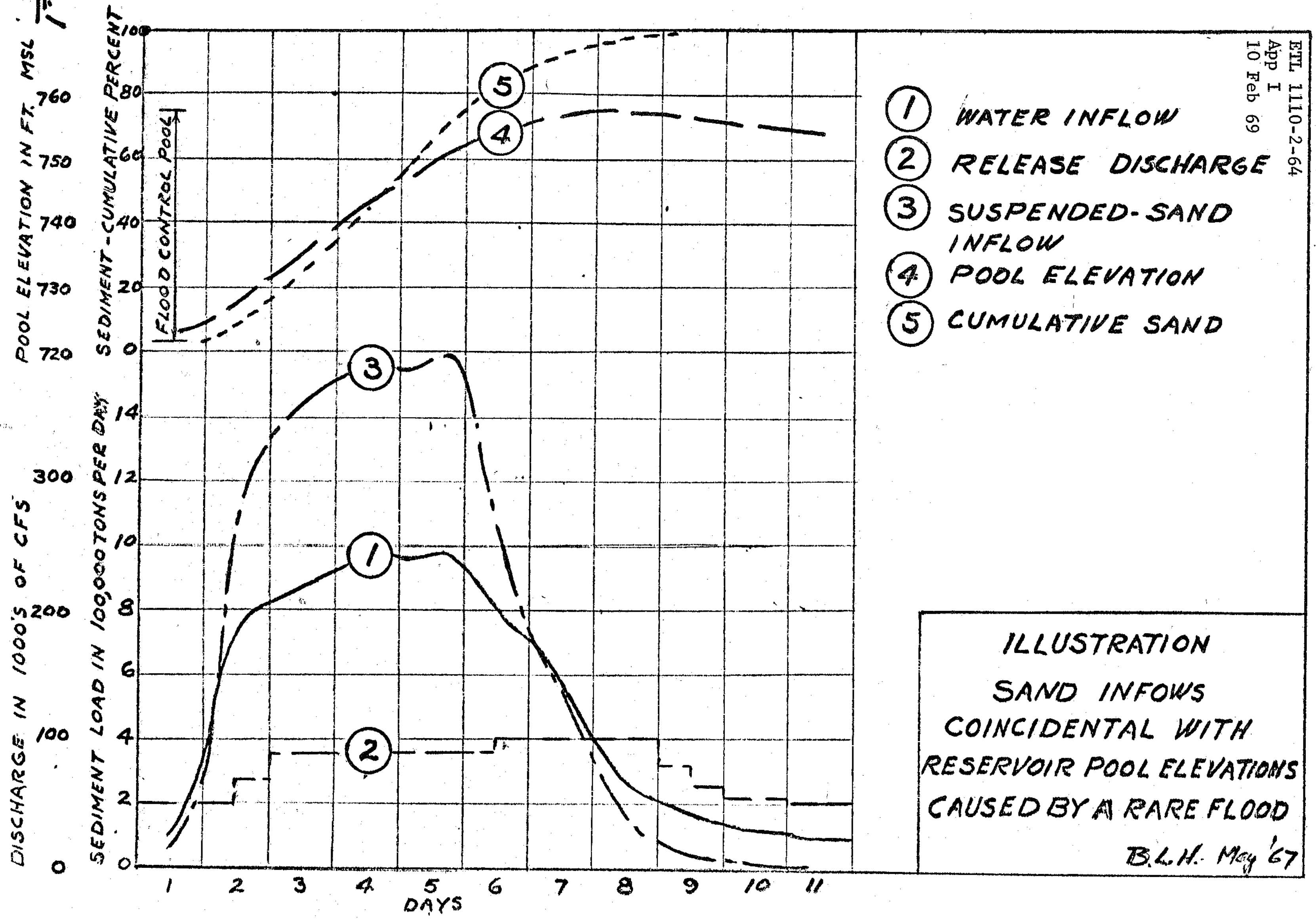
2/ L. C. Fowler, "Determination of Location and Rate of Growth of Delta Formations," Missouri River Division, Corps of Engineers, Sediment Memoranda No. 6, Nov 1957.

3/ A. S. Harrison, "Deposition at Heads of Reservoirs," Proc. Fifth Hydraulics Conference, State University of Iowa, June 9-11, 1952; Bul. 34.

4/ Project reports for "Arkansas River and Tributaries, Arkansas and Oklahoma," prepared by Corps of Engineers, Little Rock District
- (a) "Design Memorandum No. 6, Sedimentation - Part IV, Dardanelle Reservoir," Oct 1957.
- (b) "Supplement to Project Design Memorandum No. 6-4, Sedimentation, Dardanelle Reservoir, Jan 1959.

5/ W. M. Borland and C. R. Miller, "Distributions of Sediment in Large Reservoirs," Am. Soc. Civil Engrs. Journ, Hyd, Div., Vol 86, p. 61-87, Apr 1960.

6/ "A Procedure for Computation of the Total River Sand Discharge and Detailed Distribution, Bed to Surface", by F. B. Toffaleti, Nov 1968 (Technical Report No. 5, Committee on Channel Stabilization, Corps of Engineers, U. S. Army).


1 WATER INFLOW
2 RELEASE DISCHARGE
3 SUSPENDED-SAND INFLOW
4 POOL ELEVATION
5 CUMULATIVE SAND
ILLUSTRATION
SAND INFOWS
COINCIDENTAL WITH
RESERVOIR POOL ELEVATIONS
CAUSED BY A RARE FLOOD
B.L.H. May '67
FLOOD CONTROL POOL
POOL ELEVATION IN FT. MSL
720
730
740
750
760
SEDIMENT-CUMULATIVE PERCENT
0
20
40
60
80
100
DISCHARGE IN 1000'S OF CFS
0
100
200
300
SEDIMENT LOAD IN 100,000 TONS PER DAY
0
2
4
6
8
10
12
14
DAYS
1
2
3
4
5
6
7
8
9
10
11

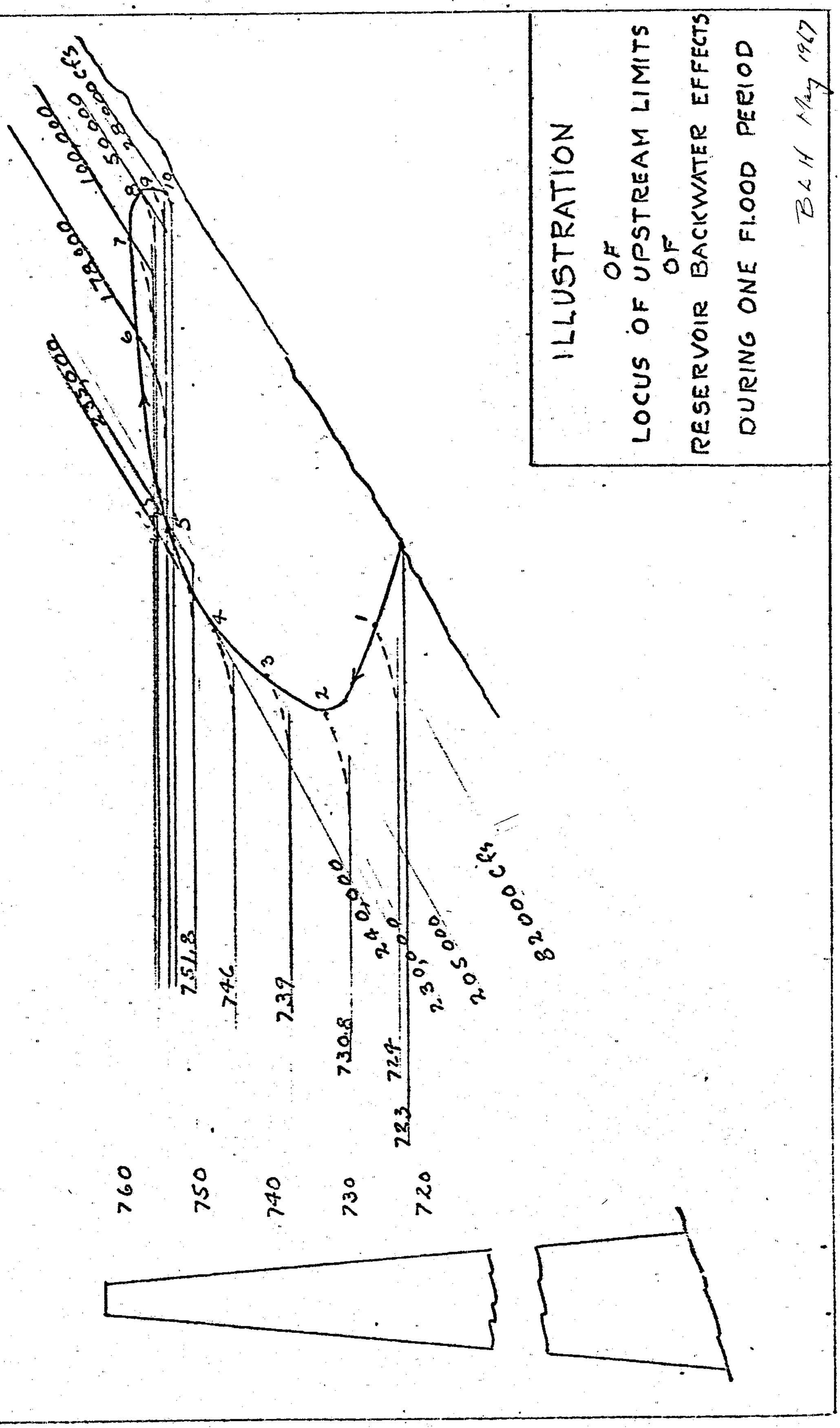


ILLUSTRATION
OF
LOCUS OF UPSTREAM LIMITS
OF
RESERVOIR BACKWATER EFFECTS
DURING ONE FLOOD PERIOD
BLH May 1967
233,000
178,000
100,000
59,000
28,000 cfs
240,000
230,000
205,000
82,000 cfs
751.8
746
739
730.8
724
723
760
750
740
730
720

INCLOSURE 3 1/

FORECASTING SEDIMENT DISTRIBUTIONS IN LARGE RESERVOIRS

POOL-ELEVATION DURATION METHOD

1. Required information.

a. Pool elevation charts developed in connection with operation studies.

b. Reservoir capacity table. (Table No. 1)

c. Estimate of total volume of sediment expected to accumulate in reservoir during period under consideration.

d. Estimate of sand fraction of total deposit.

2. Estimating procedure (use Ft. Peck Reservoir data for explanation).

a. Develop the pool elevation duration curve from pool elevation graphs (Curve 1, Fig. 1).

b. Plot first differences of capacity for depth increments (five-foot increments) on log-log paper. (Fig. 2)

c. Draw estimated distribution curve on Fig. 3 with position based on the sand-percent scale (four percent for Ft. Peck) and judgment of the plotting positions of points determined from measurements at other reservoirs. The right envelope position was selected because of the low percentage of sand and the large capacities of pools in the operating range (from about 110,000 to 19,000,000 acre-feet). (Sand scale shown on Fig. 3 is explained in paragraph 3 below.)

d. Prepare Table No. 2 as follows:

(1) Tabulate time durations (10 percent, 20 percent ... 95 percent and 100 percent) in column No. 1.

(2) Tabulate pool elevations corresponding to the durations in column No. 2 (obtain values from Curve No. 1, Fig. 1).

(3) Tabulate first differences of capacity (obtained from Fig. 2) in column No. 4.

1/ Incl 3 with paper "Forecasting Distribution of Sediment Deposits in Large Reservoirs," by Brice L. Hobbs, 10 Feb 69.

(4) Compute ratios (first differences of capacity divided by the first difference of capacity corresponding to the pool elevation that is exceeded only five percent of the time) and tabulate in column No. 5.

(5) Enter the chart (Fig. 3) with ratios from column No. 5 and tabulate the corresponding values of percent of total sediment deposits in column No. 6. These values represent the estimated distribution of deposits. Measured values are tabulated in column No. 7.

3. The sand-percent scale on Fig. 3 is plotted from values taken from Fig. 4 which is a correlation of percentages of sand with total deposits.

Bruce L. Hobbs
BRICE L. HOBBS
Hydrology & Hydraulics Branch
Engineering Division, CW. OCE

Incl. 3 (Sheet 2 of 2)

TABLE NO. 1

FORT PECK RESERVOIR
CONDENSED AREA-CAPACITY TABLE
(Based on 1961 Aggradation Survey)

ELEV (m.s.l.)	DEPTH (Ft.)	AREA (Acres)	CAPACITY (Acre-Feet)
2033	0	0	0
2035	2	103	113
2040	7	402	1,214
2045	12	1,075	5,002
2050	17	1,652	11,109
2055	22	2,305	21,423
2060	27	4,149	36,870
2070	37	10,672	106,662
2080	47	16,714	245,371
2090	57	22,966	440,692
2100	67	29,732	702,113
2110	77	38,458	1,042,665
2120	87	50,560	1,484,307
2130	97	61,391	2,044,261
2140	107	71,243	2,709,084
2150	117	81,944	3,474,396
2160	127	92,712	4,346,056
2170	137	106,393	5,335,418
2180	147	122,028	6,485,415
2190	157	936,912	7,777,395
2200	167	152,792	9,222,634
2210	177	170,021	10,839,099
2220	187	187,829	12,625,547
2230	197	206,874	14,600,015
2240	207	226,827	16,771,900
2250	217	246,919	19,138,489
2260*	227	270,200	21,704,684

*Extrapolated above elevation 2250

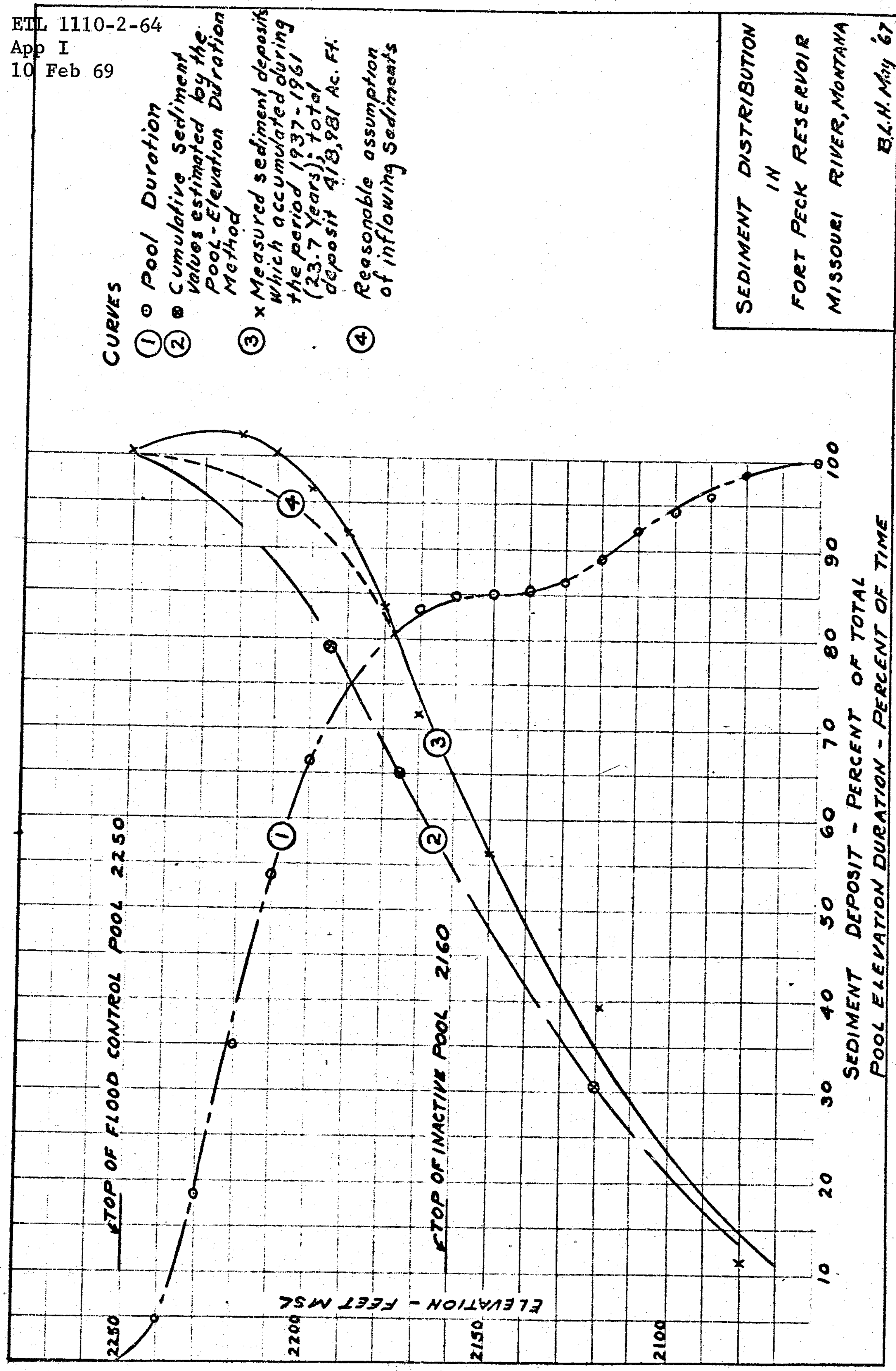

CURVES
① ○ Pool Duration
② ⊗ Cumulative Sediment Values estimated by the Pool-Elevation Duration Method
③ × Measured sediment deposits which accumulated during the period 1937-1961 (23.7 Years); total deposit 418,981 Ac. Ft.
④ Reasonable assumption of inflowing Sediments
SEDIMENT DISTRIBUTION
IN
FORT PECK RESERVOIR
MISSOURI RIVER, MONTANA
B.L.H. May '67
FIG 1
TOP OF FLOOD CONTROL POOL 2250
TOP OF INACTIVE POOL 2160
ELEVATION - FEET MSL
2250
2200
2150
2100
10
20
30
40
50
60
70
80
90
100
SEDIMENT DEPOSIT - PERCENT OF TOTAL
POOL ELEVATION DURATION - PERCENT OF TIME
1
2
3
4

Fig. 1

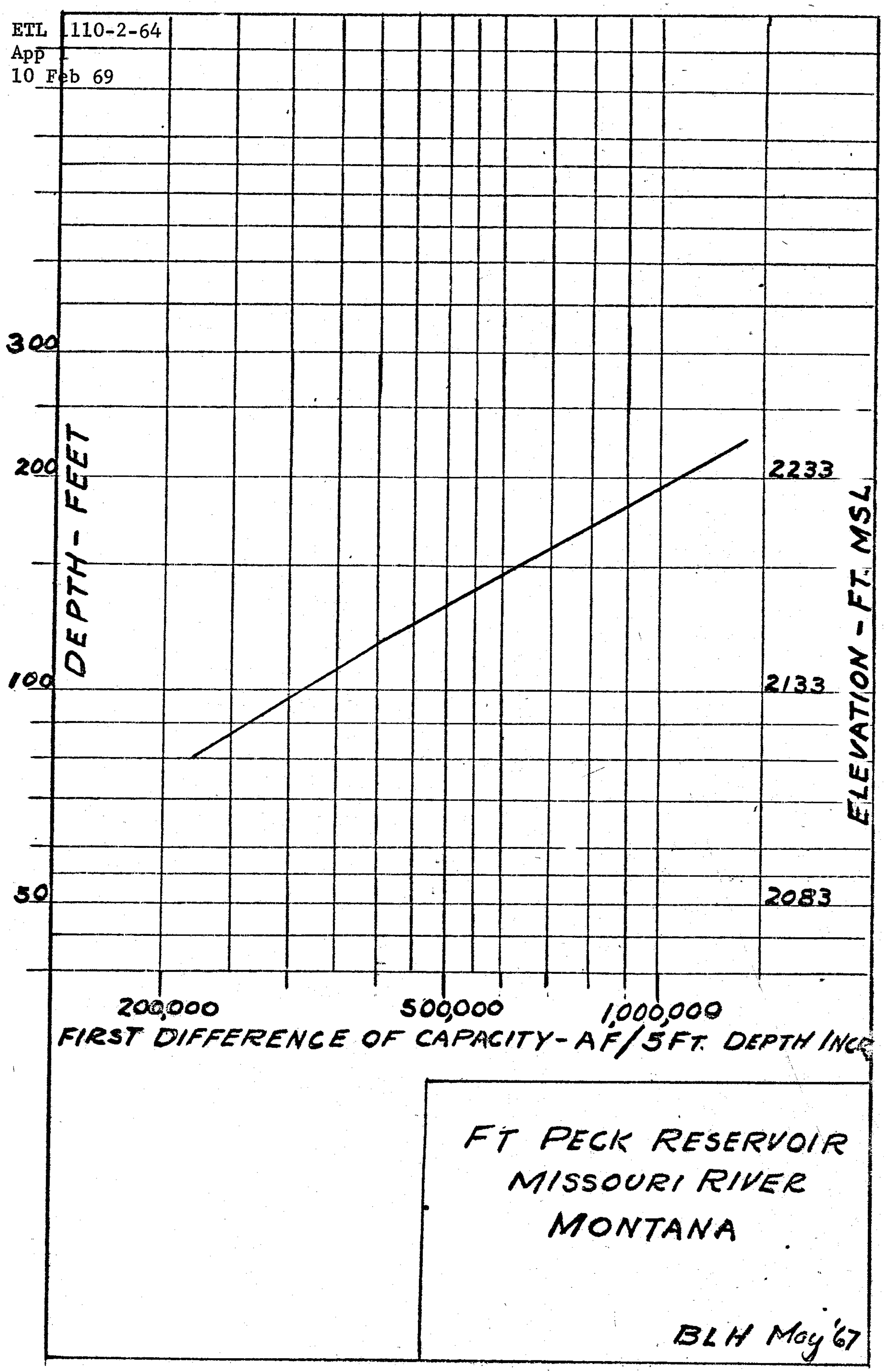

300
200
100
50
DEPTH - FEET
2233
2133
2083
ELEVATION - FT. MSL
200,000
500,000
1,000,000
FIRST DIFFERENCE OF CAPACITY - AF/5 FT. DEPTH INCR
FT PECK RESERVOIR
MISSOURI RIVER
MONTANA
BLH May '67

FIG 2

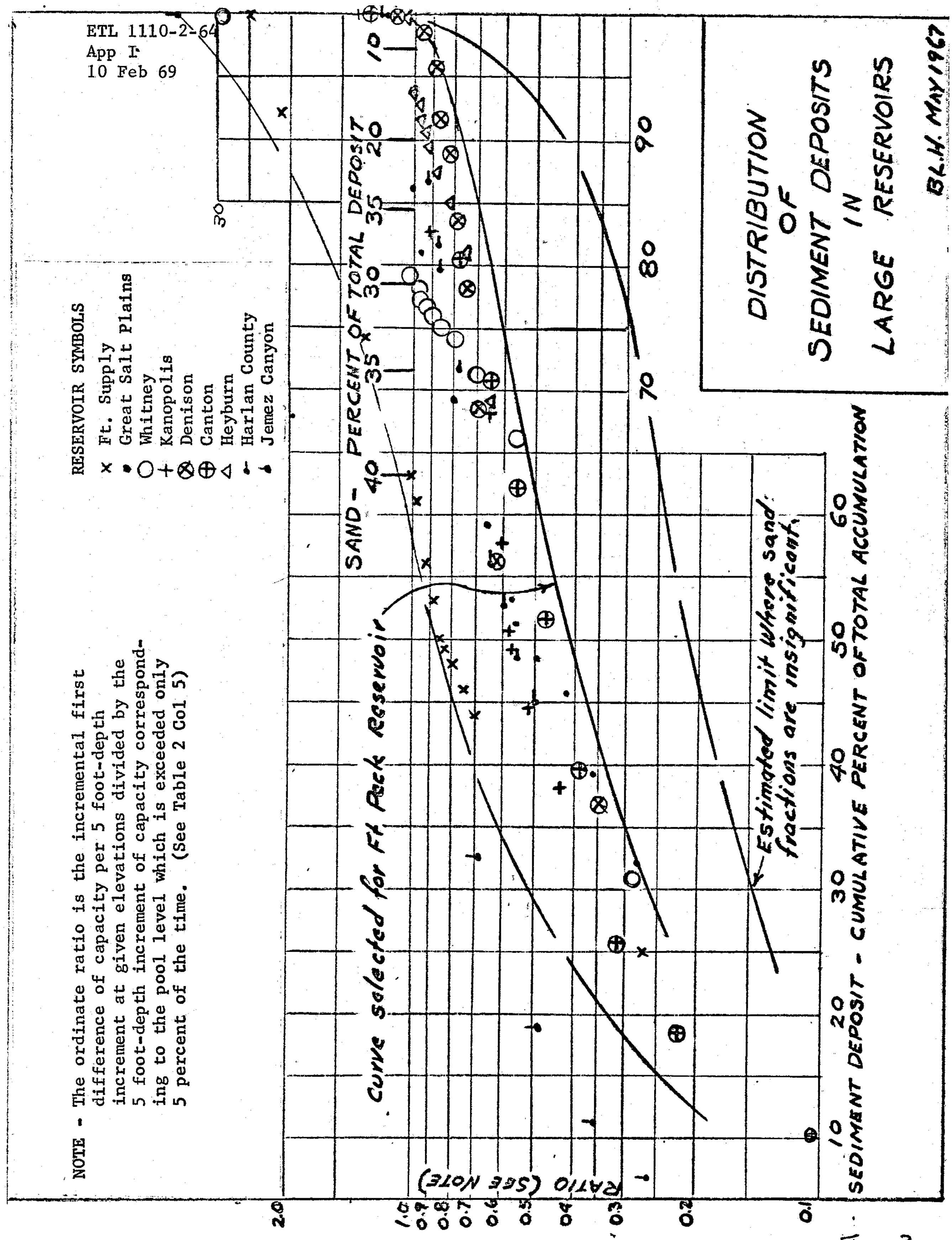

DISTRIBUTION OF SEDIMENT DEPOSITS IN LARGE RESERVOIRS
BLH. MAY 1967
RESERVOIR SYMBOLS
× Ft. Supply
• Great Salt Plains
○ Whitney
+ Kanopolis
⊗ Denison
⊕ Canton
△ Heyburn
Harlan County
Jemez Canyon
NOTE - The ordinate ratio is the incremental first difference of capacity per 5 foot-depth increment at given elevations divided by the 5 foot-depth increment of capacity corresponding to the pool level which is exceeded only 5 percent of the time. (See Table 2 Col 5)
SAND - PERCENT OF TOTAL DEPOSIT
Curve selected for Ft Peck Reservoir
Estimated limit where sand fractions are insignificant
SEDIMENT DEPOSIT - CUMULATIVE PERCENT OF TOTAL ACCUMULATION
RATIO (SEE NOTE)
10
20
30
40
50
60
70
80
90
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

FIG 3

TABLE NO. 2

ESTIMATE OF DISTRIBUTION OF SEDIMENT DEPOSITS
IN FORT PECK RESERVOIR
MISSOURI RIVER, MONTANA

POOL ELEV. DURATION (Percent of Time)[1] (1)	ELEV (Ft MSL) (2)	DEPTH (Ft) (3)	FIRST DIFF OF CAPACITY (Ac-Ft/5-Ft Depth Increment) (4)	RATIO[2] (Col. 4 ÷ 1,125,000) (5)	SEDIMENT DISTRIBUTION ESTIMATED (Σ %) (6)	MEASURED (Σ %)[3] (7)
10	2,117	84.0	236,000	0.27	30.0	32.0
20	2,116.5	143.5	580,000	0.52	65.0	78.5
30	2,195	162.0	722,600	0.64	79.0	92.0
40	2,208	175.0	828,000	0.74	88.0	95.5
50	2,212	179.0	862,000	0.77	90.0	97.8
60	2,218	185.0	915,000	0.81	94.0	98.8
70	2,225	192.0	987,000	0.88	97.0	99.5
80	2,230	197.0	1,030,000	0.92	98.5	99.8
90	2,236	203.0	1,090,000	0.97	99+	
95	2,240	207.0	1,125,000	1.00	99.5	99.95
100	2,248	215.0	1,200,000	1.07	100.0	100.0

1/ Percent of time pool was at or below corresponding elevation shown in Column No. 2.

2/ Ratio is 1.0 at the 95 percent pool.

3/ Values from Item No. 26 of Reservoir Sediment Data Summary (See Curve 3 Fig 1).

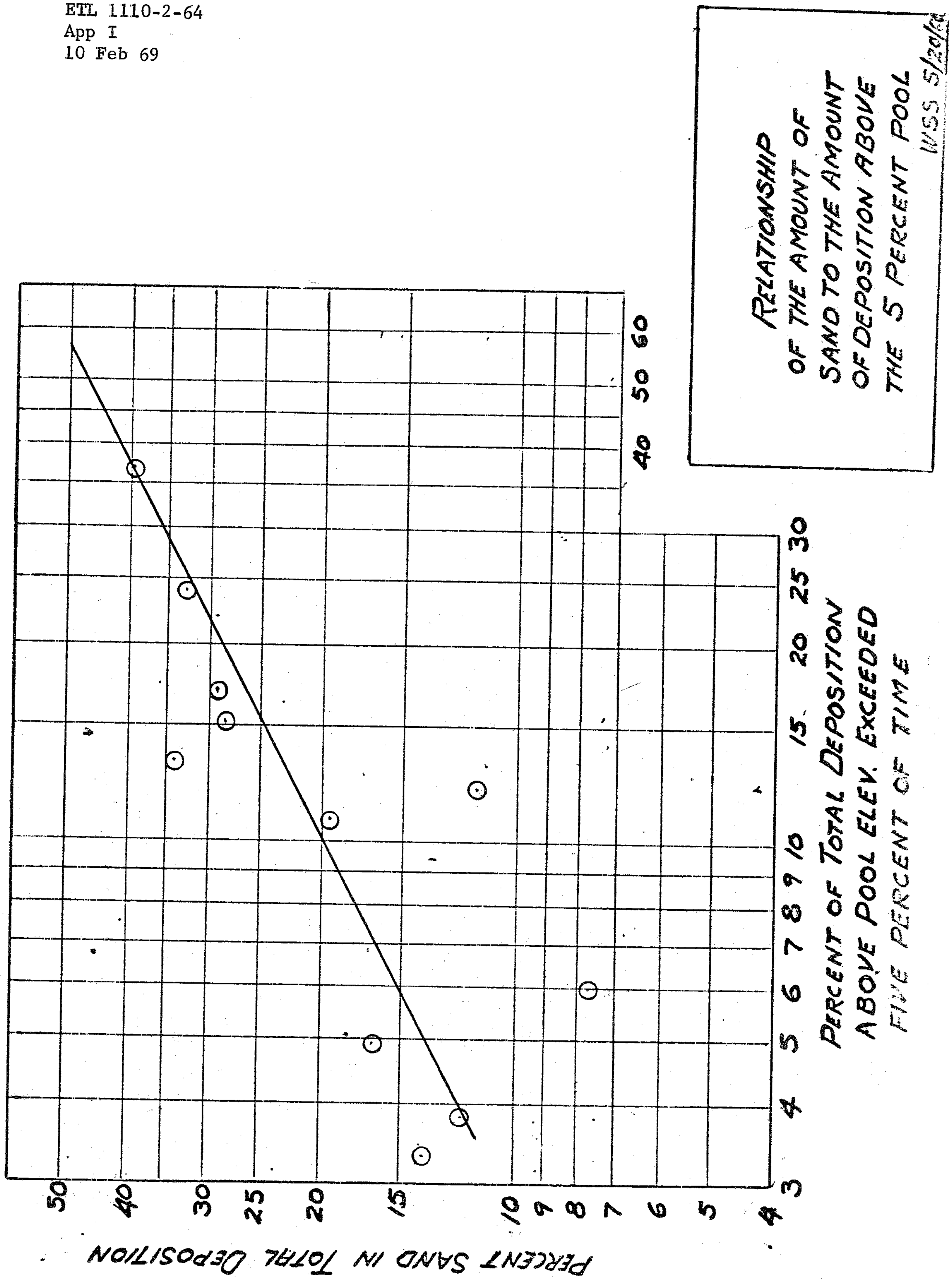

RELATIONSHIP OF THE AMOUNT OF SAND TO THE AMOUNT OF DEPOSITION ABOVE THE 5 PERCENT POOL
WSS 5/20/68
PERCENT OF TOTAL DEPOSITION ABOVE POOL ELEV. EXCEEDED FIVE PERCENT OF TIME
3 4 5 6 7 8 9 10 15 20 25 30 40 50 60
PERCENT SAND IN TOTAL DEPOSITION
4 5 6 7 8 9 10 15 20 25 30 40 50

FIG 4

Appendix 6

Deposit of Suspended Sediment in Reservoirs by Computer

DEPOSIT OF SUSPENDED SEDIMENT IN RESERVOIRS

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L264

JUNE 1967

SACRAMENTO DISTRICT, CORPS OF ENGINEERS
650 CAPITOL MALL
SACRAMENTO, CALIFORNIA

Telephone 449-3166

DEPOSIT OF SUSPENDED SEDIMENT IN RESERVOIRS

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L264

CONTENTS

EXHIBITS

DEPOSIT OF SUSPENDED SEDIMENT IN RESERVOIRS

HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 23-J2-L264

1. ORIGIN OF PROGRAM

This program was developed in the Hydrologic Engineering Center, Corps of Engineers, 650 Capitol Mall, Sacramento, California. The program is written in Fortran II and was developed by C. E. Abraham for the IBM 1620 computer with 40K memory. Dimensions are adequate for most sedimentation distribution problems in reservoir studies. Up-to-date information and copies of source-statement cards can be obtained from the Center upon request by Government and cooperating organizations. Definitions are listed in Exhibit 3. The variable locations and source statements are listed in Exhibits 4 and 5 respectively.

2. PURPOSE OF PROGRAM

The program will determine the distribution and location of sediments deposited in a reservoir, sediment inflow load, trap efficiency of the reservoir and size distribution of passing sediments. A table showing sediment deposition within specified sections in the reservoir is computed. Also, a generalized table giving an array of sediment deposited below certain elevations is computed. The program will accept various reservoir configurations such as tributary arms and will show deposition within the arms as well as the main body.

Major simplifying assumptions are that there is no temperature stratification and all sediment remaining in suspension at the dam will pass the dam. An inflow-duration relationship is used to describe inflow variations of flow and sediment. Only the load consisting of suspended sediments is considered in the program, and delta formations from bed material deposits must be determined by other methods.

3. COMPUTATION METHOD

Deposition of sediment is computed as a function of sediment size, reservoir temperature, variation of inflow, reservoir configuration, and type of reservoir operation. A table of corresponding duration, flow, and sediment values from a flow-duration relationship is used to describe variation in flow and suspended load. The ratios of flow and sediment to the input table values of flow and sediment are required to represent the inflow and load at the head of each tributary (often a certain tributary supplies a large percentage of the flow but a small percentage of sediment).

In order to determine the volume of sediment deposited, the unit weight for each of 7 size ranges is determined. The unit weight represents the initial weight of sediments and is based on results given in a paper by Lara and Pemberton.[1] The equation used to determine unit weight is:

$$UW = A(S^b) \qquad (1)$$

where:
- UW = Unit weight in lbs/cu ft.
- A = Constant depending on unit weight of silt given.
- S = Particle size in MM representing the size range.
- b = Constant depending on the unit weight of clay and silt given.

Areas and the mean depth below the water surface are computed for each cross section. The mean depth values are used in all computations.

The fall velocity of the material is based on data given in U. S. Inter-Agency Report. No. 7.[2] The program divides the sediments into 7 size ranges as follows:

Size Ranges (mm)
1.000 - 0.250
.250 - .0625
.0625 - .0312
.0312 - .0156
.0156 - .0078
.0078 - .0039
.0039 - smaller

From analysis, it was found that the fall velocity representing each size range may be described as follows:

$$Fv = K + (\log_e T)(m) \qquad (2)$$

where:
- Fv = Fall velocity in ft/sec
- K = Constant computed for each size range
- T = Temperature of reservoir in degrees F
- m = Constant computed for each size range

(1 Lara, J. M. and Pemberton, E. L., "Initial Unit Weight of Deposited Sediments", paper presented at the Federal Inter-Agency Sedimentation Conference at Jackson, Mississippi, Jan 28 - Feb 1, 1963.

(2 U. S. Inter-Agency Report No. 7, June 1943, "A Study of New Methods, for Size Analysis of Suspended Sediment Samples", U. S. Engineers Office, St. Paul, Minnesota, P. 55.

Sediment deposition is based on a formula used to determine sedimentation in settling basins. The relationship is as follows:

$$W/Wo = e^{-KL/dv} \tag{3}$$

where:
- W/Wo = Ratio of sediment left in suspension at the end of a given reach to the initial load.
- K = Constant depending on particle fall velocity.
- L = Length of reach in feet.
- d = Depth of flow in feet.
- v = Velocity of flow in ft/sec

The program defines the K value in equation (3) as follows:

$$K = c\ Fv \tag{4}$$

where:
- c = A constant usually assumed to be 1.0 for settling basins.

This is supported from results given by Einstein(3 in which sedimentation in gravel beds was investigated in flume studies. Derivation of the C value from results given in that report indicate a C of 1.055 and is described in a paper by Abraham(4. The C value in equation (4) is computed in the program by the following relationship:

$$C = (1. + FALL/DPH)^{OPR}$$

where:
- FALL = Distance the material in a particular size range has fallen.
- DPH = Mean depth within a reach.
- OPR = Operation index for reservoir. See card B on Exhibit 5.

Each size range in the sediment load is routed through each reach between sections in an iteration process. The volumes deposited are computed for each particular size range of sediment being routed. These are accumulated for each reach until all size ranges have been routed through.

(3 Spawning Grounds by H. A. Einstein, University of California, Berkeley, November 1965

(4 Sediment Problems in Artificial Spawning Beds by C. E. Abraham, Paper presented to the Water Resources Group, Sacramento Section, ASCE, Sacramento, California, March 1966

4. INPUT

Reservoir cross sections may be taken from a topographic map showing sufficient detail for the study. Stationing for the cross sections start at the head of the reservoir and increase toward the dam. However, it is not necessary to start the stationing at zero. If there is more than one tributary, tributaries may be stationed individually or as a system. Tributaries must be provided in sequence moving downstream so that sediment passing at the junctions may be added to move on downstream through the next tributary. Figure 1 shows a reservoir configuration with several

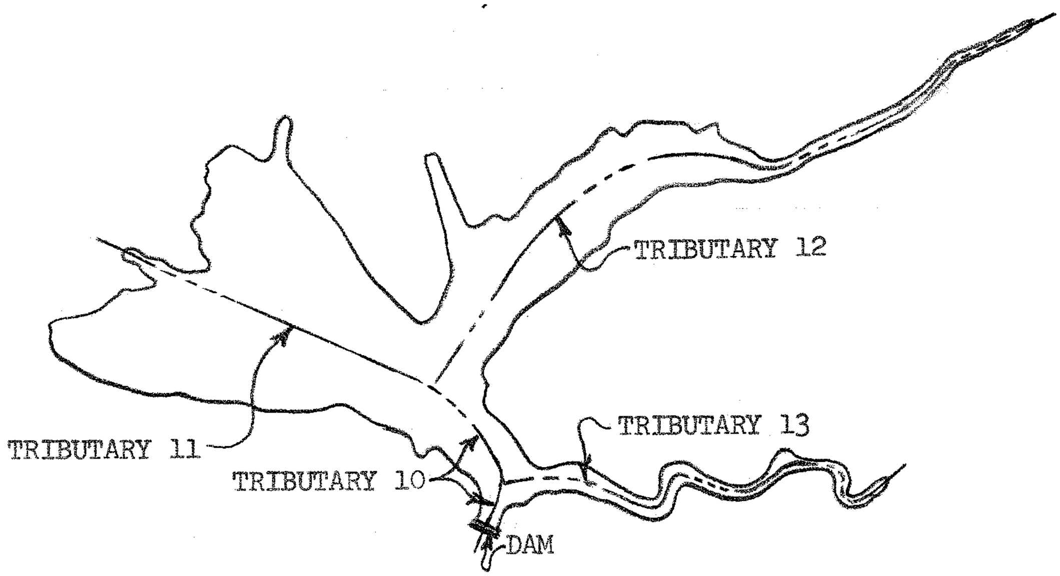


FIGURE 1

tributaries. Input should proceed in the numerical order of the tributaries. At junction points, the last cross sections from each tributary would be provided as one cross section for the beginning of the next tributary.

Card input is summarized in Exhibits 6 and 7. All data are entered consecutively on each card, using 8 columns (digits, including decimal points, if used) per variable and 10 variables per card unless fewer variables are called for. Sample input for Figure 1 is shown on Exhibit 1.

5. OUTPUT

Output includes the job specification data and the results of the computations. These data are printed out with explanations. It should be pointed out that the trap efficiency includes only the inflow in suspension. Also, the elevations in the elevation-capacity table are determined from mean elevations and may not necessarily reflect the top of sediment deposited. For detail in determining top of sediment, volumes given between sections should be applied to a topographic map. Sample output showing results of the input job is shown on Exhibit 2.

6. OPERATING INSTRUCTIONS

Standard Fortran II operation. No sense switches used.

7. DEFINITION OF TERMS

Terms used are defined in Exhibit 3.

8. EXAMPLE

Example input and output are shown in Exhibits 1 and 2.

9. PROPOSED FUTURE DEVELOPMENT

It is requested that a user who finds an inadequacy or desirable addition, notify the Hydrologic Engineering Center.

SAMPLE INPUT

```
A       LAKE PILLSBURY SUSPENDED SEDIMENT DISTRIBUTION AND TRAP EFFICIENCY
A       DAM IS AT SECTION 26000 AND TRIBUTARY 10 IS THE MAIN BODY OF RESERVOIR
A SALMON AND SQUAW VALLEY CR ARE TRIB 11,EEL RI IS TRIB 12,RICE FK IS TRIB 13
B      37       5        9      60      73      97    2.50      65       5    1830
C     .01   81000  1870000     .06   53000  700000      .3   33000  232000
C      1.   00500    80000    3.25   11000   22700     10.    4150    1270
C      20    1460      210      30     700      30      40     320       9
D      31      39       53      65      76      99     100
E      11       4    .0396   .0396       0
F   11600    1830        8
G       0    1830      100    1828     400    1825    1600    1828    1700    1830
G    2400    1822     3800    1828    4000    1830
F   14400    1820       11
G       0    1828       50    1820     700    1800    2700    1795    3200    1800
G    4500    1820     6200    1800    7000    1790    7500    1800    7550    1820
G    7600    1828
F   18000    1820       14
G       0    1828       50    1820     200    1800     500    1780    1000    1775
G    1500    1780     2400    1800    3600    1800    4500    1780    5000    1775
G    5400    1780     5450    1800    5500    1820    5550    1828
F   20800    1820       15
G       0    1828       50    1820     150    1800     200    1780     400    1760
G    1000    1750     1400    1760    1900    1760    2100    1750    2300    1760
G    2700    1760     2750    1780    2800    1800    2850    2820    2900    2828
E      12       6    .1815   .1815       0
F       0    1830        3
G       0    1830       50    1825     100    1830
F    4500    1828        6
G       0    1830       10    1828      60    1820     140    1820     190    1828
G     200    1830
F   11700    1820        6
G       0    1828       50    1820     100    1800     200    1800     250    1820
G     300    1828
F   15700    1820       12
G       0    1828       50    1820     150    1800     400    1800     600    1780
G     800    1775     1200    1780    1700    1780    2000    1780    2050    1800
G    2100    1820     2200    1828
F   19000    1820       11
G       0    1828      150    1820    1000    1800    1100    1780    1500    1760
G    2000    1755     2600    1760    2650    1780    2700    1800    2750    1820
G    2800    1828
```

EXHIBIT 1

F	20800	1820	11							
G	0	1828	100	1820	150	1800	600	1780	800	1760
G	1200	1740	1600	1760	1700	1780	1800	1800	1900	1820
G	2000	1828								
E	10	3	0	.2211	2					
F	20800	1820	26							
G	0	1828	50	1820	150	1800	200	1780	400	1760
G	1000	1750	1400	1760	1900	1760	2100	1750	2300	1760
G	2700	1760	2750	1780	2800	1800	2850	2820	2900	2828
G	3000	1828	3100	1820	3150	1800	3600	1780	3800	1760
G	4200	1740	4600	1760	4700	1780	4800	1800	4900	1820
G	5000	1828								
F	22000	1820	13							
G	0	1828	50	1820	100	1800	300	1780	450	1760
G	1200	1745	2200	1740	2300	1740	2700	1760	2800	1780
G	2850	1800	2900	1820	2950	1828				
F	24600	1820	13							
G	0	1828	50	1820	100	1800	200	1780	400	1760
G	500	1740	1000	1730	1400	1740	1450	1760	1500	1780
G	1550	1800	1600	1820	1650	1828				
E	13	5	.1089	.1089	0					
F	10800	1830	3							
G	0	1830	50	1825	100	1830				
F	16800	1820	6							
G	0	1828	50	1820	200	1800	350	1800	400	1820
G	450	1828								
F	20000	1820	8							
G	0	1828	50	1820	100	1800	200	1785	600	1785
G	650	1800	700	1820	750	1828				
F	22600	1820	11							
G	0	1828	40	1820	70	1800	150	1780	200	1760
G	300	1740	400	1760	440	1780	520	1800	560	1820
G	600	1828								
F	24600	1820	8							
G	0	1828	250	1740	400	1730	800	1730	900	1740
G	1000	1760	1100	1800	1250	1828				
E	10	3	0	.33	2					
F	24600	1820	21							
G	0	1828	50	1820	100	1800	200	1780	400	1760
G	500	1740	1000	1730	1400	1740	1450	1760	1500	1780
G	1550	1800	1600	1820	1650	1828	1700	1828	1950	1740

EXHIBIT 1

G	2100	1730	2500	1730	2600	1740	2700	1760	2800	1800
G	2950	1828								
F	25300	1820	8							
G	0	1828	200	1780	350	1760	400	1740	600	1730
G	700	1740	750	1760	950	1828				
F	26000	1820	5							
G	0	1828	200	1740	300	1725	400	1740	600	1828

EXHIBIT 1

SAMPLE OUTPUT

LAKE PILLSBURY SUSPENDED SEDIMENT DISTRIBUTION AND TRAP EFFICIENCY
DAM IS AT SECTION 26000 AND TRIBUTARY 10 IS THE MAIN BODY OF RESERVOIR
SALMON AND SQUAW VALLEY CR ARE TRIB 11,EEL RI IS TRIB 12,RICE FK IS TRIB 13

YEARS	NTRIB	NDUR	WCY	WSI	WSD	OPR	TEMP	DEL	ELMX
37	5	9	60.00	73.00	97.00	2.50	65.00	5.00	1830.00

		SEDIMENT DEPOSITED IN AC-FT	BETWEEN SECTIONS		
TRIBUTARY	11	1094.6	11600.	AND	14400.
TRIBUTARY	11	109.3	14400.	AND	18000.
TRIBUTARY	11	14.9	18000.	AND	20800.
TRIBUTARY	12	2202.5	0.	AND	4500.
TRIBUTARY	12	827.4	4500.	AND	11700.
TRIBUTARY	12	772.2	11700.	AND	15700.
TRIBUTARY	12	441.1	15700.	AND	19000.
TRIBUTARY	12	160.0	19000.	AND	20800.
TRIBUTARY	10	90.0	20800.	AND	22000.
TRIBUTARY	10	61.1	22000.	AND	24600.
TRIBUTARY	13	1872.7	10800.	AND	16800.
TRIBUTARY	13	323.1	16800.	AND	20000.
TRIBUTARY	13	121.9	20000.	AND	22600.
TRIBUTARY	13	108.6	22600.	AND	24600.
TRIBUTARY	10	70.9	24600.	AND	25300.
TRIBUTARY	10	9.4	25300.	AND	26000.
	TOTAL	8280.5			

ACCUMULATED SEDIMENT DEPOSITED BELOW INDICATED ELEVATION

ELEVATION (FT)	DEPOSITION (AC-FT)
1830.	8280.
1825.	8280.
1820.	8280.
1815.	6078.
1810.	4205.

EXHIBIT 2

1805.	2283.
1800.	2283.
1795.	1078.
1790.	1078.
1785.	1078.
1780.	515.
1775.	500.
1770.	340.
1765.	340.
1760.	231.
1755.	141.
1750.	132.

TOTAL SEDIMENT INFLOW = 10260. AC-FT   UNIT WT = 1609. TONS/AC-FT

TOTAL SEDIMENT PASSING = 1980. AC-FT   TRAP EFFICIENCY = 80.70 PERCENT

SIZE DISTRIBUTION OF PASSING SEDIMENT IN PERCENT SMALLER THAN INDICATED BY WT

.004	.008	.016	.031	.062	.250	1.000
85.57	94.97	99.93	100.00	100.00	100.00	100.00

EXHIBIT 2

EXHIBIT 3

DEFINITIONS - 23-J2-L264

ADJ	- An adjustment made necessary if durations read in cause accumulated duration to exceed 100%
AEL	- Sum of average elevations in cross section
AREA	- Cross sectional area
AS	- Constant used in computing unit weight
BS	- Exponent of size used in computing unit weight
C	- Relative depth particles have fallen with respect to mean depth
CAP	- Capacity of sediment deposited
CONS	- Sum of all sediment values read in
DEL	- Elevation difference for elevation-capacity table
DPH	- Mean depth in cross section and reach
DUMY	- Temporary variable to test delta duration
DUR	- Duration flow is equal to or exceeded
EL	- Elevation at a point in cross section
ELE	- Elevation in elevation capacity table
ELL	- Mean elevation in reach
ELMX	- Maximum elevation in elevation-capacity table
FALL	- Vertical distance particles fall in feet
I	- Index subscript
IADD	- Number of tributaries to add sediment passing the junction
IDU	- Index subscript for durations
II	- Index subscript for sediment passing a tributary
IS	- Index subscript for sections
ISZ	- Index subscript for particle size ranges
ITRB	- Index subscript for tributaries
ITRIB	- Tributary identification number
J	- Index subscript
N	- Number of stations in cross section
NCAP	- Number of values in elevation-capacity table
NDUR	- Number of points in flow-duration relationship
NSEC	- Number of sections in tributary
NSTA	- Number of stations in cross section
NTRIB	- Number of tributaries
NYR	- Number of years in study
OPR	- Variable indicating type of operation
PASS	- Volume of material passing dam
PER	- Percent of material in size range
PSIZ	- Percent of material finer than value given
Q	- Inflow in cfs
R	- Ratio of material passing section with respect to amount entering section
RATOQ	- Ratio of flow entering tributary to that given in flow-duration table
RATOS	- Ratio of sediment entering head of tributary to that given in flow-duration table

RHL - Reach length between cross sections in feet
S - Sediment passing tributary in ac-ft
SDP - Sediment deposited in section in ac-ft
SEC - Section distance in feet
SED - Sediment load given in flow-duration table in tons/day
SEIN - Total sediment inflow in ac-ft
SS - Sum of sediment passing tributaries at junction in ac-ft
SSI - Sediment inflow to reach between sections in ac-ft
SSO - Sediment passing reach between sections in ac-ft
SSS - Sum of sediment passing dam in tons in a particular size range
SSTA - Starting station in cross section entering water surface
SSUM - Sum of all sediment passing dam in tons
STA - Station distance in feet
SUM - Sum of all sediment passing dam in ac-ft
SWIM - Sum of all sediment deposited in reach between sections in ac-ft
TEE - Sediment trap efficiency of reservoir in percent
TEMP - Temperature of reservoir in degrees F
UW - Unit weight of sediment in lbs. per cu. ft.
UWT - Unit weight of inflow sediment in tons/ac-ft
VR - Average velocity of flow in reach between sections in ft/sec
W - Average fall velocity of particles in a size range in ft/sec
WCY - Unit weight of clay in lbs/cu ft
WSEL - Water surface elevation in feet
WSD - Unit weight of sand in lbs/cu ft
SSI - Unit weight of silt in lbs/cu ft
X - Area in segment of cross section. Also exponent in Vetter's Formula
XLM - Maximum duration in flow-duration table
XLTH - Length of segment in cross section in feet
Y1 - Depth below water surface at a point in cross section
Y2 - Depth below water surface at a point following Y1 in cross section
YR - Number of years in study

VARIABLE LOCATIONS

VARIABLE	STATEMENTS WHERE USED						
ADJ	310.03	310.05					
AEL	340.10	370.06	400.04	410.05	420.02		
AREA	.04	420.00	620.01				
AS	260.03	260.07	260.09	260.11	260.13	260.14	260.17
	270.00						
BS	260.02	260.03	260.07	260.09	260.11	260.13	260.14
	260.17	270.00					
C	620.04	620.07					
CAP	.04	330.03	690.00	730.00			
CONS	250.06	260.00	600.00				
DEL	240.02	250.01	440.02	460.01			
DPH	.03	420.02	440.00	440.02	620.04	620.07	680.05
DUMY	280.05	280.06	300.00	300.01	310.00	310.04	310.05
	370.00	370.01	410.00	410.02			
DUR	.03	250.04	280.02	280.03	280.05	300.00	310.02
	610.00						
EL	.04	340.09	350.00	370.00	370.04	370.06	370.07
	390.00	400.00	400.04	410.00	410.03	410.05	
ELE	.05	340.00	450.00	460.01	680.07	730.00	
ELL	680.05	680.07					
ELMX	240.02	250.01	340.00				
END	830.01						
FALL	.05	610.02	620.04	620.05			
I	230.01	250.04	250.05	250.08	260.00	280.04	280.05
	300.00	310.02	310.06	320.06	330.00	330.02	330.03
	340.00	340.07	340.08	420.00	420.02	430.02	440.00
	440.03	450.00	450.00	460.01	470.00	470.02	480.00
	580.01	580.02	590.00	680.02	680.03	680.05	690.00
	710.00	720.04	730.00	730.03	740.00	740.03	750.00
	750.03	750.04	750.05	760.05			
IADD	340.05	560.02	580.01				
IDJ	560.00	570.00	600.00	610.00	610.02	620.01	620.04
	620.05						
II	320.05	340.03	590.01	650.01			
IS	620.00	620.01	620.02	620.04	620.07	630.00	640.02
ISZ	480.02	480.03	480.05	490.00	500.00	510.00	520.00
	530.00	540.00	550.00	580.02	590.00	610.00	610.02
	620.04	620.05	650.01	670.00			
ITRB	340.02	340.05	650.00	680.03			
ITRIB	.04	340.05	680.03				
J	320.07	330.00	340.09	680.06	680.07	690.00	
LOGE	260.02	490.01	500.01	510.01	520.01	530.01	540.01
	550.01						
N	340.12	350.00	360.00	360.01	370.00	370.01	370.03
	370.04	370.06	370.07	380.00	380.01	390.00	400.00
	400.01	400.04	410.00	410.02	410.03	410.05	
NCAP	330.01	440.03	470.00	680.06	720.04		
NDUR	240.02	250.01	250.04	250.08	280.04	310.06	560.00
NSEC	340.05	340.07	430.02	440.02	470.02	620.00	680.02
NSTA	340.08	340.09	360.01	380.01			
NTRIB	240.02	250.01	340.02	660.00			
NYR	240.02	240.03	250.01	250.02			
OPR	240.02	250.01	620.07				
PASS	.04	480.03	670.00	740.00	750.00	750.04	

EXHIBIT 4

PER	490.00	500.00	510.00	520.00	530.00	540.00	550.00
	610.00						
PSIZ	.03	250.05	260.06	260.08	260.10	260.12	260.15
	260.16	260.18	260.19	270.00	490.00	500.00	510.00
	520.00	530.00	540.00	550.00	750.05	760.05	
Q	.03	250.04	620.01				
R	640.00	640.01					
RATOQ	340.05	620.01					
RATOS	340.05	610.00					
RHL	620.02	620.05	620.07				
S	.03	330.00	580.02	590.00	650.01		
SDP	.04	480.00	630.00	640.02	630.03	690.00	710.00
SEC	.03	340.08	620.02	680.03			
SED	.03	250.04	260.00	600.00	610.00		
SEIN	320.03	610.01	750.02	760.03			
SS	580.00	580.02	600.00				
SSI	600.00	610.00	610.01	630.00	640.01	640.02	640.03
SSO	630.01	640.01	640.02	640.03	650.01	670.00	
SSS	750.01	750.04	750.05				
SSTA	370.01	370.03					
SSUM	740.01	750.00	750.05				
STA	.04	340.09	370.01	370.03	400.01	410.02	
STOP	830.00						
SUM	340.11	370.05	400.03	410.04	420.00	420.02	730.01
	740.00	760.03	760.04				
SWIM	320.04	710.00	720.01				
TEE	760.03	760.04					
TEMP	240.02	250.01	490.01	500.01	510.01	520.01	530.01
	540.01	550.01					
UW	.04	260.05	260.06	260.07	260.08	260.09	260.10
	260.11	260.12	260.13	260.14	260.15	260.16	260.17
	260.18	610.00	750.00	750.04			
UWT	260.06	260.08	260.10	260.12	260.15	260.16	260.18
	270.00	280.00	750.02				
VR	620.01	620.05	620.07				
W	490.01	500.01	510.01	520.01	530.01	540.01	550.01
	620.05	620.07					
WCY	240.02	250.01	260.05				
WSD	240.02	250.01	260.02				
WSEL	340.08	350.00	370.00	370.04	370.06	370.07	390.00
	400.00	410.00	410.03	410.05	420.02	440.02	680.05
WSI	240.02	250.01	260.02	260.03			
X	370.04	370.05	370.06	400.02	400.03	400.04	410.03
	410.04	410.05	440.02	450.00	620.07	620.08	640.00
XLM	280.03	280.05	300.01	300.03	310.00	310.02	310.03
	310.04						
XLTH	370.03	370.04	400.01	400.02	410.02	410.03	
Y1	370.07	400.02	400.05				
Y2	400.00	400.02	400.05				
YR	250.02	610.00					

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EXHIBIT 4

SOURCE PROGRAM LISTING

```
C     23-J2-L264 23MAY67 1620-35K                                              1001
C     PROGRAM 23-J2-L264 SEDIMENT TRANSPORT THROUGH RESERVOIRS BY CE ABR 1002
      DIMENSION S(4,7),DUR(20),Q(20),SED(20),PSIZ(7),SEC(20),DPH(20)     , 1003
     1STA(40),EL(40),PASS(7),SDP(20),ITRIB(6),AREA(20),UW(7),CAP(35)     , 1004
     2ELE(35),FALL(7,20)                                                   1005
C                            BRANCH TO   100 FROM   230.02   240.00
C
  100 FORMAT(1X,79H                                                        1006
     1                               )                                     1007
C                            BRANCH TO   110 FROM   230.00
  110 FORMAT (1H1)                                                         1008
C                            BRANCH TO   120 FROM   240.02
  120 FORMAT (1X,I7,2I8,7F8.0)                                             1009
C                            BRANCH TO   130 FROM   250.01
  130 FORMAT (80H    YEARS   NTRIB    NDUR    WCY     WSI     WSD     OP 1010
     1R     TEMP    DEL    ELMX/3I8,7F8.2)                                 1011
C                            BRANCH TO   140 FROM   250.04
  140 FORMAT (1X,F7.0,8F8.0)                                               1012
C                            BRANCH TO   150 FROM   320.01
  150 FORMAT              (/16X,48HSEDIMENT DEPOSITED IN AC-FT     BETWE 1013
     1EN SECTIONS/)                                                        1014
C                            BRANCH TO   160 FROM   250.05   340.09
C
  160 FORMAT (1X,F7.0,9F8.0)                                               1015
C                            BRANCH TO   170 FROM   250.00   710.01
C
  170 FORMAT (1H )                                                         1016
C                            BRANCH TO   180 FROM   290.00
  180 FORMAT (44HINPUT ERROR-INC DURATIONS MUST = OR INCREASE)             1017
C                            BRANCH TO   190 FROM   310.05
  190 FORMAT (13HINPUT DUR OF ,F6.1,49H EXCEEDS 100 PERCENT IN DUR RANGE 1018
     1S,ADJ VALUE IS  ,F6.1)                                               1019
C                            BRANCH TO   200 FROM   340.08
  200 FORMAT (1X,F7.0,F8.0,2I8)                                            1020
C                            BRANCH TO   210 FROM   760.02
  210 FORMAT (/5X,23HTOTAL SEDIMENT INFLOW =,F9.0,19H AC-FT    UNIT WT = 1021
     1,F6.0,11H TONS/AC-FT)                                                1022
C                            BRANCH TO   220 FROM   340.05
  220 FORMAT(1X,I7,I8,2F8.0,I8)                                            1023
C                     THREE TITLE CARDS                                    1024
C                            BRANCH TO   230 FROM   820.04
```

EXHIBIT 5

```
  230 PRINT 110
      DO 240 I=1,3
      READ 100
C                                       BRANCH TO    240 FROM    230.01
  240 PRINT 100
C     READ RESERVOIR DATA
      READ 120 ,NYR,NTRIB,NDUR,     WCY,WSI,WSD,OPR,TEMP,DEL,ELMX
      IF(NYR )830,830,250
  250 PRINT 170
      PRINT 130 ,NYR,NTRIB,NDUR,     WCY,WSI,WSD,OPR,TEMP,DEL,ELMX
      YR=NYR
C     READ DURATION, FLOW, AND SEDIMENT DATA (NDUR SETS)
      READ 140,(DUR(I),Q(I),SED(I),I=1,NDUR)
      READ 160,(PSIZ(I),I=1,7)
      CONS=0.
C     SUM ALL SEDIMENT VALUES FOR DETERMINING TRANSPORT BELOW A TRIB
      DO 260 I=1,NDUR
  260 CONS=CONS+SED(I)
C     DETERMINE EQUATION FOR UNIT WT IN THE FORM UWT=AS*SIZE**BS
      BS=( LOGF(WSD)- LOGF(WSI))/2.7747
      AS=WSI/.0156**BS
C     DETERMINE UNIT WT OF INFLOW SEDIMENT
      UW(1)=WCY
      UWT=UW(1)*PSIZ(1)
      UW(2)=  AS*(.0055**BS)
      UWT=UWT+UW(2)*(PSIZ(2)-PSIZ(1) )
      UW(3)=  AS*(.011**BS)
      UWT=UWT+UW(3)*(PSIZ(3)-PSIZ(2))
      UW(4)=  AS*(.0321**BS)
      UWT=UWT+UW(4)*(PSIZ(4)-PSIZ(3))
      UW(5)=  AS*(.0442**BS)
      UW(6)=  AS*(.125**BS)
      UWT=UWT+UW(5)*(PSIZ(5)-PSIZ(4))
      UWT=UWT+UW(6)*(PSIZ(6)-PSIZ(5))
      UW(7)=  AS*(.5**BS)
      UWT=UWT+UW(7)*(PSIZ(7)-PSIZ(6))
      IF(PSIZ(7)-100.)270,280,280
  270 UWT=UWT+AS*(1.414**BS)*(100.-PSIZ(7))
C                                       BRANCH TO    280 FROM    260.19
  280 UWT=UWT*.2178
C     REPLACE ACCUM DURATION WITH DELTA DURATION
```

```
      DUR(1)=DUR(1)*2.
      XLM=DUR(1)
      DO 320 I=2,NDUR
      DUMY=(DUR(I)-XLM)*2.
      IF(DUMY)290,290,300
  290 PRINT 180
      GO TO 830
C                                       BRANCH TO   300 FROM   280.06
  300 DUR(I)=DUMY
      XLM=XLM+DUMY
C     CHECK IF ACCUM DURATION EXCEEDS 100
      IF(100.-XLM)310,320,320
  310 XLM=XLM-DUMY
C     MAKE NECESSARY ADJUSTMENT SO ACCUM DURATION DOES NOT EXCEED 100
      DUR(I)=(100.-XLM)
      ADJ=(XLM+100.)*.5
      DUMY=XLM+DUMY*.5
      PRINT 190,DUMY,ADJ
      NDUR=I
C                                       BRANCH TO   320 FROM   280.04   300.03
C
  320 CONTINUE
      PRINT 150
C     INITIALIZE VALUES FOR ENTERING MAJOR DO DOOP
      SEIN=0.
      SWIM=0.
      II=0
      DO 330 I=1,4
      DO 330 J=1,7
C                                       BRANCH TO   330 FROM   320.06
  330 S(I,J)=0.
      NCAP=1
      DO 340 I=1,35
      CAP(I)=0.
C                                       BRANCH TO   340 FROM   330.02
  340 ELE(I)=ELMX
C     ENTERING MAJOR DO LOOP (NUMBER OF TRIBUTARIES)
      DO 720 ITRB=1,NTRIB
      II=II+1
C     READ TRIBUTARY DATA
      READ 220,ITRIB(ITRB),NSEC,RATOS,RATOQ,IADD
```

EXHIBIT 5

```
C     READ CROSS SECTIONS AND DETERMINE AREAS                                    1100
      DO 430 I=1,NSEC                                                            1101
      READ 200 , SEC(I), WSEL , NSTA                                             1102
      READ 160,(STA(J),EL(J),J=1,NSTA)                                           1103
      AEL=0.                                                                     1104
      SUM=0.                                                                     1105
      N=2                                                                        1106
C     FIND STATION ENTERING WATER SURFACE                                        1107
C                                   BRANCH TO   350 FROM   360.01   410.06
C
  350 IF(EL(N)-WSEL)370,360,360                                                  1108
  360 N=N+1                                                                      1109
      IF(N-NSTA)350,420,420                                                      1110
C                                   BRANCH TO   370 FROM   350.00
  370 DUMY=(EL(N-1)-WSEL)/(EL(N-1)-EL(N))                                        1111
      SSTA=DUMY*(STA(N)-STA(N-1))+STA(N-1)                                       1112
C     COMPUTE AREA IN SEGMENT AFTER ENTERING WATER SURFACE                       1113
      XLTH=STA(N)-SSTA                                                           1114
      X=XLTH*(WSEL-EL(N))*.5                                                     1115
      SUM=SUM+X                                                                  1116
      AEL=AEL+(WSEL+EL(N))*.5*X                                                  1117
      Y1=WSEL-EL(N)                                                              1118
C                                   BRANCH TO   380 FROM   400.06
  380 N=N+1                                                                      1119
      IF(N-NSTA)390,390,420                                                      1120
  390 IF(EL(N)-WSEL)400,410,410                                                  1121
C     COMPUTE AREAS WITHIN CROSS SECTION                                         1122
C                                   BRANCH TO   400 FROM   390.00
  400 Y2=WSEL-EL(N)                                                              1123
      XLTH=STA(N)-STA(N-1)                                                       1124
      X=XLTH*(Y1+Y2)*.5                                                          1125
      SUM=SUM+X                                                                  1126
      AEL=AEL+(EL(N-1) +EL(N))*.5*X                                              1127
      Y1=Y2                                                                      1128
      GO TO 380                                                                  1129
C     COMPUTE LAST STATION LEAVING WATER SURFACE                                 1130
C                                   BRANCH TO   410 FROM   390.00
  410 DUMY=(WSEL-EL(N-1))/(EL(N)-EL(N-1))                                        1131
C     COMPUTE LAST SEGMENT UPON LEAVING WATER SURFACE                            1132
      XLTH=DUMY*(STA(N)-STA(N-1))                                                1133
      X=XLTH*(WSEL-EL(N-1))*.5                                                   1134
```

```
      SUM=SUM+X
      AEL=AEL+(WSEL+EL(N-1))*.5*X
      GO TO 350
C     AREA FOR CROSS SECTION IS = TO SUM
C                                BRANCH TO   420 FROM   360.01   380.01
C
  420 AREA(I)=SUM
C     COMPUTE MEAN DEPTH WITHIN CROSS SECTION
      DPH(I)=WSEL-AEL/SUM
C                                BRANCH TO   430 FROM   340.07
  430 CONTINUE
C     COMPUTE AVERAGE DEPTH BETWEEN CROSS SECTIONS
      DO 440 I=2,NSEC
  440 DPH(I)=(DPH(I)+DPH(I-1))*.5
C     DETERMINE ELEVATIONS FOR ELEVATION CAPACITY TABLE
      X=WSEL+DEL-DPH(NSEC)
      I=NCAP
C                                BRANCH TO   450 FROM   460.02
  450 IF(X-ELE(I))460,470,470
  460 I=I+1
      ELE(I)=ELE(I-1)-DEL
      GO TO 450
C                                BRANCH TO   470 FROM   450.00
  470 NCAP=I
C     INITIALIZE SUM OF DEPOSITION FOR SIZE DO LOOP
      DO 480 I=2,NSEC
  480 SDP(I  )=0.
C     START DO LOOP FOR EACH SEDIMENT SIZE RANGE
      DO 680 ISZ=1,7
      PASS(ISZ)=0.
C     COMPUTE FALL VELOCITY (W)
      GO TO (490,500,510,520,530,540,550),ISZ
  490 PER=PSIZ(ISZ)
      W=-.000081+( LOGF(TEMP))*.000036
      GO TO 560
C                                BRANCH TO   500 FROM   480.05
  500 PER=PSIZ(ISZ)-PSIZ(ISZ-1)
      W=-.000322+( LOGF(TEMP))*.00014
      GO TO 560
C                                BRANCH TO   510 FROM   480.05
  510 PER=PSIZ(ISZ)-PSIZ(ISZ-1)
```

```
      W=-.001284+( LOGF(TEMP))*.000452
      GO TO 560
C                                       BRANCH TO   520 FROM   480.05
  520 PER=PSIZ(ISZ)-PSIZ(ISZ-1)
      W=-.005159+( LOGF(TEMP))*.001752
      GO TO 560
C                                       BRANCH TO   530 FROM   480.05
  530 PER=PSIZ(ISZ)-PSIZ(ISZ-1)
      W=-.016578+( LOGF(TEMP))*.00531
      GO TO 560
C                                       BRANCH TO   540 FROM   480.05
  540 PER=PSIZ(ISZ)-PSIZ(ISZ-1)
      W=-.071296+( LOGF(TEMP))*.024125
      GO TO 560
C                                       BRANCH TO   550 FROM   480.05
  550 PER=100.-PSIZ(ISZ-1)
      W=-.125557+( LOGF(TEMP))*.07539
C     START DO LOOP FOR DURATION POINTS
C                                       BRANCH TO   560 FROM   490.02   500.02
C                                           510.02   520.02    530.02   540.02
  560 DO 680 IDU=1,NDUR
C     CHECK IF TRIBUTARIES TO BE ADDED TO THIS TRIB
      IF(IADD) 610,610,570
C     COMPUTE TOTAL SEDIMENT TRANSPORT FROM TRIBUTARIES
C                                       BRANCH TO   570 FROM   560.02
  570 IF(IDU-1)580,580,600
  580 SS =0.
      DO 590 I=1,IADD
      SS =SS +S(I,ISZ)
C                                       BRANCH TO   590 FROM   580.01
  590 S(I,ISZ)=0.
      II=1
C     PRORATE SUM SEDIMENT PASSING ACCORDING TO ORIGINAL DIST
C                                       BRANCH TO   600 FROM   570.00
  600 SSI=SS*SED(IDU)/CONS
      GO TO 620
C     COMPUTE INITIAL SEDIMENT TRANSPORT ENTERING TRIBUTARY
C                                       BRANCH TO   610 FROM   560.02
  610 SSI=DUR(IDU)*SED(IDU)*PER*YR*.0365/(UW(ISZ)*21.78)*RATOS
      SEIN=SEIN+SSI
      FALL(ISZ,IDU)=0.
```

EXHIBIT 5

```
C     ROUTE SEDIMENT THRU EACH SECTION
C                                    BRANCH TO   620 FROM   600.01
  620 DO 650 IS=2,NSEC
      VR=RATOQ*Q(IDU)/((AREA(IS-1)+AREA(IS))*.5)
      RHL=SEC(IS)-SEC(IS-1)
C     DETERMINE ADJUSTMENT FOR RELATIVE AMOUNT SETTLED
      C=1.+FALL(ISZ,IDU)/DPH(IS)
      FALL(ISZ,IDU)=FALL(ISZ,IDU)+W*RHL/VR
C     CHECK FOR RIDICULOUS EXPONENT (X)
      X= W*RHL*(C**OPR)/(VR*DPH(IS))
      IF(X-10.) 640,640,630
C     ASSUME ALL MATERIAL IN SIZE RANGE DEPOSITED
C                                    BRANCH TO   630 FROM   620.08
  630 SDP(IS)=SDP(IS)+SSI
      SSO=0.
      GO TO 660
C     DETERMINE RATIO OF SEDIMENT PASSING SECTION TO THAT ENTERING
C                                    BRANCH TO   640 FROM   620.08
  640 R=1./2.7183**X
      SSO=SSI*R
      SDP(IS)=SDP(IS)+SSI-SSO
      SSI=SSO
C                                    BRANCH TO   650 FROM   620.00
  650 CONTINUE
      S(II,ISZ)=S(II,ISZ)+SSO
C                                    BRANCH TO   660 FROM   630.02
  660 IF(NTRIB-ITRB) 670,670,680
C     DETERMINE AMOUNT PASSING AT DAM IN EACH SIZE RANGE
C                                    BRANCH TO   670 FROM   660.00
  670 PASS(ISZ)=PASS(ISZ)+SSO
C                                    BRANCH TO   680 FROM   480.02   560.00
C                                           660.00
  680 CONTINUE
C     PRINT DEPOSITION FOR EACH REACH IN TRIBUTARY
      DO 710 I=2,NSEC
      PRINT 770,ITRIB(ITRB) ,SDP(I) ,SEC(I-1),SEC(I)
C     COMPUTE AND SUM SEDIMENT DEPOSITED BELOW A GIVEN MEAN ELEVATION
      ELL=WSEL-DPH(I)
      DO 700 J=1,NCAP
      IF(ELL-ELE(J))690,690,700
  690 CAP(J)=CAP(J)+SDP(I)
```

EXHIBIT 5

```
C                                         BRANCH TO   700 FROM   680.06   680.07
C
  700 CONTINUE                                                                  1233
C     SUM DEPOSITION                                                            1234
C                                         BRANCH TO   710 FROM   680.02
  710 SWIM=SWIM+SDP(I)                                                          1235
      PRINT 170                                                                 1236
C                                         BRANCH TO   720 FROM   340.02
  720 CONTINUE                                                                  1237
      PRINT 780,SWIM                                                            1238
      PRINT 790                                                                 1239
C     PRINT MEAN ELEVATION-DEPOSITION TABLE                                     1240
      DO 730 I=1,NCAP                                                           1241
  730 PRINT 800 , ELE(I),CAP(I)                                                 1242
      SUM=0.                                                                    1243
C     DETERMINE SUM OF ALL SEDIMENT PASSING (VOLUME)                            1244
      DO 740 I=1,7                                                              1245
  740 SUM=SUM+PASS(I)                                                           1246
      SSUM=0.                                                                   1247
C     SUM ALL PASSING SEDIMENT TIMES UNIT WT FOR SIZE DIST                      1248
      DO 750 I=1,7                                                              1249
  750 SSUM=SSUM+PASS(I)*UW(I)                                                   1250
      SSS=0.                                                                    1251
C     COMPUTE SIZE DIST OF PASSING SEDIMENT                                     1252
      DO 760 I=1,7                                                              1253
      SSS=SSS+PASS(I)*UW(I)                                                     1254
      PSIZ(I)=100.*SSS/SSUM                                                     1255
C                                         BRANCH TO   760 FROM   750.03
  760 CONTINUE                                                                  1256
C     PRINT FINAL RESULTS OF TRANSPORT THRU RES                                 1257
      PRINT 210,SEIN,UWT                                                        1258
      TEE=100.*((SEIN-SUM)/SEIN)                                                1259
      PRINT 810,SUM,TEE                                                         1260
      PRINT 820,(PSIZ(I),I=1,7)                                                 1261
C                                         BRANCH TO   770 FROM   680.03
  770 FORMAT (5X,9HTRIBUTARY,I5,4X,F10.1,12X,F8.0,5H AND ,F8.0)                 1262
C                                         BRANCH TO   780 FROM   720.01
  780 FORMAT (/16X,6HTOTAL ,F11.1)                                              1263
C                                         BRANCH TO   790 FROM   720.02
  790 FORMAT (/12X,56HACCUMULATED SEDIMENT DEPOSITED BELOW INDICATED ELE        1264
     1VATION/19X,14HELEVATION (FT),7X,18HDEPOSITION (AC-FT)/)                   1265
```

```
C                                         BRANCH TO   800 FROM   730.00
  800 FORMAT (21X,F8.0,12X,F10.0)
C                                         BRANCH TO   810 FROM   760.04
  810 FORMAT(/1X,24HTOTAL SEDIMENT PASSING =,F9.0,28H AC-FT       TRAP EFF
     1ICIENCY =,F8.2,8H PERCENT/)
C                                         BRANCH TO   820 FROM   760.05
  820 FORMAT (1X,78H SIZE DISTRIBUTION OF PASSING SEDIMENT IN PERCENT SM
     1ALLER THAN INDICATED BY WT/1X,70H       .004       .008       .016
     2   .031      .062      .250     1.000//1X,7F10.2)
C     BRANCH TO BEGINNING FOR NEXT JOB
      GO TO 230
C                                         BRANCH TO   830 FROM   240.03   290.01
C
  830 STOP
      END
```

EXHIBIT 5

EXHIBIT 6

INPUT DATA 23-J2-L264

A. Three output title cards

B. Job specification

1. NYR = Number of years for study

2. NTRIB - Number of tributaries used in study

3. NDUR - Number of flow-duration points used in study

4. WCY - Unit weight of clay (lbs/cu-ft)

5. WSI - Unit weight of silt (lbs/cu-ft)

6. WSD - Unit weight of sand (lbs/cu-ft)

7. OPR - Operation index. Values of zero or above are acceptable and may be approximated by:

$$OPR = (1 + dur) \cdot (1 + cap/QI)$$

where:

dur = Duration of sediment producing inflow as a ratio to entire year

cap = Capacity of reservoir in same units as QI

QI = Average annual inflow

This variable is intended to reflect the type of operation and affects the trap efficiency. If trap efficiency is too low, increase this variable. A 0 would be used for channels where a great deal of turbulence occurs with no storage whereas 2 or 3 may be reasonable for normally operated reservoirs. A 5.0 would be used for long term flood storage.

8. TEMP - Average temperature of reservoir

9. DEL - Difference in feet desired for the elevation - sediment capacity table. The table starts at ELMX (B-10) and decreases by DEL.

10. ELMX - Maximum elevation in feet desired for the elevation - sediment capacity table

C. Inflow-duration data

1. DUR - Accumulated duration read from a flow-duration curve in percent. Points should progress from low to large values such as 1, 5, 10, 20, and etc.

2. Q - Flow in cfs corresponding to DUR (C-1)

3. SED - Sediment in tons/day corresponding to Q (C-2). Data continued in 3-fields for each set and 3 sets per card (9 fields) until NDUR sets are satisfied.

D. Size distribution of suspended sediment

Accumulated percent smaller than indicated amount.

1. PS1Z(1) - 0.004 mm

2. PS1Z(2) - 0.008 mm

3. PS1Z(3) - 0.016 mm

4. PS1Z(4) - 0.031 mm

5. PS1Z(5) - 0.062 mm

6. PS1Z(6) - 0.250 mm

7. PS1Z(7) - 1.000 mm

E. Tributary specification. Repeat for each tributary (B-2) sets.

1. ITRIB - Tributary identification number. Four digits or less without a decimal.

2. NSEC - Number of sections along tributary

3. RATOS - Ratio by which input sediment (C cards) is to be multiplied for the particular tributary.

4. RATOQ - Ratio by which input flow (C cards) is to be multiplied for the particular tributary.

5. IADD - Number of tributaries to be added at the confluence to continue operation through the present tributary.

F. Section specification. Repeat for each section (E-2) sets.

1. SEC - Section station in feet from beginning (need not start with zero). Sections must increase from head of reservoir toward dam.

2. WSEL - Water surface elevation in reservoir. May vary from one section to another.

3. NSTA - Number of stations in section (see G).

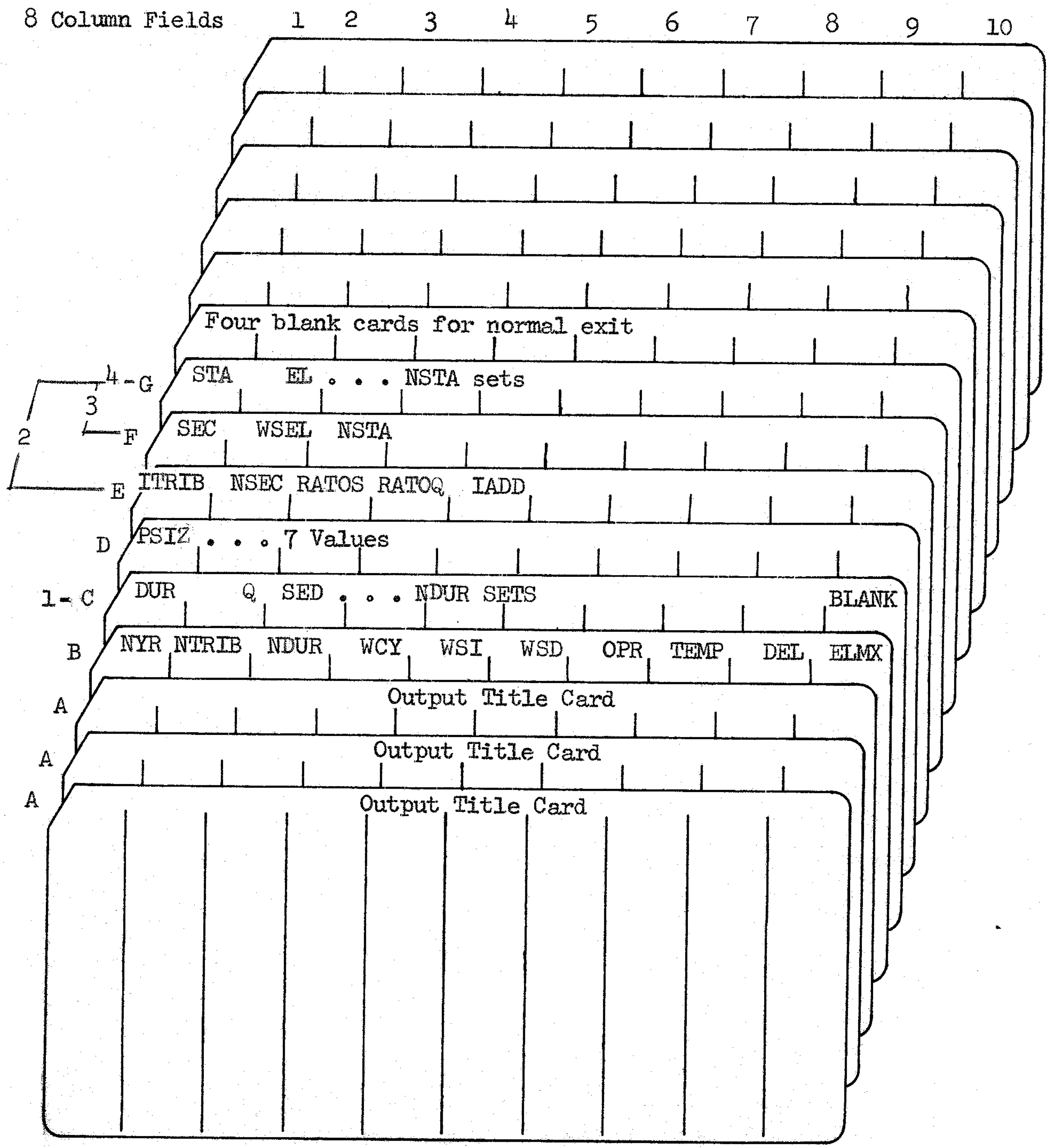
G. Cross-section data. Repeat as required to read in cross-section data (F-3) sets.

1. STA - Station in feet (need not start with zero)

2. EL - Elevation corresponding to station. Data continued in two fields for each corresponding set and 5 sets (10 fields per card). NSTA (F-3) sets required. Stations must increase and elevation must start at or above WSEL (F-2).

EXHIBIT 7

23-J2-L264 - SUMMARY OF REQUIRED CARDS



1. Repeat as necessary to satisfy NDUR (B-3) sets.
2. Repeat NTRIB (B-2) sets of data.
3. Repeat NSEC (E-2) sets of data.
4. Repeat NSTA (F-3) sets of data.

Appendix 7

Scour and Deposition in Rivers and Reservoirs

SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS

USERS MANUAL

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SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS

THE HYDROLOGIC ENGINEERING CENTER
COMPUTER PROGRAM 723-G2-L2470

INTRODUCTION

1. ORIGIN OF PROGRAM

This program was completed at The Hydrologic Engineering Center by William A. Thomas. Initial work was accomplished by the same author while in the Little Rock District, Corps of Engineers.

2. PURPOSE OF PROGRAM

This is a simulation program 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 flow.

It is sometimes possible to separate sedimentation studies from those involving the hydraulics of flow. For example, deposition in deep reservoirs can be studied from the standpoint of a reduction in reservoir storage capacity because there is no reentrainment of material once it is deposited. On the other hand, sedimentation studies in shallow reservoirs, downstream from dams or in natural rivers require treatment of the entire movable boundary problem because both scour and deposition are involved. It is for this more general case of problems that this simulation model is designed.

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.

3. LIMITATIONS OF THE PROGRAM

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 subdivided into two parts with input data--that part which has a movable bed, and that which does not; and the boundary between these parts remains fixed for the study. The entire movable 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.

4. POTENTIAL APPLICATIONS OF THE PROGRAM

Reservoir deposition can be analyzed to determine both the volume and location of sediment deposits. Degradation of the streambed downstream from a dam can be determined. Long term trends of scour or deposition in a stream channel, such as would result from modifying frequency and duration of the water discharge or stage or from encroaching on flood plains, can be simulated. Channel contraction required to either maintain navigation depths or diminish the volume of maintenance dredging can be studied--but not in the detail obtainable from movable bed hydraulic model studies. The influence that dredging has on the rate of deposition can be simulated, and scour during floods can be investigated. Sediment laden runoff through concrete channels can be analyzed to determine if, where and how much deposition will occur.

Nature maintains a delicate balance between the water-sediment mixture flowing in a natural stream, size and gradation of sediment material forming the stream's boundary and hydraulics of flow. When man establishes a reservoir or maintains a minimum depth of flow for navigation, that balance is upset. This computer program can be used to measure the impact of changing one or more of the above parameters directly in terms of the water surface profile and the water depth.

PROGRAM DESIGN

The utility of a generalized computer program can be described in terms of these four characteristics:

- <u>Flexibility</u> - The program provides the necessary functional relationships to accommodate the many varied requirements of a wide range of problems; physical systems are modeled with tables of data specified in units common to field problems so that the program is responsive to a wide range of problems requiring varying levels of detail.

- <u>Adaptability</u> - The state-of-the-art theory is coupled with a data structure that encourages evolution of the program as this theory evolves with use.

- <u>Usability</u> - The practicing engineer can approach problems in a straight-forward manner using the program users manual to set up and run the digital computer model. Input data requirements are user-oriented.

- <u>Portability</u> - The program is written in ASA Standard FORTRAN so that it is portable from one computer to another.

Considerable emphasis was given to the flexibility of this model. In simulation studies it is important for the engineer to apply the computer program to his study rather than to spend time simplifying and approximating the study to fit the requirements of a computer program. Detailed sediment studies involve large amounts of data, whereas the more general case involves studies in which only a small amount of data is available. These are conflicting requirements which often diminish flexibility of a program.

In this case, provision was made for the program to generate much of its data subject to being overridden if such data were supplied for the study. This option permits the engineer to use his data to the fullest extent that it is available rather than forcing him to acquire a high level of detailed data before the program can be applied. Of course, the result is no more dependable than the data used to obtain it.

Even in studies involving a fixed bed, open-channel hydraulics problems require a large amount of data. Extending solution techniques to include the movable boundary is even a greater task because not only do data requirements increase, but also the body of theory available to describe the physical process is not completely developed. It is possible, however, to extend open-channel hydraulics programs to include some aspects of sedimentation and thereby increase the engineer's capability, by use of digital modeling, to analyze a much wider range of open-channel flow problems.

5. CAPABILITY OF COMPUTER PROGRAM

The movable boundary problem is simplified into one involving a movable bed in a channel. The horizontal location of the channel banks is considered fixed, and the flood plain on each side of the channel is considered as having a fixed ground surface. This is similar in concept to the movable bed hydraulic model. However, if movement of the bed is expected in the flood plains, as in the case of deposition in a reservoir, the entire width can be considered as channel.

By entering a sequence of water discharges from a discharge hydrograph, changes are calculated with respect to time and with respect to distance along the model for each of the following: total sediment load; volume and gradation of sediment that is deposited; armoring of the bed surface; and the resulting bed elevation. In addition, sediment outflow at the downstream end of the model is calculated. The location and amount of material that has to be dredged is calculated if desired.

Geometry of the physical system is represented by cross sections, specified by coordinate points (stations and elevations), and the distance between cross sections. Hydraulic roughness is measured by Manning's n-values and can vary from cross section to cross section. At each cross section n-values may vary vertically and horizontally. The program raises or lowers cross section elevations to reflect deposition or scour.

The water discharge hydrograph is approximated by a sequence of steady flow discharges each of which occurs for a specified number of days. Water surface profiles are calculated by using the standard step method to solve the energy equation. Friction loss is calculated by Manning's equation, and expansion and contraction losses will be included if the representative loss coefficients are specified. The velocity distribution across each section is calculated unless this option is suppressed.

It is necessary to specify the water surface elevation at the downstream end of the model to initiate water surface profile calculations. In the case of a reservoir, the operating policy is utilized, but if open river conditions exist, a stage-discharge rating curve is usually specified for the downstream end of the model.

The inflowing sediment load is related to water discharge by a rating table at the upstream end of the model. If the gradation of material in the bed is known, and it must be if realistic depths of scour and the bed are required, this gradation is specified for each cross section. (However, if only deposition is expected, the gradation of material in the bed can be calculated by the program based upon the inflowing water-sediment mixture.)

Sediment mixtures are classified by grain size using the American Geophysical Union scale. The program accommodates clay (up to .004 mm), four classes of silt (.004 - .0625 mm), five classes of sand (very fine sand @ .0625 mm to very coarse sand @ 2 mm), and five classes of gravel (very fine gravel @2 mm to very coarse gravel @ 64 mm).

Transport capacity is calculated at each cross section by using hydraulic data obtained during the calculation of water surface profiles (e.g., width, depth, energy slope and velocity of flow) and the gradation of bed material for that cross section.

Three options are available for calculating transport of bed material: Toffaleti's application of Einstein's Bed Load Function, reference 5; Laursen's relationship as modified by Madden for large rivers, reference 8; or a special relationship can be developed for the particular study and specified as transport capacity per unit of width versus the water depth-energy slope product. Deposition of cohesive material is based on bed shear stress.

6. THEORETICAL BASIS FOR THE PROGRAM

The theoretical basis for the program is discussed in exhibit 3.

7. PROGRAM ORGANIZATION AND SIZE

In its present configuration the entire program resides in 40,000 words (Univac 1108) of memory without chaining. The various modules function together as subprograms where data is transferred in "Labeled Common" or in "Call Linkage." However, the location for tape commands is identified by Comment Cards in the source program to assist if chaining is required. The functional flow chart is shown in figure 1.

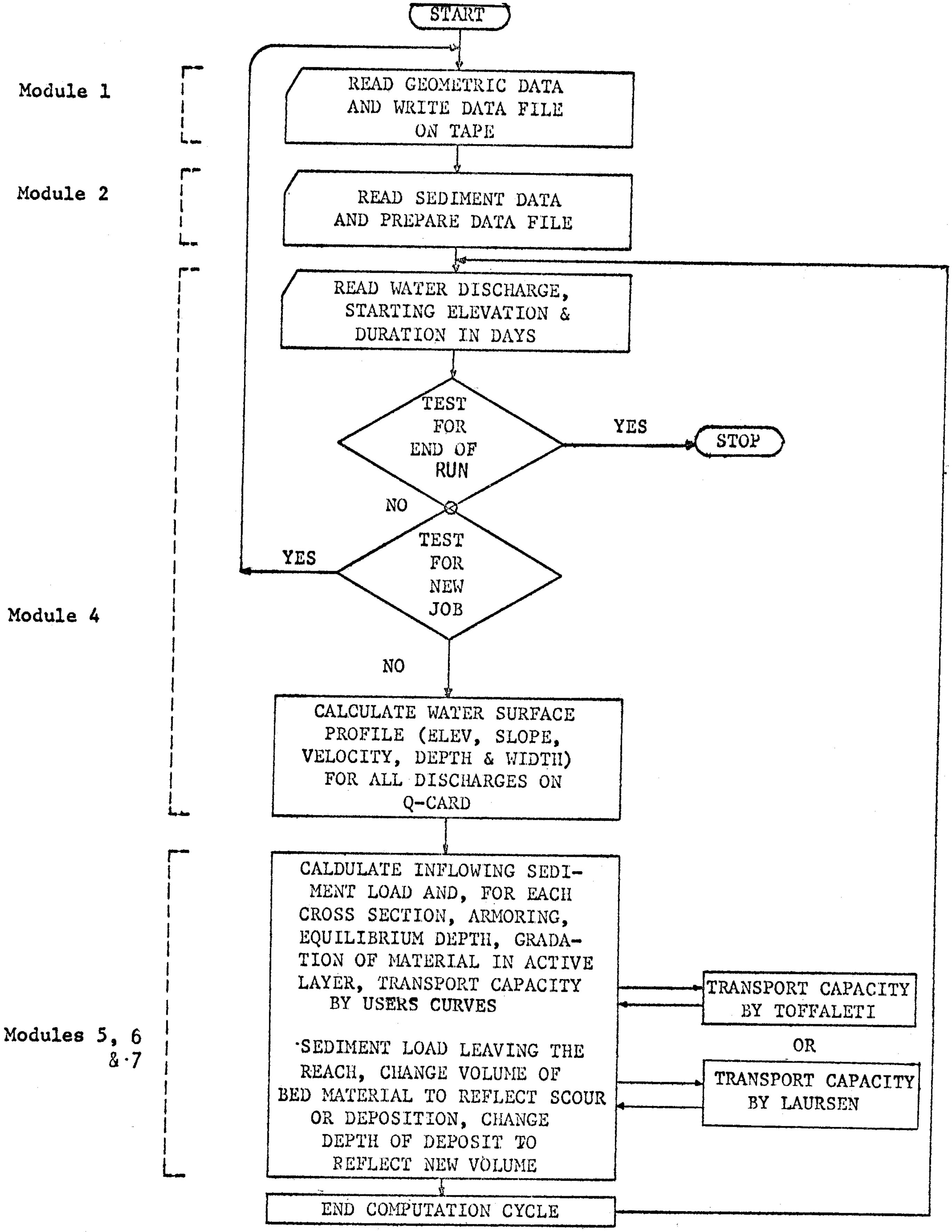

Figure 1. Functional flow chart.

PROGRAM USAGE

8. INTRODUCTION TO PROGRAM USAGE

Problem analysis by simulation is a two step process. First the model is calibrated and verified. Second, the problem analysis is made.

9. SUMMARY OF INPUT DATA

Input data are grouped into four categories as described below. A summary of input variables is contained in exhibit 7, and a detailed description of each variable is contained in exhibit 6.

a. Geometric Data. This category includes cross sections, reach lengths and n-values, existing at the beginning of the study, as required for water surface profile calculations. In addition the movable bed portion of each cross section and the depth of sediment material in the model bed are established.

b. Sediment Data. This category is specified on cards I through O and contains the inflowing sediment load data, gradation of material in the stream bed and information about fluid properties, and sediment properties.

c. Hydrologic Data. This category is specified on cards Q through W and contains water discharges, temperatures and flow durations.

d. Operating Rule. The operating rule is the functional relationship between the starting water surface elevations and time. It controls the water surface elevation at the downstream end of the study area and is specified on R cards in the Hydrologic Data. This can be a rating curve or a single elevation. It can be changed at any water discharge in the hydrologic data.

10. ESTIMATING DATA REQUIREMENTS

Estimate the number of cross sections (NR) that will be required to define the study area for water surface profile calculations. Also, determine the number of grain size classifications that are desired for describing the sediment load (NGS). (For example, use bed gradation curves to determine the maximum grain size present in the bed and from table 2 determine the number of size classifications required to define the bed gradation.) From table 1, determine the maximum number of water discharges that can be coded on each Q-card. The absence of a value indicates impossible combinations in which case either the number of cross sections (NR) or the number of grain sizes (NGS) must be decreased.

In no case can NR exceed 150, NGS exceed 15 or MNQ exceed 10. A short test case is recommended before coding an extensive problem.

11. DEVELOPING DATA DECKS THAT MODEL THE PHYSICAL PROBLEM (GENERAL CONCEPTS)

With the study reach located on a topographic map, mark the upstream boundary, the downstream boundary, the lateral limits and the location of each cross section. Assign an identification number to each cross section--miles above the mouth are recommended. Subdivide the flood plain into channel and overbank portions. These can be considered as strips having similar hydraulic properties in the direction of flow. Within a strip, flow conditions (depth, velocity, roughness) are similar and n-values and reach lengths can be assigned. Locations where strip lines intersect cross sections are called subsection stations.

In most cases, three strips will be used--left overbank, main channel and right overbank, but up to seven are permitted. An alternate data format is presented in exhibit 5-2 if more than three strips are required.

Table 1. Maximum Number of Grain Sizes(1)

Cross Sections	Number of Parallel Discharges Desired (See p. 19)									
	1	2	3	4	5	6	7	8	9	10
50	15	15	15	15	15	15	15	15	15	12
60	15	15	15	15	15	15	15	10	3	
70	15	15	15	15	14	6				
80	15	15	15	15	13	5				
90	15	15	15	14	6					
100	15	15	15	9	1					
110	15	15	12	3						
120	15	15	8							
130	15	13	5							
140	15	10	2							
150	15	8								

(1) The combinations in table 1 were determined from the following inequalities:

$$NR(NGS + 8*MNQ + 10) \leq 5{,}100$$

$$NTRIB(LG(NGS + 1)) + 3(NGS + 1) + NR(NGS + 4) \leq 6{,}000$$

Plot each cross section as it appears at the starting time of the study, time zero, and divide each into two parts; the movable bed part in the main channel and the fixed bed part in the overbanks.

Mark the top of rock elevations on each cross section, or if no rock is present, the program will arbitrarily assign 10 feet below channel bottom to provide some finite depth of sediment material in the model. (If more than 10 feet of scour is expected, assign a lower bottom elevation. This elevation is not critical except that sediment volumes are in tons or cubic feet which can result in numbers sufficiently large to cause word length problems in some computers.)

12. GEOMETRIC DATA

Two data formats are available for coding the geometric data: The HEC-2 "Water Surface Profiles" format and an optional format for this scour and deposition program which is described in exhibit 5.

a. Cross Sections. Cross sections are specified for conditions existing at the beginning of the study, and calculations are made directly from coordinate points (stations, elevations) - not from tables or curves of hydraulic elements. The number of coordinate points per section is limited to 100. Enter new coordinate points as desired to change the cross section from that described downstream. Correction for skew and changes in elevation can be made, if desired, without re-entering coordinate points (X1-card).

Elevations may be positive, zero or negative, but stations must not be negative. If the water surface elevation exceeds the end elevations of a section, calculations continue by extending the walls vertically up but ignoring that portion of the wetted parimeter.

b. Subsections. Each cross section is subdivided into parts called subsections - for example, left overbank, main channel and right overbank. Reach lengths and n-values are assigned to each subsection. The calculation of friction loss through the reach is made by averaging the end area of a subsection, averaging the end hydraulic radius and applying the subsection n-value and reach length to get a length-weighted subsection conveyance. Subsection conveyances are summed to get a total value for the reach which is used to calculate friction loss. If more than three subsections are required or if overbank n-values need to vary in the vertical, the optional format may be used as illustrated in exhibit 5. The values may be changed at any reach by inserting an n-value card (NC or NV) in front of the X1-card for the upstream end of that reach.

c. Reach Length. The cross section provides two dimensions for defining the geometric model; the distance between cross sections provides the third. Each subsection must have a reach length and it extends from the present section (where entered) to the downstream cross section.

d. Manning n-Values. An n-value is required for each subsection. **It will be utilized at all cross sections unless changed. It is not** possible to automatically change n-values with respect to time.

Only one n-value can be specified for an overbank subsection, but n can vary with either discharge or elevation in the main channel. When n varies with discharge, the first one should be **minus**. In all cases, code n-values in sequence from high to low discharge or elevation.

e. Bridges. This model has no provision for calculating flow at bridges except by normal backwater calculations. Subtract pier widths from the total width to reflect net flow area if detailed scour is of interest at the bridge. Otherwise ignore bridges and match water surface profiles by adjusting n-values to avoid the short time intervals required for analyzing scour at bridges.

f. Weirs. The abrupt head loss at a weir may be reflected by calculating critical depth or, if the weir is gated, an operating pool may be specified (X5-card). When the operating pool option is used, a head loss may be specified to simulate open river conditions at high flow.

The presence of a weir causes the program to establish an outflow point there and sediment quantities are accumulated at that point. Trap efficiency is calculated between each inflow and outflow point. Up to 20 weirs may be entered (see "Operating rule or rating curve.").

g. Movable Bed and Fixed Bed. Part or all of the channel portion of each cross section can be divided into movable and fixed bed portions. Scour and deposition will cause the movable bed to fall and rise by changing the cross section elevations after each cycle through the program. (A cycle is illustrated in figure 1.)

It is necessary to position the downstream end of the model where there is a stable rating curve or known water surface elevation. In degradation studies this may be several miles downstream from the dam at a rock outcrop or concrete weir. For studies in reservoirs the operating policy will establish the reservoir level for the water surface profile computations and the program will adjust the bed according to calculated results. The overbank subsections do not have a movable bed.

h. Dredging. Part or all of the movable bed portion of a cross section can be dredged at the beginning of each computation cycle or at selected points in time. The bottom elevation, lateral limits and depths of overdredging are specified on H-cards. When bottom elevations are higher than that specified for the dredged channel bottom, all points are lowered to the depth of overdredging. Outside of the dredged channel the points are not changed. Sediment material is assumed to be removed from the channel, but does not decrease the cross sectional area of the overbank as an actual spoil pile would.

The elevation of channel bottom is calculated at the end of each computation cycle (W-card). The total volume of deposits is calculated and dredging is done after this calculation is made. Two options are available for dredging. The $DREDGE card triggers a detailed calculation for the amount of material to be dredged. This material is removed from the section and coordinate points are modified. This option is expensive to run and can be turned off with a $NO DREDGE card. An alternative option is to emulate dredging by changing cross section coordinates but not the actual volume of deposits. Therefore, the volume of deposits continues to increase even though, at the time a water surface profile is calculated, the proper dredged channel is used.

This is a computation expedient to save computer time--not a short cut in the calculations. As long as dredging is requested for each computation cycle, (col. 7 on card *, Hydrologic Data) results will be correct. However, if this emulation is stopped by the "N" opt (*-card, col. 7), subsequent results will be completely erroneous unless the $DREDGE option was requested just prior to that *-card. The $DREDGE option is required to reshape each cross section and calculate the correct volume of deposits.

i. Ineffective Area. When high ground or some other obstruction prevents water from flowing into a subsection, the area up to that point is ineffective for conveying flow and should be suppressed until the water surface exceeds the top elevation of the obstruction. An elevation can be established to identify the point below which overbank area is ineffective.

The program automatically tests the first and last points in the movable bed to ascertain if natural levees are forming during the computations. If so, these override ineffective area elevations specified by input data. In fact, natural levees formed by the movable bed are always considered to establish ineffective areas even if that option was not selected by input data.

13. SEDIMENT DATA

The inflowing sediment load, transport capacity relationship, depth of sediment material in the bed, gradation of material in the bed, armor layer, and unit weight of suspended material as well as fully consolidated deposits form the sediment data.

The grain size of sediment particles commonly transported by rivers ranges over 7 log cycles. Small sizes behave considerably different from large sizes. Therefore, it is necessary to classify sediment material into groups for application of different transport theory. The three basic groups considered by this computer program are clay, silt and sand (and larger). The groups are identified and subdivided based on the American Geophysical Union classification scale as shown in table 2.

a. Inflowing Sediment Load. The aggradation or degradation of a stream bed profile depends upon the amount of sediment inflow and its size relative to the transport capacity of the stream. The sediment load entering the upstream end of the geometric model is called the inflowing load and is expressed in tons/day. An inflowing sediment load is needed for each inflowing water discharge. It should include both bed load and suspended load and can be expressed as a log-log function of water discharge in cfs vs. sediment load in tons/day as shown in figure 2.

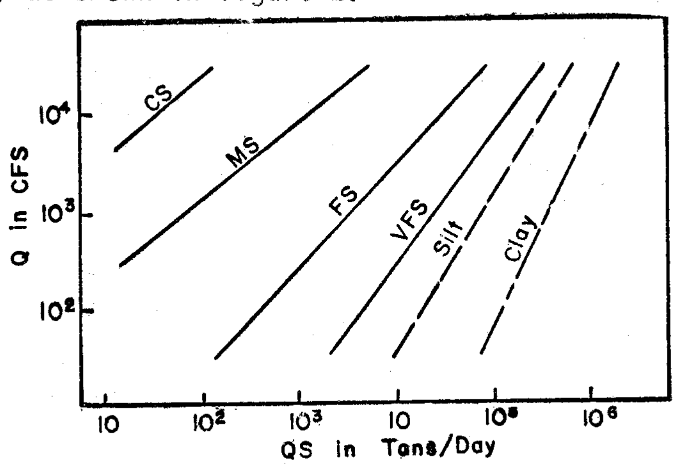

Fig. 2. Water-sediment inflow relationship

Table 2. Grain size classification of sediment material

No.	Sediment Material	Classification	Grain Diameter (mm)
	CLAY		
1.	Clay	(Clay)	.004
	SILT		
1.	Very Fine Silt		.004 - .008
2.	Fine Silt		.008 - .016
3.	Medium Silt		.016 - .032
4.	Coarse Silt		.032 - .0625
	SAND AND GRAVEL		
1.	Very Fine Sand	(VFS)	0.0625- 0.125
2.	Fine Sand	(FS)	0.125 - 0.250
3.	Medium Sand	(MS)	0.250 - 0.500
4.	Coarse Sand	(CS)	0.500 - 1.000
5.	Very Coarse Sand	(VCS)	1.000 - 2.000
6.	Very Fine Gravel	(VFG)	2.000 - 4.000
7.	Fine Gravel	(FG)	4.000 - 8.000
8.	Medium Gravel	(MG)	8.000 - 16.000
9.	Coarse Gravel	(CG)	16.000 - 32.000
10.	Very Coarse Gravel	(VCG)	32.000 - 64.000

Data is entered into the computer as a table where it is transformed into $\log_{10}$ values. Straight line interpolation of the log values is used by the program to get sediment inflows.

Table 3. Water-Sediment Discharge Relationship

Data Card Label	Comment Field	Values		Remarks
LQ		500	100000	Water discharge in cfs
LQS	CLAY	425	81400	Clay load in tons/day
LQS	SILT	160	33500	Silt load in tons/day
LQS	VFS	28	40500	VFS load in tons/day
LQS	FS	36	63900	FS load in tons/day
LQS	MS	0.99	5160.	MS load in tons/day
LQS	CS	0.1	14.	CS load in tons/day

If the inflowing sediment load is essentially of one grain size, it can be located in table 2 and classified for the computer program by identifying it as sand, silt or clay and assigning the number of its grain size class. But if the inflowing load is composed of a range of grain sizes, it is desirable to further subdivide sand and perhaps silt into the classifications shown in table 2. Use as many of these classifications as are required to describe the problem. It is not necessary to start with the smallest sand size nor is it necessary to go to the coarsest gravel, but once a range of sizes is selected, all grain sizes within that range must be included. The same is true for silt. The above classification is stored internally in the program and cannot be modified with input data.

b. Sediment Material in the Streambed. Transport theory for sand relates the total sand load moving to the gradation of sediment particles on the bed surface. Armor calculations require the gradation of material beneath the bed surface and knowledge about the depth to bed rock or some other material that might arrest degradation.

These requirements are accommodated in the sediment program by assigning a depth of sediment material to each cross section and specifying the surface gradation and the subsurface gradation as illustrated in the following sketch.

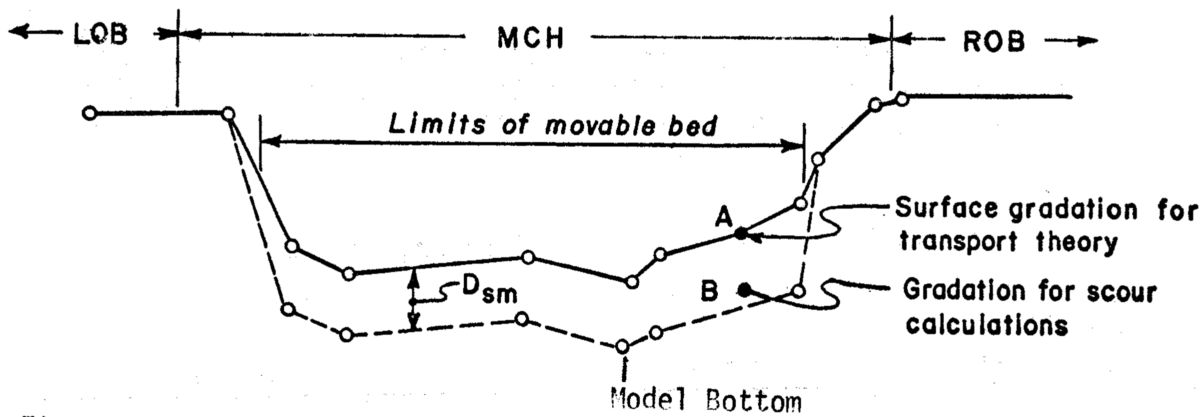

Fig. 3. Sediment material in the streambed

Coordinates connected with the solid line define the cross section at the beginning of the study. The computer lowers all coordinates within the "movable bed" by an amount D_{sm} and calculates the amount of sediment material available for transport from the cross sectional area defined by D_{sm}. If no model bottom elevation is specified, a default value of 10 feet is used for D_{sm}.

The total depth of sediment material, D_{sm}, is divided into two layers: active and inactive. All scour and deposition occur in the active layer, and subsequently, material is exchanged with the inactive layer based on equilibrium depth requirements.

The gradation of sediment particles on the streambed, point A (fig. 3), and the distribution of sizes in the inflowing load are redundant data sources. One must complement the other in transport theory. The gradation for scour calculations, region around point F (fig. 3), is a completely different data source and easier to sample than the bed surface gradation. Therefore, in using the computer program it is customary to specify inflowing sediment load and gradation of the region identified by point B and have the program calculate the bed surface gradation which is required to transport the inflowing load.

If the inflowing sediment load is not defined, the program can calculate it from gradation curves for the bed surface material. This procedure is less desirable than that discussed above because of the difficulty of obtaining representative sediment samples for the entire bed surface. However, simulating conditions along a segment of the river permits using indicators such as aggradation, degradation and fluctuation in sediment discharge from one cross section to another to make a better estimate of the noncohesive sediment load than can be made by applying transport theory at a point on the river.

The gradation of sediment material in the streambed is not coded as percent finer for input to the program; rather, the fraction of material contained in each grain size class is entered.

c. Armor Layer. A streambed having a gravel or cobble surface underlain by sand is said to be armored. This condition does not reduce the stream's potential to transport sediment but rather reflects a limited supply of sediment material such that transport theory does not give reliable results for grain sizes finer than those in the armor layer. The armor layer forms when fines are transported away more rapidly than they are replaced by the inflowing load allowing the coarser grain sizes to dominate the bed surface gradation and arrest further degradation.

The program approximates this process by subdividing the bed into two layers: (1) the active layer which predicts bed surface gradation and armoring and (2) the inactive layer which contains the gradation of the bed beneath the armor layer. Material is moved from one layer to the other as layer thickness changes with water depth, velocity and slope.

The stability of the armor layer is determined from the ratio of critical shear stress to actual shear stress using the statistical relationship presented in reference 2. This calculation is discussed in exhibit 3 of this manual.

d. Sediment Transport. Three transport relationships are available for noncohesive material. Toffaleti's application of Einstein's Bed Load Function, reference 5, Madden's application of Laursen's relationship as calibrated for large rivers, reference 8, and a relationship expressed as transport capacity per foot of width vs. the depth-slope product.

Silt and clay material is transported or deposited based upon a critical value for bed shear. If the actual bed shear is greater than critical, no deposition occurs. When the actual bed shear stress drops below the critical value, deposition occurs as an exponential decay function of stream velocity and fall velocity of the sediment grains.

Provision is made to include a critical shear value for scour. However, versions 2.0 - 2.9 of the program do not calculate the removal of silt and clay material from the bed once deposition has occurred.

Default values for critical bed shear are 0.02 lbs/ft^2 for both silt and clay. This was taken from reference 10.

e. Unit Weight. Silts and clay are expected to consolidate with time according to the following relationship

$$\gamma = \gamma_i + K\log_{10}(\text{Time})$$

γ_i = initial unit weight

K = coefficient of compaction

Time = time in years

Default values from reference 9 are provided for γ_i and K.

f. Sediment Properties. Four basic properties are considered: grain size, grain shape factor, specific gravity and fall velocity. Grain size classification is fixed in the program and is shown in exhibit 6 for I-cards. The grain shape factor enters into transport calculations as presented in reference 5, but no satisfactory relationship between grain shape and fall velocity was achieved and therefore, all particles are treated as if they were spheres for calculating fall velocity. The program defaults to a specific gravity of 2.65 if no value is specified. The grain shape factor defaults to 0.667 if no value is specified.

14. THE HYDROLOGIC DATA

Having specified the initial conditions of the geometric model and the sediment relationships for the stream the final step in sediment calculations is to simulate the response of these data to hydrologic inputs and perhaps, reservoir operation rules. A continuous simulation is needed for a water discharge hydrograph since both sediment transport and hydraulics of flow are nonlinear functions of water discharge. The operation rules for reservoirs vary with time and impact directly on hydraulics of flow. The lack of coincidence between mainstem and tributary flood hydrographs makes it desirable to enter flow from tributaries at their correct locations along the mainstem.

It is important that the water discharges in the hydrograph reproduce the anticipated flow duration curve. If a period of record of flows is not available, an annual pattern hydrograph can be determined from the duration curve and knowledge about the annual sequence of flows. It is desirable to include a wet and a dry year in addition to the average year.

It is desirable to repeat discharges at selected time intervals throughout the hydrologic period to provide a common basis for comparing rates of change. For example, the ending of each year with the same discharge will permit comparing water surface and bed profiles as time progresses.

The hydrologic data set also includes water temperature and the operating rule for the downstream end of the model.

a. Water Discharges and Durations. This program treats a continuous hydrograph as a sequence of discrete steady flow events, each having a specified duration in days as illustrated in figure 4.

A discharge hydrograph blocked out in this manner will be referred to as a discharge histogram. Each water discharge is coded on a Q-card and its corresponding duration in days is coded, in the corresponding field, on a W-card as illustrated in figure 5.

Representing the discharge hydrograph with a histogram requires the preservation of total annual volume while reproducing the shape and peak discharges in flood events. The duration of each discharge in the histogram should be at least long enough to permit that flow

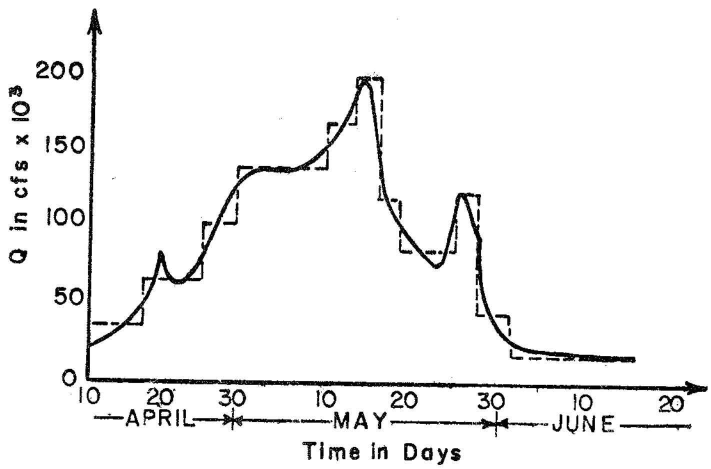

Fig. 4. Water discharge hydrograph

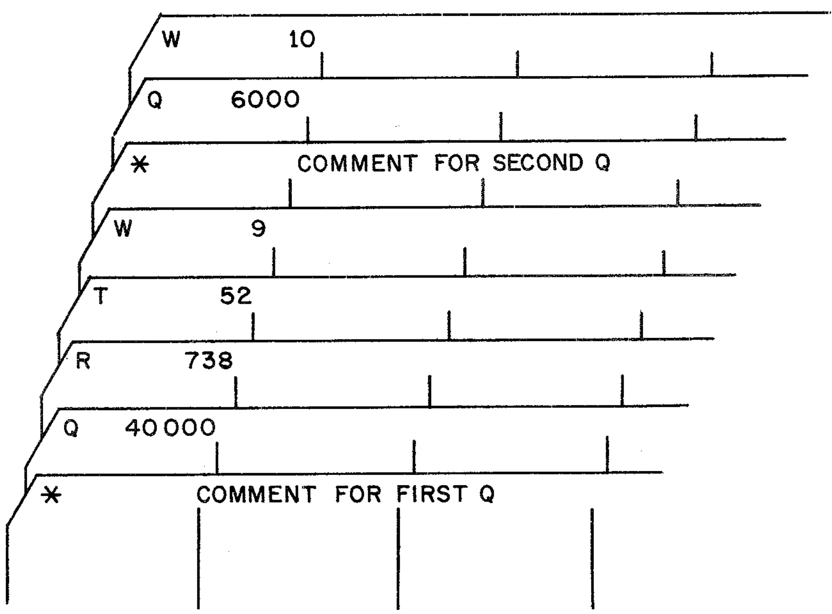

Fig. 5. Coding the discharge histogram

to pass through the model, and longer durations are acceptable and will be accommodated internally by the program. However, this is an explicit formulation of the basic equations and care must be taken to insure that flow durations are not so long that oscillations are induced into bed and water surface profiles. It is usually acceptable to approximate an annual hydrograph with 15 to 25 discharge segments. In general, the larger the discharge the shorter its duration must be because the larger discharges produce the greater amount of bed movement. A constant discharge can be entered as several successive increments to satisfy the requirement for short duration. Each increment is then treated like a discrete discharge segment from the histogram.

b. Parallel Versus Serial Computations. When tributary inflow points are not specified in the geometric model, the user has the option of calculating up to 10 water surface profiles in parallel. That is, the first cross section is read and starting water surface elevations for up to 10 water discharges are established. The next cross section data set is read in and all water surface profiles are calculated up to that point. The procedure is repeated through the entire geometric model. Sediment calculations are then made and the bed profile adjusted to reflect changes due to movement. This is contrasted with serial computations which calculate an entire water surface profile, analyze sediment movement, adjust the cross sections and repeat the procedure for the next discharge.

The advantage of parallel computations is a saving in computer time. The disadvantage is that changes in the bed are not reflected in the calculations until the next Q-card is read and oscillation is likely to occur. Problems involving deposition in deep reservoirs can usually be analyzed with parallel calculations.

When tributary inflow points are specified in the geometric model, only serial calculations are permitted. Water discharge at the downstream boundary of the geometric model is specified in field 1 of the Q-card. Tributary inflow is read from fields 2 through 10 and continues in field 1 of a continuation Q-card if 10 or more tributaries are present. Field 2 would contain inflow for the most downstream tributary, field 3 for the next and so forth to the most upstream tributary.

c. Operating Rule or Rating Curve. The starting water surface elevation is used by this program to accomplish the same purpose that it is used for in water surface profile computations. It is required at the downstream end of the geometric model (i.e., the downstream boundary), and operating rules may be imposed at up to 20 dams or other controls in the geometric data to permit continuous analysis through reservoirs in series.

d. Downstream Boundary. Two options are available for establishing the water surface elevation at the downstream boundary: (1) the rule curve option or (2) a stage-discharge rating table. The rule curve option is exercised by placing an R-card after the Q-card in the hydrologic data set. The program will continue to reuse this rule curve elevation; therefore, the next R-card should be inserted only when the operating rule changes to a new elevation. If the "parallel computations" option is exercised, enter a starting water surface elevation for each discharge on the Q-card.

The option for having the computer program determine starting water surface elevation from a stage or elevation-discharge rating curve is identified by the command $RATING, and the rating table must follow.

A shift in these rating curves or operating rules can be specified on the S-card. It will be retained in memory and applied to all subsequent starting water surface elevations at the downstream boundary until a new shift is entered. All shifts are relative to the original rating curve or operating rule; therefore, to return to the original rating, enter a zero shift. A sequence of either or both operating rules and rating curves is permitted in a data set. The computer program operates under an option until that option is changed by encountering a new option in the hydrologic data set. Card identification in column 1 identifies the option and values on the card specify the elevation or rating curve values to be used.

e. Internal Controls. A rule-curve-type of option can be specified to establish the constant operating elevation of a navigation pool. This is accomplished with an A-card (X5-card in HEC-2 data format) which specified a POOL (X5-2) elevation and a head loss, HLOSS (X5-3). When the tailwater elevation plus the head loss term is higher than the specified pool elevation, the pool rises.

Critical depth is always monitored and overrides all rule curves or other artificial controls to insure that flow depth is always at or above critical.

f. Water Temperature. The water temperature is specified on the T-card which triggers the calculation of fall velocities for the particles. Temperature can be changed by inserting T-cards in the *, Q, R, T and W data set. Each time, new fall velocities will be calculated. However, only the first water temperature on the card (field 1) is utilized, and if temperature changes with time or discharge only those flows having the same temperature should be coded on a single Q-card.

15. PROGRAM COMMANDS

A command card structure, identified by a $ in card column 1, was developed to enhance the flexibility of the program. Two commands are required for all data sets: $HYD which identifies the cards that follow it as hydrologic data; and $$END which identifies the End of the computer run. Other commands are optional and are provided only when that option is exercised. These are presented in detail in exhibit 6.

16. OUTPUT

The user must select what information he wants and request a level of output that contains it. The program is designed to print out a minimum amount of information just so the user will know that computations are finished, but it will not be sufficient to display model performance.

Each major data group (i.e., geometric, sediment and hydrologic) has a "normal" printout and one or more "options" for additional printout. These, as illustrated in the example that follows, are specified on the comment cards in each data group.

The second output mode is punch cards. Often, it is desirable to break a long hydrograph into shorter segments and evaluate the output from each before analyzing the next segment. If so, the program can punch the model status on N and O-cards, and no keypunching is required to resume computations. The $PCH O-cards command exercises this punch option.

Output is organized to aid the user in establishing the point in his data deck where computations abort. That is, the program version number and date are printed out before the first card of input data is read. Title information is read from the data deck and immediately printed. Each cross section identification number is printed as the data for that section is being read in. At the end of the geometric data a message is printed which reads

END OF GEOMETRIC DATA

NO. OF CROSS SECTIONS READ IN = _____

NO. OF INPUT DATA MESSAGES = _____

Beginning at the top of a new page the five title cards of the sediment data are printed immediately after they are read. Before the first sediment data is read the title cards from the geometric model are listed under the note

BASIC BACKWATER TAPE.

This is followed by the note

SEDIMENT PARAMETER DATA,

which is printed just before the I1-14 cards are read. The I1-14 card data that is printed shows what the computer program is using for each variable. Where default options are elected, default values will be printed.

The note

FOLLOWING GRAIN SIZES UTILIZED

is followed by the geometric mean diameter in feet for each grain size class requested on the I-cards.

Data following the note

Q-QS RATING TABLE

is the inflowing water-sediment rating curve at the upstream boundary (L-Card Data). Each card image is printed out before the next card is read.

The next label

VOLUME VS. DEPTH OF DEPOSITS

identifies the data that follows as pertaining to the movable bed in the model. The column "Movable Bed Width" is calculated from the depth of material in the model bottom (H-2) and not from left and right limits (H-3 and H-4). This information is printed even if no M-cards are present.

Sediment material in the streambed is printed out as each card is read, but the note

INACTIVE BED, GRAIN SIZE DISTRIBUTION BY SIZE FRACTION (N-CARDS)

is printed before the first N-card is read.

After the last N-card, the note

ACTIVE DEPOSITS, VOL. IN TONS

is printed in anticipation of O-cards. If present, the O-cards are printed out as data for each section is read in. If no O-cards the message

NONE SPECIFIED, ASSUMED ZERO

is printed.

When tributaries are present in the geometric model, the sediment model expects to find sediment inflow rating curves for each and prints the note

TRIBUTARY INFLOW DATA

Q-QS RATING TABLE

The cards that follow are in the same form as L-cards above, and card images are printed out as discussed for the upstream boundary.

The last line of printout from the sediment data input module is

NO. OF INPUT DATA MESSAGES = _____

The next "normal" line of printout will come from the Hydraulics Module and will be either the first command card present (e.g., $RATING, $DREDGE, etc) or the first "*" card of information requesting printout for that discharge event, whichever comes first.

Normal printout (No options selected) would be the note

END OF JOB

followed by the table of information of accumulated time and quantities and status of bed at each cross section at that time, water discharge and sediment load corresponding to that water discharge at each section.

Optional output is essential within the simulation run, and the most useful is B-level in the sediment calculations. A-level gives volumes only, and C-level is too much detail for most cases. Optional output from the hydraulics calculations is not particularly useful once the n-values are calibrated and A-level is usually adequate.

Since the entire water surface profile is calculated before the sediment calculations begin, an A-level printout for the first discharge calculations in the hydraulics model is useful for diagnosing data problems that might arise on the first pass. Subsequently, only request printout there when interested in velocity.

Likewise, a C-level printout in the sediment module is usually helpful on the first discharge. This amounts to about 1/2 page per cross section, however.

Table 4 shows a listing of the data cards for an example problem, and table 5 shows printout from the executed example problem.

Table 4. Example Problem, Input Data

```
T1        EXAMPLE PROBLEM NO. 1, USERS MANUAL   ***HEC-2 FORMAT***
T2        OZARK RESERVOIR SEDIMENT STUDY DATA, W.A. THOMAS, HEC,DEC1971
T3        HYPOTHETICAL TRIBUTARIES ADDED TO BASIC MODEL, VERSION 2+ FORMAT
NC    .06     .06   .0285
X1308.75      13       0    1365
GR   380       0     353      82     343     200     338     300     332     400
GR   325     520     321     680     325     820     327     900     330    1000
GR   337    1200     353    1290     380    1365
H 308.75     321     130    1285
X1 318.6      16    1522    3000    5000           51330
GR   390       0     370      50     370    1500   362.6    1522     353    1700
GR   348    1800     343    1900     336    2020   332.0    2170     336    2320
GR   338    2400     340    2500     342    2660   344.0    2870   362.5    2930
GR   390    3000
H  318.6            1576    2920
QT
X1 322.7      18    3600    5050   18474           18474
GR   400     200     375     500     360    1000     360    1400     380    1550
GR   375    3600   366.2    3630     355    3800     349    3900     341    4020
GR   340    4175     341    4320     342    4400     343    4500   345.2    4630
GR   349    4930   366.2    4975     390    5050
H  322.7            3686    4970
X1   329      19   13000   14310   30956   30956   30956
GR   385       0     385    3000     360    3050     365    3150     375    3200
GR   377   13000     370   13100     358   13300     350   13450     345   13520
GR   343   13670     345   13820     348   13900     350   14000     356   14170
GR   370   14280     375   14310     369   18000     390   21300
H  329.0           13065   14300             360   13520   13820
QT
X1 333.2      19    3200    4294   16700   16700   16700
X3    10
GR   385       0     380     200     380    1200     360    1300     370    1400
GR   385    1700     382    3200     377    3246     360    3420     354    3560
GR   350    3640     347    3720.    345    3880     347    4020     350    4070
GR   354    4140     360    4240     380    4300     385    5200
H  333.2   345.0    3261    4280             360    3720    4020
X1 337.1      17    3000    4095   18650   18650   18650
GR   390       0     380    1000     370    1200     400    1300     385    3000
GR   378    3020     372    3200     368    3300     363    3410     361    3520
GR   354    3680     361    3820     363    3920   365.5    4040     385    4090
GR   383    5095     390    6095
H  337.1     354    3020    4045             360    3520    3820
X1 342.4      21    2500    3678   24730   24730   24730
GR   400       0     390     200     385     300     385     500     385    2500
GR   380    2530     362    2580     359    2680     355    2700     353    2860
GR   355    3000     356    3020     360    3200     364    3400     364    3600
GR   380    3650     390    3680     385    3700     385    4000     390    5000
GR   395    8000
H  342.4            2530    3650             360    2700    3000
X1346.29      16    5000    6080   21880   21880   21880
GR   400       0     390    1000     395    3000     391    4900     385    5000
GR   369    5190     365    5460     364    5500     362    5640     364    5800
GR   365    5840     366    5900     385    6080     390    6580     397    7580
GR   400   13000
H 346.29            5050    5950             360    5500    5800
EJ
*1        SEDIMENT MODEL INCLUDES CLAY,SILT, AND SAND.  TOTAL SAND LOAD IS DIVIDED
*2        INTO 4 CLASSES-VERY FINE,FINE,MEDIUM,AND COARSE.
*3        BED MATERIAL GRADATION =DM 6-4,P.16, REACH V.
*4        TRANSPORT CAPACITY= TOFFALETI      (J & K CARDS ARE IN BUT NOT USED)
*5        MODEL VERIFIED FOR Q=50000 CFS FOR 1 YEAR PRIOR TO STUDY
I1                              5
I2
I3                     3        3
```

Table 4 (cont.)

```
I4                2       1       4    2.65
J    VFS .000104 2.1776  .0000871
J    FS  .000268 2.3064  .000165
J    MS  .000526 2.4705  .000273
J    CS  .000924 2.5847  .000273
K    N   5.194   -3.22
L    Q   7600.   30000.  100000. 430000.
L CLAY   9000.   40000.  180000. 1340000.
L SILT   9270.   41140.  182800. 1335000.
L    VFS 190.    1700.   11800.  120000.
L    FS  800.    6600.   43000.  430000.
L    MS  490.    2300.   15000.  265000.
L    CS  190.    540.    3000.   90000.
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .031    .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
N S/S/C          .06     .03     .95               .049     .05     .044     .324
N        .311    .164
$TRIB
L  Q     1.      100000.
L CLAY   0.      0.
L SILT   10.     400000.
L VFS    1.      4000.
L  FS    .5      6000.
L  MS    0.      50.
L  CS    0.      0.
L  Q     10.     500.    5800.
L CLAY   .01     200.    10000.
L SILT   .1      15.     5000.
L VFS     .001   1.      200.
L  FS    .001    1.      100.
L  MS    .001    .5      100.
L  CS    .001    .1      10.
$HYD
*     B   RUN 1.  THE FOLLOWING HYDROLOGIC DATA ILLUSTRATES HOW TO RUN A  YEAR  OF
Q  50000     1000      200
R  346.5
T      65
W      1
*     B   RUN 2.  WATER DISCHARGE THROUGH THE MODEL, AND THEN SIMULATE IMPOUNDING
Q  50000     1000      200
W      64
*     B   RUN 3.  THE POOL TO START A RESERVOIR DEPOSITION STUDY.
Q  50000     1000      200
W     100
*     B   RUN 4.  MODEL VERIFICATION
Q  50000     1000      200
W     100
*     B   RUN 5.  MODEL VERIFICATION
Q  50000     1000      200
W     100
*    AB   RUN1, REGULATED FLOW HYDROGRAPH, BEGINNING 1923,1FEB.
Q 150000     8000     2000


R     372
W       4
$$END
```

Table 5. Example Listing, Executed Results

```
* . .
************************SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS************************
VERSION 2.3 05NOV1974

T1      EXAMPLE PROBLEM NO. 1, USERS MANUAL  ***HEC-2 FORMAT***
T2      OZARK RESERVOIR SEDIMENT STUDY DATA, W.A. THOMAS, HEC,DEC1971
T3      HYPOTHETICAL TRIBUTARIES ADDED TO BASIC MODEL, VERSION 2+ FORMAT

    ALER      ASEL       CE        CC        LFA      NR      YAN      CRL
P  .050000  0.000000  1.000000  1.000000      1

    ALER      ASEL       CE        CC        LFA      NR      YAN      CRL
                      1.000000  1.000000

SEC NO.   308.750

SEC NO.   318.600
TRIBUTARY ENTRY POINT      =0 OCCURRS AT X-SECTION  NO.     3

SEC NO.   322.700

SEC NO.   329.000
TRIBUTARY ENTRY POINT      =0 OCCURRS AT X-SECTION  NO.     5

SEC NO.   333.200

SEC NO.   337.100

SEC NO.   342.400

SEC NO.   346.290
NO. OF CROSS SECTIONS READ IN =    8
NO. OF INPUT DATA MESSAGES=    0
END OF GEOMETRIC DATA
```

Table 5 (cont.)

```
*1      SEDIMENT MODEL INCLUDES CLAY,SILT, AND SAND.  TOTAL SAND LOAD IS DIVIDED
*2      INTO 4 CLASSES-VERY FINE,FINE,MEDIUM,AND COARSE.
*3      BED MATERIAL GRADATION FOM 6-4,P.16, REACH V.
*4      TRANSPORT CAPACITY= TOFFALETI    (J & K CARDS ARE IN BUT NOT USED)
*5      MODEL VERIFIED FOR Q=50000 CFS FOR 1 YEAR PRIOR TO STUDY

BASIC BACKWATER TAPE
EXAMPLE PROBLEM NO. 1, USERS MANUAL  ***HEC-2 FORMAT***


OZARK RESERVOIR SEDIMENT STUDY DATA, M.A. THOMAS, HEC,DEC1971
HYPOTHETICAL TRIBUTARIES ADDED TO BASIC MODEL, VERSION 2+ FORMAT


SEDIMENT PARAMETER DATA
        SPI       IBG      MNQ      SPGF      ACGR
I1      -0        -0       5        1.000     32.174

        MTCL                        SPGC      DTCL      STCD      PUCD      UHCL      CCCD
I2      1                           2.650     .020      .020      78.000    30.000    16.000

        MTCL      IASL     LASL     SGSL      DTSL      STSD      PUSD      UHSD      CCSD
I3      1         3        3        2.650     .020      .020      82.000    65.000    5.700

        MTC       IASA     LASA     SPGS      GSF       BSAE      PSI       UXD
I4      2         1        4        2.650     .667      .500      30.000    93.000

FOLLOWING GRAIN SIZES UTILIZED
CLAY SIZE=        .000013
SILT SIZES=       .000101
SAND SIZES UP=    .000285    .000580    .001160    .002319    .

TRANSPORT CAPACITY RELATIONSHIPS FURNISHED BY USER, MTC=  2


DS AND N CORRECTION COEF

J   VFS           .000       2.178       .000
J   FS            .000       2.306       .000
J   MS            .001       2.471       .000
J   CS            .001       2.585       .000
K   N            5.190      -3.220      -0.000


Q-QS RATING TABLE

L   Q          7600.000    30000.000   100000.000   430000.000
L CLAY         9000.000    40000.000   180000.000  1340000.000
L SILT         9270.000    41140.000   182600.000  1335000.000
L   VFS         190.000     1700.000    11800.000   120000.000
L   FS          800.000     6600.000    43000.000   430000.000
L   MS          490.000     2300.000    15000.000   245000.000
L   CS          190.000      540.000     3000.000    90000.000


VOLUME VS DEPTH OF DEPOSITS

             VOLUME        MOVEABLE    !              ELEVATIONS
   SEC NO.  SHAPE FACTOR   BED WIDTH   ! LEFT SIDE    RIGHT SIDE     THALWEG
    308.750                  1104.0       348.00        342.00        326.00
    318.600                  1289.0       353.00        344.00        332.00
    322.700                  1237.5       355.00        349.00        340.00
    329.000                  1245.0       370.00        370.00        343.00
    333.200                   934.0       365.00        365.00        350.00
    337.100                  1055.0       383.00        370.50        359.00
```

Table 5 (cont.)

```
  342.400                 1149.0     380.00     380.00     353.00
  346.290                  895.0     369.00     366.00     362.00

INACTIVE BED, GRAIN SIZE DISTRIBUTION BY SIZE FRACTION,(N-CARDS)

N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .031      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164
N            -0.000      .060      .030      .950     -0.000      .049      .050      .044      .324
               .311      .164

ACTIVE DEPOSITS, VOL. IN TONS

NONE SPECIFIED, ASSUMED ZERO

TRIBUTARY INFLOW DATA

Q-QS RATING TABLE

L  Q          1.000  100000.000
L CLAY        0.000       0.000
L SILT       10.000  400000.000
L VFS         1.000    4000.000
L  FS          .500    6000.000
L  MS         0.000      50.000
L  CS         0.000       0.000

TRIBUTARY INFLOW DATA

Q-QS RATING TABLE

L  Q         10.000     500.000    5800.000
L CLAY         .010     200.000   10000.000
L SILT         .100      15.000    5000.000
L VFS          .001       1.000     200.000
L  FS          .001       1.000     100.000
L  MS          .001        .500     100.000
L  CS          .001        .100      10.000

NO. OF INPUT DATA MESSAGES=    0

END OF SEDIMENT DATA


    B  RUN 1.  THE FOLLOWING HYDROLOGIC DATA ILLUSTRATES HOW TO RUN A  YEAR  OF
```

Table 5 (cont.)

DOWNSTREAM BOUNDARY DATA
WATER DISCHARGE= 50000.00
ELEVATION= 346.50
TEMPERATURE= 65.00
FLOW DURATION(DAYS) 1.00

ACCUMULATED AC-FT BY ENTRY DAYS	POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
1.00	346,290	112.42			53.09			11.74		
	329,000	.03			.00			.00		
	318,600	.00			4.08			.15		
TOTAL	308,750	112.45	112.45	-.00	57.17	57.17	0.00	11.89	13.60	-.14

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346,290	.02	378.64	362.02	48800	73456	75164	15922
342,400	-.04	376.16	352.96	48800	73456	75164	60722
337,100	.01	371.35	354.01	48800	73456	75164	53455
333,200	.00	365.44	345.00	48800	73456	75164	53455
329,000	-.01	362.24	342.99	49000	73476	75168	73072
322,700	.01	355.63	340.01	49000	73476	75168	61645
318,600	.01	352.17	332.01	50000	73477	80939	41139
308,750	.01	346.50	321.01	50000	73477	80939	27540

B RUN 2. WATER DISCHARGE THROUGH THE MODEL, AND THEN SIMULATE IMPOUNDING

DOWNSTREAM BOUNDARY DATA
WATER DISCHARGE= 50000.00
ELEVATION= 346.50
TEMPERATURE= 65.00
FLOW DURATION(DAYS) 64.00

ACCUMULATED AC-FT BY ENTRY DAYS	POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
65.00	346,290	7307.38			3451.05			763.15		
	329,000	1.96			.21			.02		
	318,600	.10			264.96			9.52		
TOTAL	308,750	7309.43	7309.43	-.00	3716.22	3716.22	.00	772.69	521.11	.33

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346,290	1.31	378.63	363.31	48800	73456	75164	14595
342,400	-.34	376.15	352.66	48800	73456	75164	20515
337,100	.00	371.35	354.00	48800	73456	75164	20613
333,200	.00	365.44	345.00	48800	73456	75164	20613
329,000	-.36	362.24	342.04	49000	73476	75168	27981
322,700	-.12	355.61	339.88	49000	73476	75168	30790
318,600	.12	352.16	332.12	50000	73477	80939	27402
308,750	.56	346.50	321.56	50000	73477	80939	16062

Table 5 (cont.)

* B RUN 3, THE POOL TO START A RESERVOIR DEPOSITION STUDY,

DOWNSTREAM BOUNDARY DATA

WATER	DISCHARGE=	50000,00
	ELEVATION=	346,50
	TEMPERATURE=	65,00
FLOW DURATION(DAYS)		100,00

ACCUMULATED AC-FT BY DAYS	ENTRY POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
165,00	346,290	18549,49			8760,35			1937,23		
	329,000	4,97			,54			,04		
	318,600	,25			672,59			24,15		
TOTAL=	308,750	18554,71	18554,71	0,00	9433,48	9433,48	0,00	1961,43	1325,38	,32

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346,290	3,22	378,71	365,22	48800	73456	75164	15096
342,400	-,38	376,04	352,62	48800	73456	75164	15582
337,100	,00	371,33	354,00	48800	73456	75164	15583
333,200	,00	365,24	345,00	48800	73456	75164	15583
329,000	-,47	362,03	342,53	49000	73476	75168	17109
322,700	-,32	355,71	339,68	49000	73476	75168	20032
318,600	,06	352,42	332,06	50000	73477	80939	21601
308,750	,96	346,50	321,96	50000	73477	80939	16291

* B' RUN 4, MODEL VERIFICATION

DOWNSTREAM BOUNDARY DATA

WATER	DISCHARGE=	50000,00
	ELEVATION=	346,50
	TEMPERATURE=	65,00
FLOW DURATION(DAYS)		100,00

ACCUMULATED AC-FT BY DAYS	ENTRY POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
265,00	346,290	29791,61			14069,65			3111,32		
	329,000	7,97			,87			,07		
	318,600	,41			1080,22			38,79		
TOTAL=	308,750	29799,99	29799,99	-,00	15150,74	15150,74	0,00	3150,18	2163,74	,31

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346,290	4,95	379,08	366,95	48800	73456	75164	15904
342,400	-,44	376,02	352,56	48800	73455	75164	16642
337,100	,00	371,32	354,00	48800	73456	75164	16641
333,200	,00	365,13	345,00	48800	73456	75164	16641
329,000	-,53	361,88	342,-7	49000	73476	75168	17581
322,700	-,38	355,69	339,02	49000	73476	75168	18319
318,600	-,01	352,56	331,99	50000	73477	80939	20040
308,750	1,20	346,50	322,20	50000	73477	80939	16981

* B RUN 5. MODEL VERIFICATION

DOWNSTREAM BOUNDARY DATA
WATER DISCHARGE= 50000.00
ELEVATION= 346.50
TEMPERATURE= 65.00
FLOW DURATION(DAYS) 100.00

ACCUMULATED AC-FT BY ENTRY DAYS	POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
365.00	346.290	41033.73			19378.95			4285.40		
	329.000	10.98			1.20			.10		
	318.600	.55			1487.84			53.43		
TOTAL=	308.750	41045.27	41035.27	-.00	20868.00	20868.00	-.00	4338.93	3033.46	.30

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346.290	6.60	379.43	368.00	48800	73456	75164	16251
342.400	-.52	376.00	352.48	48800	73456	75164	17237
337.100	.00	371.32	354.00	48800	73456	75164	17261
333.200	.00	365.08	345.00	48800	73456	75164	17261
329.000	-.60	361.82	342.40	49000	73476	75168	18200
322.700	-.38	355.66	339.02	49000	73476	75168	18198
318.600	-.07	352.61	331.93	50000	73477	80939	19853
308.750	1.37	346.50	322.37	50000	73477	80939	17616

* AB RUN1, REGULATED FLOW HYDROGRAPH, BEGINNING 1923,1FEB.

TRIB. INFLOW WATER DISCHARGES(CFS)
1 8000 2000

DOWNSTREAM BOUNDARY DATA
WATER DISCHARGE= 150000.00
ELEVATION= 372.00
TEMPERATURE= 65.00
FLOW DURATION(DAYS) 4.00

**** N	DISCHARGE CFS	WATER SURFACE	ENERGY LINE	VELOCITY HEAD	ALPHA	TOP WIDTH	AVG BED	AVG VELOCITY IN SUBSECTION 1	2	3	4	5	6	7
SEC NO. 308.750														
**** 1	150000.0	372.000	372.156	.156	1.000	1318.48	336.12	0.00	3.17	0.00	0.00	0.00	0.00	0.00
SEC NO. 318.600														
**** 1	150000.0	373.864	374.038	.174	1.222	2918.49	343.41	.41	3.37	0.00				
TRIBUTARY INFLOW POINT, NO= 1 Q= 8000.00														
SEC NO. 322.700														
**** 1	142000.0	374.727	374.905	.178	1.332	2400.72	347.53	.87	3.49	0.00				

Table 5 (cont.)

```
SEC NO.   329.000
**** 1  142000.0   376.961   377.189      .228      3.025  15915.20    354.02   .27  4.11   .68

TRIBUTARY INFLOW POINT, NO=    2 Q=   2000.00

SEC NO.   333.200
**** 1  140000.0   378.835   379.308      .472      1.000   1067.80    354.98  0.00  5.51   .17

SEC NO.   337.100
**** 1  140000.0   383.136   383.933      .797      1.600   1079.90    365.03  0.00  7.16  0.00

SEC NO.   342.400
**** 1  140000.0   387.804   388.082      .278      1.047   4302.01    360.62   .45  5.28   .34

SEC NO.   346.290
**** 1  140000.0   391.141   392.009      .868      1.237   2502.78    374.25   .50  7.54  1.10
```

Table 5 (cont.)

ACCUMULATED DAYS	AC-FT BY ENTRY POINT	CLAY INFLOW	CLAY OUTFLOW	CLAY TRAP EFF	SILT INFLOW	SILT OUTFLOW	SILT TRAP EFF	SAND INFLOW	SAND OUTFLOW	SAND TRAP EFF
369.00	346.290	42784.65			20196.02			4540.06		
	329.000	22.17			2.33			.19		
	318.600	.56			1598.39			56.27		
TOTAL=	308.750	42807.39	42807.39	-.00	21796.73	21796.74	0.00	4596.51	3053.86	.34

SECTION ID NO	BED CHANGE FEET	WS ELEV FEET	THALWEG EL FEET	Q CFS	SEDIMENT LOAD IN TONS/DAY CLAY	SILT	SAND
346.290	6.86	391.14	368.66	140000	286013	289180	95982
342.400	-.68	387.80	352.32	140000	286013	289180	148121
337.100	.03	383.14	354.03	140000	286013	289180	139264
333.200	.00	378.84	345.40	130000	286013	289180	139264
329.000	-.43	376.96	342.57	142000	287241	289551	81399
322.700	-.29	374.73	339.71	142000	287641	289551	69177
318.600	-.01	373.86	331.99	150000	287842	328706	17731
308.750	1.39	372.00	322.39	150000	287662	328706	10330

END OF JOB

EXHIBIT 1

REFERENCES

REFERENCES

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2. Gessler, Johanes, "Beginning and Ceasing of Sediment Motion," Proceedings of the Institute of River Mechanics, Colorado State University, Fort Collins, Colorado, 15-26 June 1970.

3. Kindsvater, Carl E., Roland W. Carter and H. J. Tracy, "Computations of Peak Discharge at Contractions," U. S. Geological Survey, Circular No. 284, 1953.

4. Laursen, Emmett M., "The Total Sediment Load of Streams," Journal of the Hydraulics Division, American Society of Civil Engineers, Vol. 84, No. HY1, February 1958, p. 1530-1 to 1530-36.

5. Toffaleti, F. B., "A Procedure for Computation of Total River Sand Discharge and Detailed Distribution, Bed to Surface," Committee on Channel Stabilization, U. S. Army Corps of Engineers, November 1966.

6. U. S. Army Corps of Engineers, "Backwater Curves in Open Channels," EM 1110-2-1409, 7 December 1959.

7. U. S. Army Engineer District, Little Rock, "Navigation Channel and Appurtenances, Normal Pool Elevations and Dam Sites," Project Design Memorandum 5-3, Arkansas River and Tributaries, Arkansas and Oklahoma, Little Rock, Arkansas, May 1960.

8. U. S. Department of Agriculture, Proceedings of the Federal Inter-Agency Sedimentation Conference, Miscellaneous Publication No. 970, 1963.

9. Rouse, Hunter, Engineering Hydraulics, John Wiley & Sons, Inc., 1950, fifth printing October 1965, pp. 828-829.

10. Graf, Walter H., Hydraulics of Sediment Transport, McGraw-Hill Book Company, 1971, p. 95.

EXHIBIT 2

NOTATION IN USERS MANUAL

NOTATION

a	=	Increment of cross section area defined by two successive coordinate points of the cross section and the water surface elevation
A_j	=	Area of flow in a subsection
A_t	=	Total area of cross section
A1	=	Depth at left side of increment of cross section area
B_o	=	Width of movable bed at point P
BSAE	=	Exponent of armor function
BSF	=	Bed Stability factor
B1	=	Depth of right side of increment of cross section area
C_e	=	Coefficient of contraction or expansion
CRT	=	Critical section factor
CSAE	=	Y-intercept of armor function
d	=	Grain size
D	=	Water depth
DD	=	Duration in days
D_{a1}	=	Actual depth of water
D_{avg}	=	Average depth
$DELY_o$	=	Vertical difference between bottom elevation at left and right sides of increment, cross section area
D_{eq}	=	Water depth for equilibrium conditions (grains on streambed are stable)
D_{se}	=	Depth of bed material that will be removed by scour to reach D_{eq}
DZ_L	=	Distance to nodal point, left side
DZ_R	=	Distance to nodal point, right side
d_1	=	Grain size at PC_1 on gradation curve

EFD = Effective depth

EFW = Effective width

g = Acceleration of gravity

G = Sediment load

G_L = Sediment load at nodal point L

G_R = Sediment load at nodal point R

H_L = Total head loss

h_o = Other losses such as contraction and expansion

K' = Average conveyance/square root of length

K_j = Conveyance of subsection j

K_t = Total conveyance of cross section

L_j = Length of j^{th} strip

LTI = Number of subdivisions to time interval to calculate transport capacity

n = Manning's n-value

NGS = Number of grain size fractions present

NSS = Number of subsections

p = Wetted perimeter of increment cross section area

PC = Percent coarser, bed material gradation

PI = Fraction of bed material composed of that grain size

P_j = Wetted perimeter of subsection j

PROB = Probability grains will stay in armor layer

q = Unit discharge

Q = Water Discharge

R = Hydraulic radius

RAE = Ratio of actual to equilibrium depth

RL = Reach length

S = Slope of energy line

SA = Area of bed surface

SAE = Fraction of SA exposed in cases where partial or complete shielding exists

SD = Sieve diameter

S_f = Friction slope

UDF = Unit discharge function developed in equilibrium depth equations

V = Average velocity of flow

V_j = Velocity in subsection j

VOL_A = Volume of bed material in the active layer

V_{SE} = Volume of bed material that will be scoured to achieve D_{eq}

WAVG = Width of an increment, cross section area

WS = Water surface elevation

W_t = Total width of water surface

Ys = Depth of sediment deposit above model bottom

Y_{sp} = Depth of sediment deposit above model bottom at beginning of interval, $\Delta\overline{DD}$

$Y_{sp'}$ = Depth of sediment deposit above model bottom at end of interval, Δt

x = Distance along the channel

ZSQ = Actual section factor

α = Alpha, velocity distribution coefficient

γ = Unit weight of water

γ_s = Unit weight of sediment particles

ρ_s = Density of material in sediment particles

ρ = Density of fluid

τ_a = Actual tractive force

τ_c = Critical tractive force

Ψ = Psi from Einstein's ϕ-Ψ relationship

EXHIBIT 3

THEORETICAL BASIS

Exhibit 3. Theoretical Basis

Contents

FIGURES

Theoretical Basis

1. Introduction

The basis for water surface profile calculations is essentially Method II in reference 6 (all reference numbers refer to exhibit 1). Conveyance is calculated from average areas and average hydraulic radii of adjacent cross sections. Transport capacity is calculated using a method from reference 4 or 5 at the beginning of each time interval. It is the potential transport for each grain size class in the bed as though that size occupied 100 percent of the bed material, multiplied **times** the fraction of each size class present in the bed. These fractions often change significantly during a time interval so an iteration technique is used to account for the effect of this change on the transport capacity. The primary controls on rate of scour are thickness of the active bed and amount of surface area armored. The thickness of active bed is calculated at the beginning of each interval and is the layer of material between the bed surface and a hypothetical depth at which no transport will occur for the given gradation of bed material and flow conditions. The amount of surface area armored is proportional to the amount of active bed removed by scour. The basis for adjusting bed elevations for scour or deposition is the Exner equation. The basis for stability of the armor layer is given in reference 2.

2. Equation for Continuity of Sediment Material

The basis for simulating the movable bed is the solution of the continuity equation for sediment material (the Exner equation):

$$\frac{\partial G}{\partial x} + B_o \frac{\partial y_s}{\partial (DD)} = 0 \qquad (1)$$

where:

- G = sediment load in cubic feet/day
- DD = time in days
- y_s = depth of sediment deposit above model bottom
- x = distance along the channel
- B_o = width of deposit (movable bed)

This equation is expressed in finite difference form for point P using the notation shown in fig. 1

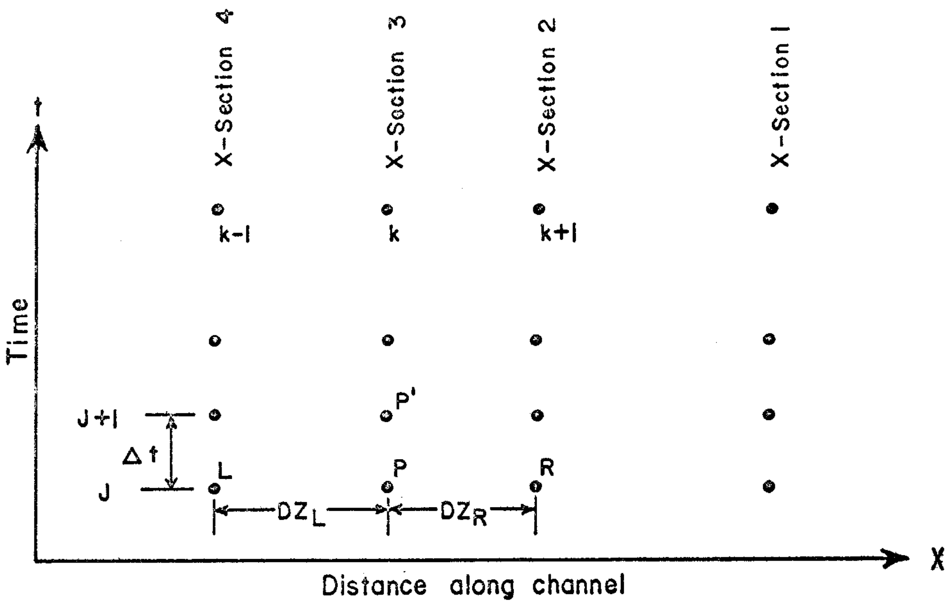


Fig. 1. Computation net

$$\frac{G_L - G_R}{(DZ_L + DZ_R)} + \frac{B_{op}\,(Y_{sp'} - Y_{sp})}{\Delta\overline{DD}} = 0 \qquad (2)$$

$$Y_{sp'} = Y_{sp} - \frac{\Delta\overline{DD}}{B_{op}} \left(\frac{G_L - G_R}{DZ_L + DZ_R}\right) \qquad (3)$$

The variables DZ_L and DZ_R are reach lengths between cross sections and are specified at the beginning of the study. The variable B_o is width of the movable bed at point P and is calculated at the beginning of the study. The initial depth of bed material in the model at point P is specified at the beginning of the study which defines initial conditions for Y_{sp}. The sediment load, G_R, is a boundary condition and is related to the inflowing water discharge at the upstream boundary of the model for each grain size class present. This is moved from section to section through the model.

The sediment load, G_L, is calculated from transport capacity at point P, the sediment inflow, availability of material in the bed and armoring. The difference between G_L and G_R is the amount of material deposited or scoured in the reach between points L and R, and is converted to a change in bed elevation as shown in equation 3.

The value, $\Delta\overline{DD}$, is the time interval in days that a water discharge flows. It is important that each time interval be short enough so that changes in bed elevation due to scour or deposition during that time interval do not significantly influence the transport capacity by the end of the time interval because, as shown in fig. 1, transport capacity is calculated for the bed elevation at the beginning of the time interval $\Delta\overline{DD}$, and it is not recalculated during that interval.

Fractions of a day are typical for large water discharges and several days or even months are satisfactory for low flows. The amount of change in bed elevation that can be tolerated is a matter of judgment. However, good results have been achieved by using either one foot or ten percent of the water depth, whichever is less.

The gradation of the bed material, on the other hand, is recalculated during the time interval because the amount of material transported is very sensitive to the gradation of bed material. The following section presents the methods used in calculations.

3. Hydraulic Parameters

The basic hydraulic parameters needed to calculate sediment transport capacity are velocity, depth, width and slope--all of which come from water surface profile calculations. The one-dimensional energy equation, shown below, is solved using the standard step method, and the above hydraulic parameters are calculated at each cross section.

$$WS_2 + \frac{\alpha_2 Q^2}{2gA_2^2} = WS_1 + \frac{\alpha_1 Q^2}{2gA_1^2} + H_L \qquad (4)$$

$$H_L = h_f + h_o \qquad (5)$$

The energy loss term, H_L, in equation 5 is composed of friction loss, h_f, and form losses, h_o. Only contraction and expansion losses are considered in the form loss term.

a. Friction Loss. Basic geometry is specified by cross sections and reach lengths, and friction loss is calculated by Method II of reference 6. To account for the distribution of flow across the cross section, the valley is divided into strips having similar hydraulic properties in the direction of flow. This subdivides each cross section into portions which are referred to as subsections. Friction loss is calculated as shown below.

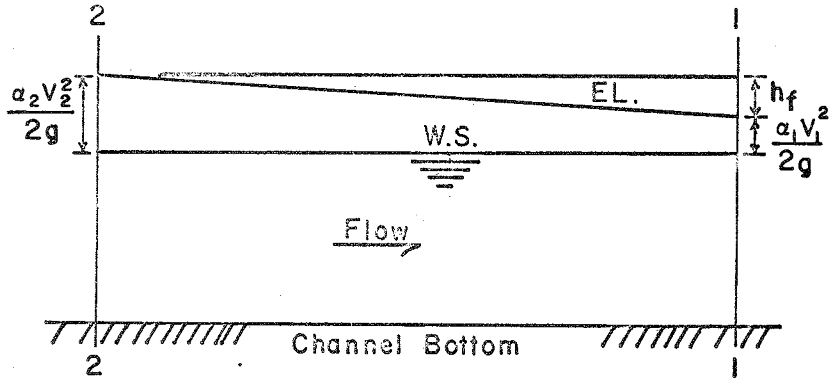


Fig. 2. The friction loss equation

$$h_f = (Q/K')^2 \tag{6}$$

$$K' = \Sigma_{j=1}^{J} \frac{1.486}{n_j} \frac{\frac{(A_2 + A_1)_j}{2} \left(\frac{(R_2 + R_1)}{2}\right)_j^{2/3}}{\sqrt{L_j}} \tag{7}$$

where:

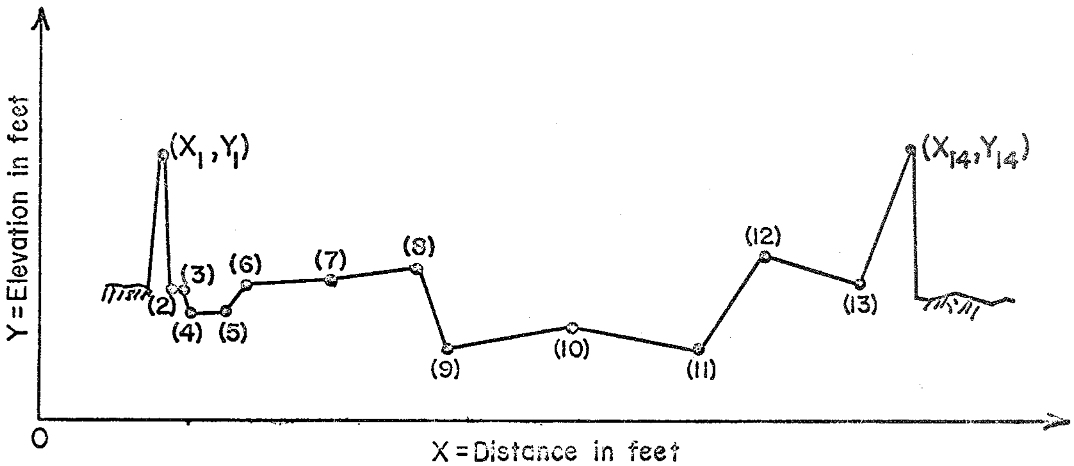
J = total number of strips across the valley

b. <u>Other Losses</u>. For cases where it is desirable to include energy loss due to contractions and expansions, the following equation is provided:

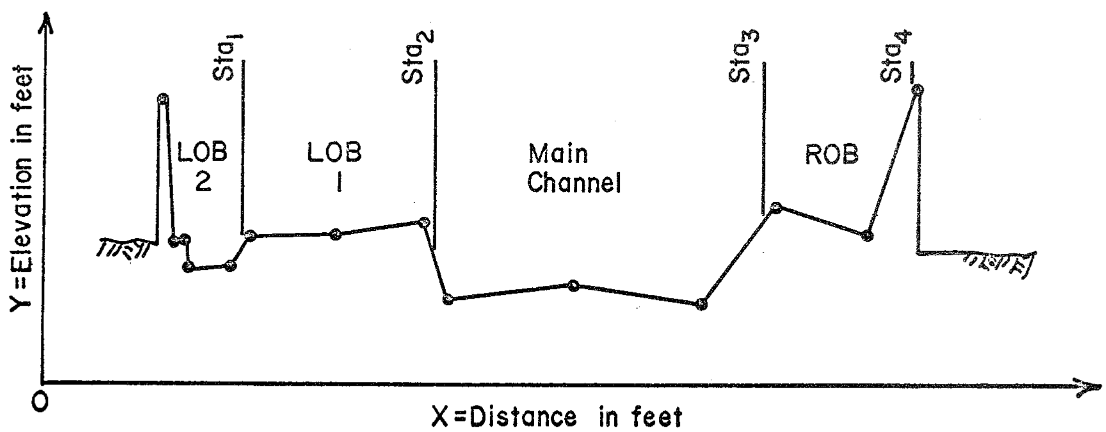
$$h_o = C_e \left(\frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g}\right) \tag{8}$$

If the value in parenthesis is negative, flow is expanding and C_e is the coefficient of expansion. If the value in paranthesis is positive, flow is contracting and C_e is the coefficient of contraction.

c. Computation of Hydraulic Elements. Each cross section is defined by (X,Y) coordinates:



a. Typical cross section



b. Subdivisions of typical cross section

For convenience of assigning n-values, reach lengths, etc., each cross section can be divided into subsections.

This example shows a cross section which has four subsections. The station at the end of each subsection defines it. The notations Left Overbank #2, Left Overbank #1, Main Channel, and Right Overbank are shown to relate the need for subsection stations to requirements the engineer has experienced in hand computations. Hydraulic elements are computed for each subsection.

(1) <u>Subsection Area</u>. The area is computed within each subsection by summing incremental areas between consecutive coordinates of the cross section. Fig. 4 illustrates the technique by using subsection (3) of the previous figure as an example.

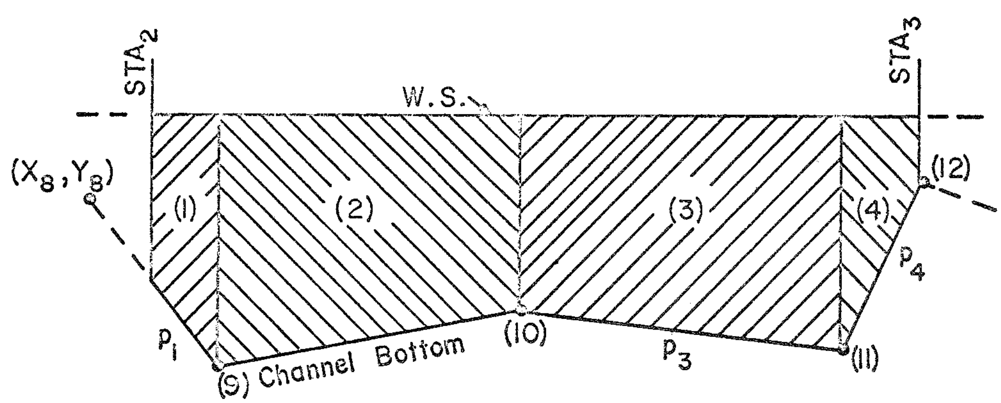


Fig. 4. Incremental areas in subsection

$$A_3 = a_1 + a_2 + a_3 + a_4 \tag{9}$$

The equation for an incremental area is:

$$a = \frac{(A_1 + B_1)\ W_{avg}}{2} \tag{10}$$

Normally, where A_1, B_1 and W_{avg} are defined as shown in fig. 5 an incremental area is defined by two consecutive cross section coordinates. However, at the first and last increments in each subsection, a subsection station defines one side of the incremental area. If the subsection station does not coincide with an X coordinate, as below, straight line interpolation is used to compute the length of either A_1, B_1, or both.

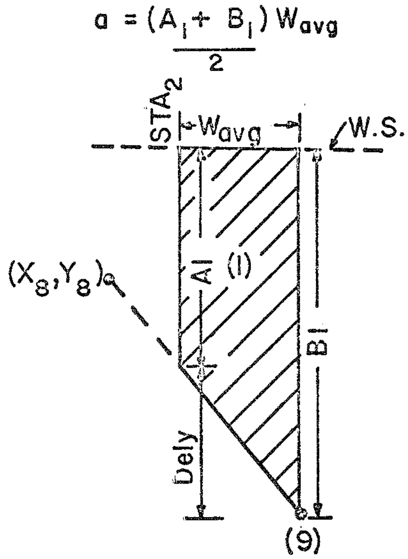


Fig. 5. An incremental area

(2) Wetted Perimeter. The wetted perimeter is computed as the length of cross section below the water surface. In the case of fig. 4 this is:

$$P_3 = p_1 + p_2 + p_3 + p_4 \quad (11)$$

The equation for wetted perimeter of each incremental area is:

$$p = \sqrt{D_{ely}^{\,2} + W_{avg}^{\,2}} \quad (12)$$

where D_{ely} and W_{avg} are defined in fig. 5. Note that only the line between coordinate points and neither A_1 nor B_1 is considered in p. No energy is transferred between adjacent subsections.

(3) Hydraulic Radius. The hydraulic radius is calculated for each subsection:

$$R_j = \frac{A_j}{P_j} \tag{13}$$

d. Conveyance. The conveyance is computed for each subsection by:

$$K_j = \frac{1.49}{n_j} A_j R_j^{2/3} \tag{14}$$

The total conveyance in the cross section is:

$$K_t = \Sigma_{j=1}^{NSS} K_j \tag{15}$$

e. Alpha, the Velocity Distribution Factor. Alpha is a factor to account for the distribution of flow across the flood plain and not the vertical shape of the velocity profile. Large values (>2) of alpha may occur if the depth of flow on the overbanks is shallow, the conveyance small, and the area large. Alpha is computed as follows:

$$\alpha = \frac{(\frac{K_1}{A_1})^2 K_1 + (\frac{K_2}{A_2})^2 K_2 + \ldots + (\frac{K_j}{A_j})^2 K_j + \ldots (\frac{K_{NSS}}{A_{NSS}})^2 K_{NSS}}{\left(\frac{K_t}{A_t}\right)^2 K_t} \tag{16}$$

where A_t is the sum of the subsection areas and K_t is sum of conveyances.

f. Critical Depth. To insure the backwater profiles remain above critical depth, the critical section factor is compared with the computed section factor at each cross section.

$$\text{Critical section factor (CRT)} = \frac{Q}{\sqrt{g/\alpha}} \tag{17}$$

Q = discharge

g = acceleration of gravity

α = velocity distribution factor

$$\text{Computed section factor (ZSQ)} = A_t \sqrt{A_t/W_t} \tag{18}$$

A_t = total area of cross section

W_t = water surface width

if (CRT < ZSQ) subcritical flow exists and computations continue. Otherwise, critical depth is calculated by tracing the specific energy curve to the elevation of minimum total energy and the resulting water surface elevation is compared with the water surface elevation calculated by equation 4 to decide if flow is supercritical. If supercritical flow is indicated, critical depth is adopted, a note is printed and calculations continue.

g. Convergence Equations. Fig. 6 shows the sequence of successive trials to converge the standard step method. Oscillation between positive and negative "error" is permitted. A note is printed in the event a solution is "forced" in which the "error" is greater than the allowable error, as when critical flow or a discontinuity in the conveyance function occurs.

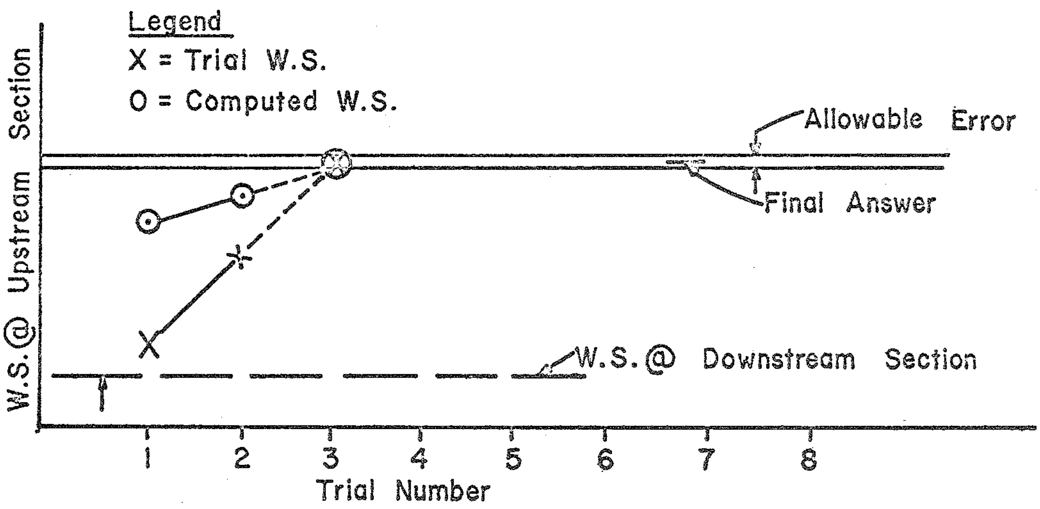


Fig. 6. Convergence of assumed to computed water surface elevations

Three equations are used to converge trial to computed water surface elevations:

Trial 1: H_L is average slope times reach length.

Trial 2: Assume 0.2 of the distance from computed to trial water surface in trial 1. H is computed Water Surface + 0.2* (Computed - Trial) water surface of trial 1.

Trial 3 and subsequently: Results from two previous trials are used to estimate the new trial water surface elevation for intersection.

h. Effective Depth and Width. To account for the influence of non-rectangular cross section shapes on transport capacity, a weighted depth, called the effective depth, (EFD), is calculated.

$$EFD = \left(\sum_{\ell=1}^{L}\left(D_{avg} \cdot a \cdot D_{avg}^{2/3}\right)\right) / \sum\left(a \cdot D_{avg}^{2/3}\right) \tag{19}$$

$$EFW = \left(\sum_{\ell=1}^{L}\left(a \cdot D_{avg}^{2/3}\right)\right) / EFD^{5/3} \tag{20}$$

where L is the total number of trapezoidal elements in the subsection.

The effective width, EFW, is calculated from effective depth to preserve the proper $A \cdot D^{2/3}$ for the cross section. The effective values do not enter into water surface profile calculations.

4. Representative Hydraulic Parameters

Hydraulic parameters are converted into representative values for each reach prior to calculating transport capacity. General equations are shown below. Weighting factors can be modified with input data.

Interior Points

$$VEL = XID*VEL(k-1) + XIN*VEL(K) + XIU*VEL(K+1) \quad (21)$$

$$EFD = XID*EFD(K-1) + XIN*EFD(K) + XIU*EFD(K+1) \quad (22)$$

$$EFW = XID*EFW(K-1) + XIN*EFW(K) + XIU*EFW(K+1) \quad (23)$$

$$SLØ = .5*(SLØ(K) + SLØ(K+1) \quad (24)$$

Upstream Boundary

$$VEL = UBN*VEL(K) + UBI*VEL(K-1) \quad (25)$$

$$EFD = UBN*EFD(K) + UBI*EFD(K-1) \quad (26)$$

$$EFW = UBN*EFW(K) + UBI*EFW(K-1) \quad (27)$$

$$SLØ = SLØ(K) \quad (28)$$

Downstream Boundary

$$VEL = DBN*VEL(K) + DBI*VEL(K+1) \quad (29)$$

$$EFD = DBN*EFD(K) + DBI*EFD(K+1) \quad (30)$$

$$EFW = DBN*EFW(K) + DBI*EFW(K+1) \quad (31)$$

$$SLØ = SLØ(K) \quad (32)$$

Several different weighting factors were investigated during the formulation of the computation scheme. The following table shows the one which appeared to give the most stable calculation and thereby permit the longest $\Delta\overline{DD}$ time periods (scheme 1) and also the one which is the most sensitive to changes in bed elevation but requires shorter time periods $\Delta\overline{DD}$ to be stable (scheme 2).

	Weighting Factors for Representative Hydraulic Parameters							Remarks
	DBI	DBN	XID	XEN	XIU	UBI	UBN	
Scheme 1	0.5	0.5	.25	0.5	0.25	0	1.0	Most Stable
Scheme 2	0.	1.0	1.0	1.0	0.	0.	0.	Most Sensitive

The program defaults to scheme 2.

5. Equilibrium Depth Calculations

The minimum water depth required for a particular grain size to be immobile on the bed surface can be calculated by combining Manning's, Strickler's, and Einstein's equations:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \tag{33}$$

$$n = \frac{d^{1/6}}{29.3} \tag{34}$$

$$\psi = \frac{p_s - p_f}{p_f} \frac{d}{DS} \tag{35}$$

where d is grain diameter

D is flow depth
p_s is density of the sand grains
p_f is density of the water
ψ is from Einstein's bed load function

For the condition of no transport ψ equals 30. Solving equation 35 in terms of S for a specific gravity of sand of 2.65 yields

$$S = \frac{d}{18.18D} \tag{36}$$

Combining this with the Manning and the Strickler equations, in which R has been replaced with D, yields

$$q = \frac{1.486 \text{ X } 29.3}{d^{1/6}} D^{5/3} \left(\frac{d}{18.18D}\right)^{1/2} \tag{37}$$

$$q = 10.21\ D^{7/6}\ d^{1/3} \tag{38}$$

where q is water discharge per unit of width of flow.

The equilibrium depth for a given grain size and unit discharge is

$$D_e = D = \left(\frac{q}{10.21^{1/3}}\right)^{6/7} \quad (39)$$

where D_e is the water depth for the condition of no transport (i.e., the equilibrium depth)

Where the bed material is a mixture of grain sizes, the depth required to accumulate a sufficient amount of coarse material to armor the bed is calculated as follows:

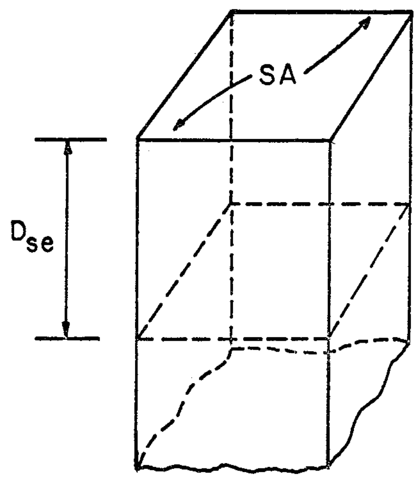


Fig. 7. A column of bed material having surface area **SA**

The number of grains times the surface area shielded by each equals total surface area of a vertical column, illustrated in figure 7.

$$SA = N\left(\frac{\pi d^2}{4}\right) \quad (40)$$

$$N = \frac{SA}{\left(\frac{\pi d^2}{4}\right)} \quad (41)$$

Often the surface area of the column is partially shielded by a rock outcrop or a partially developed armor layer such that the potential scour area is less than the surface area of the column.

$$N = \frac{SA \cdot SAE}{(\frac{\pi d^2}{4})} \qquad (42)$$

where SAE is the ratio of surface area of potential scour to total surface area.

Assuming a heterogeneous mixture, the depth of scour required to produce a volume of a particular grain size sufficient to completely cover the bed to a thickness of one grain diameter is equal to

$$V_{se} = PC \cdot SA \cdot D_{se} = N\ (\frac{\pi}{6}\ d^3) \qquad (43)$$

where PC is percent of bed material coarser than size d.

D_{se} is the depth of bed material which must be removed to scour to equilibrium

V_{se} is the volume of bed material which must be removed to scour to equilibrium

Combining the surface area and volume equations and solving for the required depth of scour to fully develop the armor layer gives:

$$D_{se} = \frac{SA \cdot SAE}{(\frac{\pi d^2}{4})} \cdot \frac{\pi}{6} \frac{d^3}{PC \cdot SA} \qquad (44)$$

$$D_{se} = 2/3 \cdot \frac{SAE \cdot D}{PC} \qquad (45)$$

This equation can be combined with 39 to permit calculating the equilibrium depth in a mixture of grain sizes by approximating the functional relationship between D and PC, the gradation curve, with a sequence of straight line segments as shown in fig. 8.

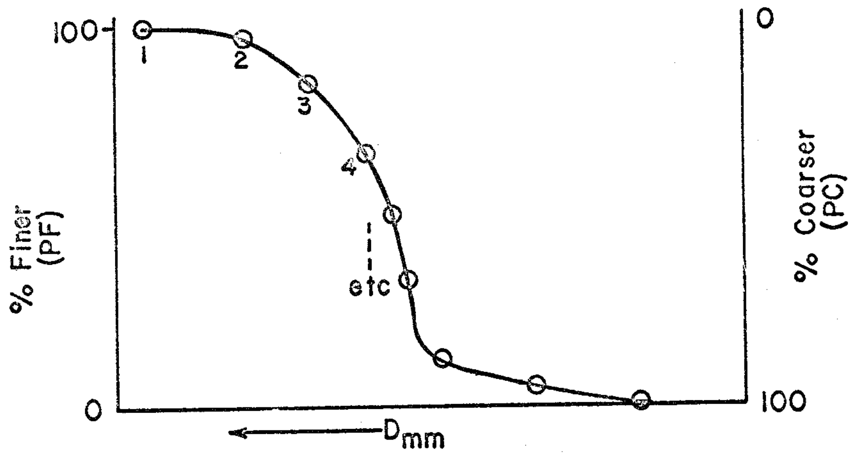


Fig. 8. Gradation of bed material

The first step in locating the proper segment on the gradation curve is to calculate the equilibrium depths, $D1_{eq}$ and $D2_{eq}$ for the grain sizes at points 1 and 2, respectively. If the actual water depth, D_{AL}, is less than $D2_{eq}$, the straight line segment from 1 to 2 defines the required functional relationship and the final equilibrium depth is calculated. If D_{AL} is greater than the equilibrium depth for grain size at point 2, computations move down the gradation curve and try points 2 to 3, 3 to 4, etc., until either the proper segment is located or even the smallest grain size is sufficient to armor the bed in which case scour will not occur.

Relating depth of scour and equilibrium depth requires consideration of two conditions as follows:

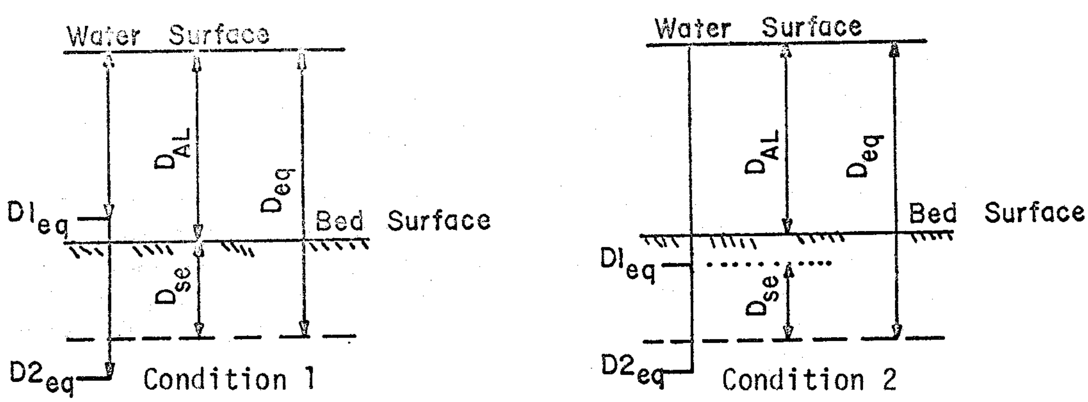


Fig. 9. Equilibrium Depth Conditions

When D_{AL}, the actual depth of flow, is between $D1_{eq}$ and $D2_{eq}$ CONDITION 1 is satisfied and

$$D_{eq} = D_{AL} + D_{se} \tag{46}$$

When D_{AL} is less than $D1_{eq}$ CONDITION 2 is satisfied and

$$D_{eq} = D1_{eq} + D_{se} \tag{47}$$

A general expression is

$$D_{eq} = D_u + D_{se} \tag{48}$$

where D_u is either D_{AL} or $D1_{eq}$.

The technique for determining D_{eq} for a mixture of grain sizes is to calculate $D2_{eq}$ and accumulate the amount of bed surface that would be covered by all stable grains present in the layer. If this bed surface is less than 100%, the next deeper $D2_{eq}$ is defined and accumulations are continued until 100% of the bed surface is shielded.

The program designates the zone of material between the bed surface and equilibrium depth as Active and the zone from equilibrium depth to the model bottom as Inactive. Only the material in the Active zone is subject to scour. When all material is removed from the Active zone, the bed is completely armored for that hydraulic condition. Assuming a heterogeneous mixture, the rate of armoring is proportional to the volume of material removed, and the surface area exposed for scour is:

$$SAE = \frac{VOL_A}{VOL_{SE}} \tag{49}$$

where:

VOL_A = volume remaining in Active zone
VOL_{SE} = total volume in Active zone

Each time a new discharge is analyzed a new equilibrium depth is required. The armor layer formed by previous discharges is tested for stability and it is disturbed when found to be unstable. An initial amount of armor layer is usually present to partially armor the bed as new equilibrium depth calculation is made for each new water discharge.

6. Stability of Armor Layer

The stability of the armor layer is based on a normal probability distribution function in which the ratio of critical to actual tractive force is the independent variable. Equations used for the two tractive forces are:

$$\tau_c = 0.047\ (\gamma_s - \gamma)\ d_m \quad \text{(critical tractive force after Meyer-Peter and Mueller)} \qquad (50)$$

$$\tau_a = \gamma D_{EF} S \quad \text{(actual tractive force)} \qquad (51)$$

D_{EF} = effective depth
d_m = median grain diameter of the grain size classification being tested
S = energy line slope
γ = unit weight of water
γ_s = unit weight of sediment particles
.047 = Y-intercept of empirical data

The probability relationship presented in Chapter 7 of the course notes, River Mechanics Institute, Colorado State University, 1970, by Dr. J. Gessler is shown in fig. 10.

According to the work presented by Gessler, the stability of sediment particles on the bed surface is a probability relationship. (Shields deterministic curve for movement of sediment particles corresponds to a tractive force ratio of 1.0 in figure 10 and actually indicates a probability of movement of 0.5.) As the actual tractive force increases, the tractive force ratio decreases to reflect a much less probability that the grains will remain immobile but does not guarantee movement. Neither do tractive force ratios greater than 1 guarantee that sediment particles will remain immobile on the bed.

This relationship is used to calculate a bed stability coefficient which includes the particle size distribution of the bed material as follows:

$$BSF = \frac{\Sigma_{i=1}^{NGS}\ PROB \cdot PROB \cdot PI_i \cdot d_{mi}}{\Sigma_{i=1}^{NGS}\ PROB \cdot PI_i \cdot d_{mi}} \tag{52}$$

BSF = bed stability factor (coefficient)
PROB = probability the grains will stay
PI = fraction of bed composed of that grain size classification
d_m = median grain diameter for grain size classification being tested
i = summation counter by grain size classification
NGS = number of grain sizes present

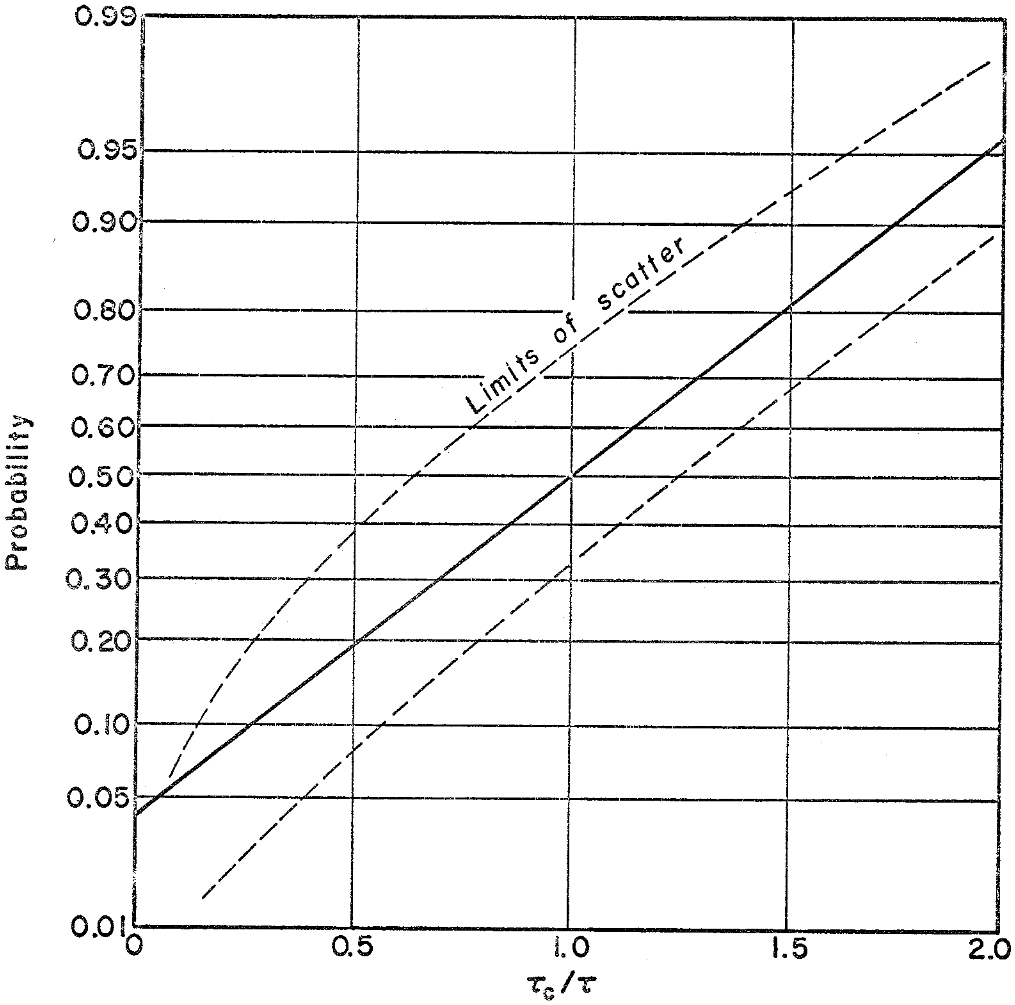


Fig. 10. Probability of grains to stay

Gessler recommended a stability factor greater than or equal to 0.65 be utilized in designing for a stable armor layer. This value is used in this program to begin the destruction of the armor layer.

The probability function could be used to determine the amount of armor layer destroyed. However, a simple linear relationship is now being used. The amount of armor layer destroyed is related to the size of the stability coefficient as

$$SAE_N = 1. - \frac{BSF}{0.65} (1. - SAE_\emptyset) \qquad (53)$$

where subscripts N and Ø represent new and old values of SAE.

7. Transport Capacity

Laursen's transport relationship is presented in reference 4, and reference 5 shows Toffaleti's modification of the Einstein procedure. Figure 11 shows Madden's modification of Laursen's relationship.

8. Movement of Sediment Material

The program satisfies continuity of material, the Exner equation. If transport capacity is greater than sediment discharge, available sediment is removed from the bed to satisfy continuity. Since transport capacity for a given size depends upon the fraction of bed material composed of that size, it is necessary to recalculate fractions present as material is being exchanged with the bed. The number of recalculations is related to flow duration, velocity and reach length at each reach by:

$$LTI = \frac{DURATION \cdot VELOCITY}{REACH\ LENGTH} \qquad (54)$$

This value affects computation time, and often the results are just as satisfactory with LTI = 1. Therefore, the value of LTI can be spacified with input data using variable SPI.

9. Influence of Armoring on Transport Capacity

All grain sizes are analyzed each iteration, and before the next iteration the surface area exposed for scour is calculated. In

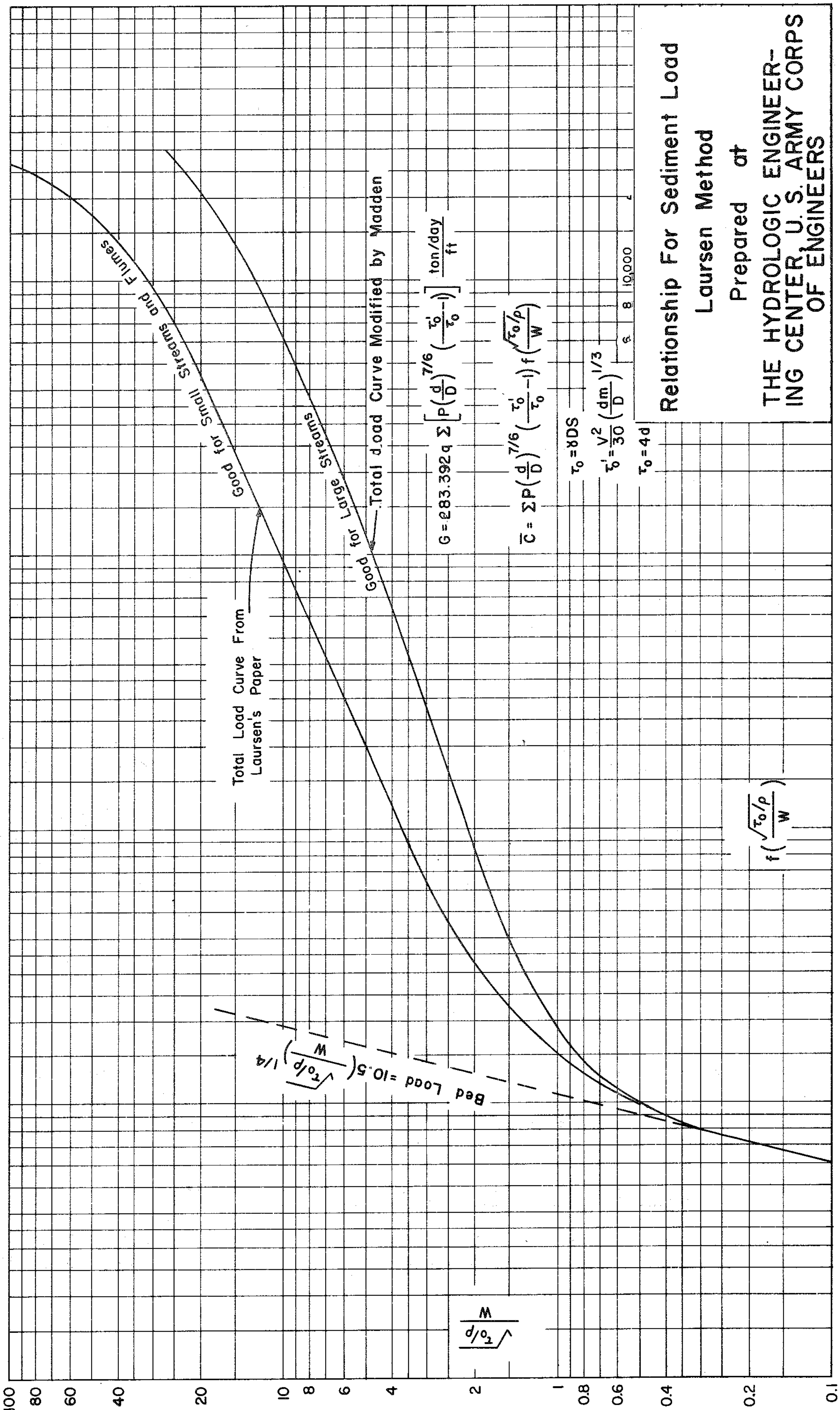


Fig. 11. Relationship for sediment load, Laursen method

Einstein's relationship the hiding factor adjusts transport capacity to account for armoring. In the other transport relationships the transport capacity is corrected for armoring by a parabolic relationship which attempts to account for extra scour due to presence of large individual pieces of material rather than using the straight line relationship, for surface area exposed. The equation is:

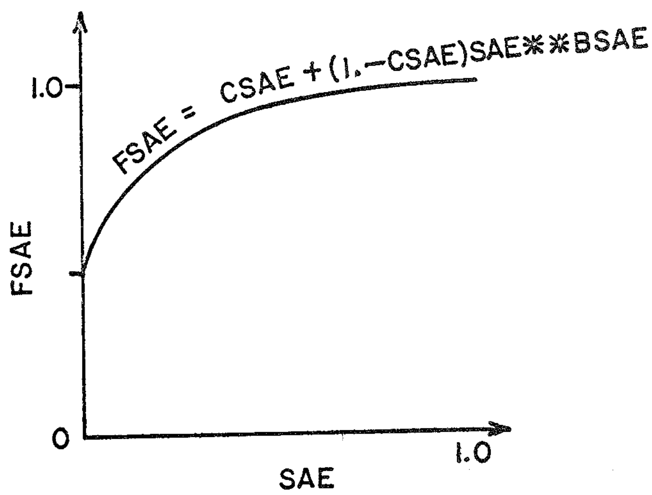


Fig. 12. Reducing Transport Capacity to Account for Armoring

The value of CSAE is the fraction of transport capacity just sufficient to pass the inflowing sediment discharge with no deposition. The program assigns the value of 0.5 for BSAE unless input data specifies otherwise.

EXHIBIT 4

VARIABLE DEFINITIONS

AI	- ACCUMULATED AREA OF WATER SURFACE ACRES
ALER	- MAXIMUM ALLOWABLE ERROR BETWEEN TRIAL AND COMPUTED WATER SURFACE ELEVATION
ALFA	- CORIOLIS COEFFICIENT
ASEL	- AVERAGE SLOPE OF THE ENERGY LINE
ASIO	- ACCUMULATED SEDIMENT INFLOW SUMMED FOR ALL ENTRY POINTS ON THE CONTROL VOLUME BOUNDARY
AUGK	- AVERAGE CONVEYANCE FOR THE REACH
AUGS	- AVERAGE CROSS-SECTION NUMBER FOR IDENTIFICATION OF PRINTOUT
AVGS OR ASN	- AVERAGE SECTION IDENTIFICATION.
BE	- BOTTOM ELEVATION OF DREDGED CHANNEL.
BSAE	- B-COEFFICIENT IN EQUATION FSAE=A*SAE**BSAE.
CAR	- THE PRIMARY COEFFICIENT ARRAY.
CC	- COEFFICIENT OF CONTRACTION
CCCL	- COEFFICIENT IN THE EQUATION FOR RATE OF COMPACTION OF CLAY DEPOSITS
CCSL	- COEFFICIENT IN EQUATION FOR RATE OF COMPACTION OF SILT DEPOSITS
CDTEMP	- DUMMY VARIABLE TO SIMPLIFY DISCHARGE COEFFICIENT COMPUTATIONS
CE	- COEFFICIENT OF EXPANSION
CF	- COEFFICIENT OF FREE FLOW FOR WEIR EQUATION
CHST	- CROSS SECTION STATION AT RIGHT SIDE OF MAIN CHANNEL
CLBK	- CRITICAL DEPTH WATER SURFACE
COEF	- COEFFICIENTS FOR FREE AND SUBMERGED FLOW OVER WEIRS OR ENERGY LOSS AT BRIDGES
COR	- CORRECTION OF TRANSPORT CAPACITY FOR N-VALUE.
COUNT	- COUNTS THE NUMBER OF TRIALS REQUIRED IN THE TRIAL AND ERROR COMPUTATIONS FOR WATER SURFACE PROFILES
CPAR	- EITHER ELEVATION OR DISCHARGE FOR ENTERING THE N- TO VALUE TABLE
CRL	- CONSTANT REACH LENGTH.
CRT	- CRITICAL SECTION FACTOR
CWS	- COMPUTED WATER SURFACE ELEVATION FOR MOST RECENT TRIAL
CWS1	- COMPUTED WATER SURFACE ELEVATION FROM A PREVIOUS TRIAL
CYV	- COEFFICIENT OF DEPTH TO END AREA.
D2	- DIAMETER OF GRAINS JUST LARGER THAN REQUIRED TO ARMOR THE BED (FIGURE B-9).
DAL	- DEPTH OF WATER (EFFECTIVE).
DD	- DURATION OF DISCHARGE IN DAYS
DED1	- DEPTH OF SCOUR TO EQUILIBRIUM IF ALL BED MATERIAL WAS OF GRAIN DIAMETER D1, (FIGURE B-9).
DED2	- DEPTH OF SCOUR TO EQUILIBRIUM IF ALL BED MATERIAL WAS OF GRAIN DIAMETER D2 (FIGURE B-9).
DEQ	- DEPTH OF SCOUR TO EQUILIBRIUM.
DH	- DIFFERENCE IN ELEVATION OF CROSS SECTION CO-ORDINATES WHEN MODIFYING THE PREVIOUS CROSS-SECTION FOR REUSE AT THE CURRENT LOCATION
DHU	- DIFFERENCE IN VELOCITY HEAD BETWEEN THE DOWNSTREAM AND UPSTREAM CROSS SECTIONS OF A REACH
DIF	- A TEMPORARY STORAGE VARIABLE USED WHEN TAKING THE DIFFERENCE BETWEEN TWO VARIABLES
DIFFER	- H(I)-VPRIME, DIFFERENCE BETWEEN CURRENT FALL VELOCITY AND ITERATIVE COMPUTED VELOCITY.
DLY	- THE DEPTH IN FEET OF SEDIMENT DEPOSITS OVER THE ELEVATIONS SHOWN ON THE G-CARDS.
DLYR	- DEPTH OF SEDIMENT DEPOSIT READ IN.
DMAX	- MAXIMUM PIECE SIZE OF SEDIMENT PARTICLES (100 PERCENT FINER ON GRADATION CURVE).
DOD	- DEPTH OF OVER DREDGING.
DS	- DEPTH SLOPE PRODUCT.
DTCL	- DEPOSITION THRESHOLD TRACTIVE FORCE FOR CLAY MATERIAL
DTSL	- DEPOSITION THRESHOLD TRACTIVE FORCE FOR SILT MATERIAL
DWS	- DIFFERENCE BETWEEN CURRENT AND PREVIOUS COMPUTED WATER SURFACE ELEVATIONS
DXPI	- DIAMETER OF GRAINS THAT XPI IS PERCENT FINER.
ECOM	- CURRENT VALUE OF THE TRIAL WATER SURFACE ELEVATION
ECOM1	- TRIAL WATER SURFACE ELEVATION FROM A PREVIOUS TRIAL
EDC	- ELEVATION OF DREDGED CHANNEL.
EFW	- EFFECTIVE WIDTH.
EL	- ELEVATION OF TOTAL ENERGY LINE AT UPSTREAM CROSS SECTION
ELM	- CONSTANT = FOR CONVERTING PERCENT TO TONS PER DAY IN THE

LAURSEN RELATIONSHIP FOR TRANSPORT CAPACITY

ELMOD7	= MODULE THAT CALCULATES TRANSPORT CAPACITY BY LAURSEN RELATIONSHIP
EMB	= ELEVATION OF MODEL BOTTOM.
EMIN	= THE ELEVATION OR DISCHARGE BELOW WHICH NO WATER CAN ENTER A STRIP (OR SUBSECTION OF A CROSS SECTION)
ENST	= THE CROSS SECTION STATION TO END COMPUTATIONS WHEN ALL OF THE CROSS SECTION IS NOT BEING UTILIZED
FAC	= A TEMPORARY STORAGE VARIABLE FOR ACCUMULATING VOLUME BENEATH THE SURFACE PROFILE
FLAG	= A PROGRAM VARIABLE SET EQUAL TO THE SMALLEST, PREVIOUS VALUE OF *DIF* DURING TRIAL AND ERROR COMPUTATIONS
FSFBL	= BED LOAD FUNCTIONAL RELATIONSHIP SHOWN AS STRAIGHT LINE, DASHED, IN LAURSEN RELATIONSHIP
FSVFV	= SHEAR VELOCITY/FALL VELOCITY RATIO
G	= ACCELERATION OF GRAVITY
GAL	= GRAIN SIZE IN ARMOR LAYER THAT IS JUST STABLE AT EQUILIBRIUM DEPTH.
GD	= THE PRIMARY SEDIMENT DATA ARRAY.
GD(1)	= FIRST SAND FRACTION, LOAD DEPOSITED, TONS
GD(2)	= SECOND SAND FRACTION, LOAD DEPOSITED, TONS
GD(3)	= THIRD SAND FRACTION, LOAD DEPOSITED, TONS
GD(4)	= FOURTH SAND FRACTION, LOAD DEPOSITED, TONS
.	
.	
.	
GD(NGS)	= LAST SAND FRACTION LOAD DEPOSITED IN TONS
GD(NGS+1)	= TOTAL SAND LOAD IN LIFT, LOAD DEPOSITED IN TONS
GD(NGS+2)	= REACH LENGTH
GD(NGS+3)	= AVERAGE SECTION NUMBER
GD(NGS+8+1)	= DS FOR FIRST Q
GD(NGS+8+2)	= DS FOR SECOND Q
.	
.	
.	
GD(NGS+8+NQ)	= DS FOR LAST Q
GD(NGS+8+NQ+1)	= N VALUE FOR Q1 IN THIS REACH
GD(NGS 2)	= N VALUE FOR Q2 IN THIS REACH
.	
.	
.	
GD(NGS+8+NQ+NQ)	= N VALUE FOR LAST Q IN THIS REACH
GD(NGS+8+2NQ+1)	= TOP WIDTH FOR Q1 IN THIS REACH
GD(NGS+8+3NQ)	= TOP WIDTH FOR LAST Q IN THIS REACH
GMOD	= SUBROUTINE TO TRANSLATE THE GEOMETRIC MODEL INPUT BY USER INTO ONE THE COMPUTER CAN USE
GP	= POTENTIAL TRANSPORT CAPACITY. IT IS TRANSPORT CAPACITY WHICH HAS NOT BEEN MULTIPLIED BY PERCENT OF MATERIAL IN BED
GS	= SEDIMENT DISCHARGE, TONS/DAY.
GSF	= GRAIN SHAPE FACTOR.
GT	= TOTAL SAND LOAD IN TONS/DAY
I	= GENERAL SUBSCRIPT =COUNTER= FIXED POINT VARIABLE. NO SPECIFIC DEFINITION
HYD	= $HYD, A PROGRAM COMMAND, HYDROLOGIC MODEL FOLLOWS.
IABS	= A LIBRARY SUBROUTINE FOR ESTABLISHING THE ABSOLUTE VALUE OF AN INTEGER NUMBER.
IALP	= A POINTER THAT SELECTS SPECIFIC ENTRY POINTS ON THE CONTROL VOLUME BOUNDARY RELATIVE TO LALP
IB	= TEMPORARY STORAGE VARIABLE
IBLL	= POINTER, ELEMENT NO OF FIRST VALUE OF LAURSEN RELATIONSHIP IN TABLE, LOWER PORTION OF CURVE.
IBLH	= POINTER, ELEMENT NO OF FIRST VALUE OF LAURSEN RELATIONSHIP IN TABLE, UPPER PORTION OF CURVE
IBS	= A POINTER VARIABLE LOCATING THE BASE ELEMENT OF THE SSE(ARRAY) WHEN UTILIZING THE UPPER 8K OF STORAGE IN A GE 225 OR SIMILAR PROGRAMMING PROBLEM.
IBX	= A POINTER VARIABLE LOCATING THE BASE ELEMENT OF THE X(ARRAY) WHEN UTILIZING THE UPPER 8K OF STORAGE IN A GE 225 OR SIMILAR PROGRAMMING PROBLEM.
IBY	= REMOVE A TEMPORARY PROGRAM VARIABLE SPECIFYING THE ENDING INDEX LIMIT OF A DO LOOP.
ICS	= IDENTIFIES THE SMALLEST GRAIN SIZE OF CLAY MATERIAL TO BE

		TRANSPORTED.
ICV	=	COUNTER DO LOOP INDEX THAT COUNTS INCREMENTS FROM 1 TO THE TOTAL NUMBER OF CONTROL VOLUMES (MSOR).
IDF	=	IDENTIFIER, TYPE OF ENERGY LOSS EQUATION TO USE, (MANNING, WEIR EQUATION, BRIDGE EQUATION)
IDM	=	ELEMENT IN X,Y(ARRAY) REPRESENTING LEFT SIDE OF DREDGED CHANNEL (BOTTOM), MUST HAVE 3 CO-ORDINATE POINTS DESCRIBING BOTTOM OF DREDGED CHANNEL.
IDS	=	IDENTIFY SPECIFIC REQUIREMENT OF SUBROUTINE HYDLMT
IE	=	TEMPORARY STORAGE VARIABLE
IEN	=	A PROGRAM VARIABLE WHICH DISTINGUISHES ENST VALUES INPUT FROM THOSE ASSIGNED INTERNALLY BY THE PROGRAM.
IFM	=	ELEMENT IN (X,Y) ARRAY TO STOP CHANGING BOTTOM ELEVATIONS TO SIMULATE SEDIMENT DEPOSITS.
IFS	=	A POINTER VARIABLE LOCATING THE BASE ELEMENT OF EACH SET OF CROSS SECTIONS STORED IN THE X AND Y(ARRAYS). (NOTE * AT BRIDGES THE LOW CHORD AND TOP OF ROAD PROFILES ARE STORED IN THE X AND Y(ARRAYS) AS WELL AS THE TOP OF GROUND X-SECTION).
IGS	=	INITIAL (FIRST, SMALLEST) SAND SIZE CLASS TO INCLUDE IN THE CALCULATIONS
IGS	=	INITIAL GRAIN SIZE - IDENTIFIES THE ELEMENT NUMBER OF THE FIRST GRAIN SIZE FRACTION BEING CONSIDERED IN THE STUDY.
II	=	THE ABSOLUTE LOCATION OF EACH ELEMENT IN THE LSS(ARRAY).
ILCL	=	POINTER, POINTS TO RELATIVE POSITIONS OF THE CLAY SIZE FRACTION IN THE IOTL ARRAY.
ILSA	=	POINTER, POINTS TO THE RELATIVE POSITION OF THE SAND SIZE FRACTION IN THE IOTL ARRAY.
ILSL	=	POINTER, POINTS TO THE RELATIVE POSITION OF THE SILT SIZE FRACTION IN THE IOTL ARRAY.
IN	=	TEMPORARY STORAGE VARIABLE
IN2	=	LOCATOR, THE RELATIVE LOCATION IN THE SEDIMENT RATING TABLE OF THE WATER DISCHARGE JUST ABOVE THE VALUE OF Q.
INS	=	IDENTIFIES THE SMALLEST GRAIN SIZE OF NON-COHESIVE MATERIAL TO BE TRANSPORTED
INT	=	IDENTIFIER, SELECTS INTERPOLATION IS REQUIRED OR NO INTERPOLATION IS REQUIRED IN CALCULATING THE INFLOWING SEDIMENT LOAD FROM THE RATING TABLE.
IP1	=	DREDGING IS PERFORMED IF IP1=1, NO DREDGING IS PERFORMED IF IP1=2.
IPA	=	THE INTERPOLATED POINT ARRAY IS A PROGRAM VARIABLE WHICH KEEPS TRACK OF SUBSECTION STATIONS WHICH DO NOT COINCIDE WITH CO-ORDINATE POINTS SO INTERPOLATED VALUES CAN BE INSERTED BY THE PROGRAMMER FOR MORE EFFICIENT PROCESSING.
IPX	=	THE INTERPOLATED POINT COUNTER ACCUMULATES THE NUMBER OF INTERPOLATED POINTS INSERTED.
IR	=	COUNTER ON DO LOOP FOR NUMBER OF REACHES
IRC	=	COUNTER, REVERSES THE ORDER OF ACCESSING CROSS SECTION DATA FOR TRACING SEDIMENT MOVEMENT DOWN THE MODEL.
IS	=	SOMETIMES USED WHEN A VARIABLE IS NEEDED FOR THE STARTING INDEX OF A DO LOOP.
ISE	=	A PROGRAM VARIABLE WHICH IDENTIFIES A SUBSECTION STATION WHOSE VALUE IS OUTSIDE OF THE STST OR ENST VALUES SPECIFIED IN INPUT DATA.
ISGS	=	IDENTIFIES THE SMALLEST GRAIN SIZE OF SILT MATERIAL THAT WILL BE INCLUDED IN THE CALCULATIONS
ISM	=	ELEMENT IN X,Y(ARRAY) TO START MANIPULATING BOTTOM ELEVATIONS TO SIMULATE SEDIMENT DEPOSITS.
IST	=	A PROGRAM VARIABLE WHICH DISTINGUISHES STST VALUES INPUT FROM THOSE ASSIGNED INTERNALLY BY THE PROGRAM.
ISXY	=	IDENTIFY FOR THE PROGRAM WHEN G-CARDS ARE NOT PRESENT (NO LONGER REQUIRED BUT STILL PERMISSIBLE)
IT	=	A TEMPORARY VARIABLE.
ITER	=	VARIABLE TO COUNT NUMBER OF ITERATIONS IN VELOCITY COMPUTATIONS
ITM	=	THE DIFFERENCE BETWEEN THE NUMBER OF CROSS SECTIONS SPECIFIED BY NR ON THE P-CARD AND THE NUMBER OF AVGS ACTUALLY READ FROM A-CARDS
ITP	=	SAVE THE VALUE OF IPX FOR USE LATER.
ITR	=	A PROGRAM VARIABLE WHICH IDENTIFIES LOCATION IN PROGRAM FOR TRACE PRINTOUT.
ITRB	=	COUNTER, DO LOOP INDEX THAT INCREMENTS FROM 1 TO NTCV (NO.

OF TRIBUTARIES) FOR EACH CONTROL VOLUME

IXS = A PROGRAM VARIABLE WHICH IDENTIFIES WHICH CROSS SECTION IN THE X AND Y(ARRAYS) IS BEING ANALYZED.

IY = THE ABSOLUTE LOCATION OF EACH ELEMENT IN THE Y(ARRAY).

J = TEMPORARY STORAGE VARIABLE

JB = TEMPORARY STORAGE VARIABLE

JBS = THE ELEMENT NUMBER IN THE X(ARRAY) WHOSE VALUE EQUALS A SUBSECTION STATION, ENST OR STST VALUE.

JJ = TEMPORARY STORAGE VARIABLE

JP = A VARIABLE WHICH KEEPS TRACK OF CURRENT LOCATION IN PROGRAM FOR USE IN LOCATING ERROR MESSAGES

K = TEMPORARY STORAGE VARIABLE

K5 = POINTER, ABSOLUTE LOCATION OF THE TOTAL VOLUME OF BED MATERIAL FOR EACH CROSS SECTION CAR(ARRAY).

KDEC = NOT USED, REMOVE FROM PROGRAM

KDU = A DUMMY NAME ASSIGNED FOR SOLE PURPOSE OF PROVIDING A STATEMENT NUMBER

KF = LOCATOR, ABSOLUTE LOCATION OF BASE ELEMENT FOR THE ENTIRE DATA SET FOR EACH CROSS SECTION, CAR(ARRAY).

KFCR = A COUNTER VARIABLE TO DISTINGUISH BETWEEN THE FIRST AND SUBSEQUENT ENTRIES INTO SUBROUTINE ERROR FOR CURRENT CROSS SECTION

KFT = AN IDENTIFIER VARIABLE TO DISTINGUISH BETWEEN THE FIRST AND SUBSEQUENT CROSS SECTIONS IN A COMPUTER RUN

KQCH = A PROGRAM VARIABLE WHICH IDENTIFIES THE PRESENCE OF A *CHANGE IN DISCHARGE* CARD IN THE REACH DATA SET

KSE = THE ELEMENT NUMBER IN THE LLT(ARRAY) EQUAL TO 1 FOR TESTING STST AND 2 FOR TESTING ENST VALUES FOR INTERPOLATION IN THE X AND Y(ARRAYS).

KSKEW = A COUNTER VARIABLE WHICH KEEPS TRACK OF THE NUMBER OF LINES PRINTED FOR USE IN DETERMINING WHEN TO SKIP TO A NEW PAGE

KSL = A VARIABLE TO SIMULATE SENSE LIGHTS IN PROGRAM LOGIC

KSW = A VARIABLE TO SIMULATE SENSE SWITCHES IN PROGRAM LOGIC

KXY = A VARIABLE TO IDENTIFY CROSS SECTIONS CODED (ELEVATION,STATION) ON G-CARDS

L = A TEMPORARY STORAGE VARIABLE

L5 = THE ABSOLUTE LOCATION OF THE ARRAY ELEMENT CONTAINING TOTAL SAND LOAD FOR EACH CROSS SECTION, GD(ARRAY) (NOT THE ABSOLUTE LOCATION IN COMPUTER MEMORY BUT IN THE GD ARRAY).

LALP = LOCATOR, THE BASE ELEMENT IN ARRAY G D WHICH LOCATES VALUES OF ACCUMULATED VOLUMES OF SAND,SILT AND CLAY THAT ARE MOVING PAST EACH ENTRY POINT, AND END BOUNDARIES.

LB = A POINTER VARIABLE LOCATING THE BASE ELEMENT OF EACH CROSS SECTION STORED IN THE X AND Y(ARRAY) AT AN AVERAGE SECTION.

LC = THE NUMBER OF COEFFICIENTS AT EACH CROSS SECTION, RELATING VOLUME TO DEPTH OF SEDIMENT DEPOSITS

LCH = THE STORAGE ELEMENT NUMBER WHERE PROPERTIES OF THE MAIN CHANNEL PORTION OF A CROSS SECTION ARE STORED (IE AREA R43 N-VALUES ECT)

LCS = IDENTIFIES THE LARGEST GRAIN SIZE OF CLAY MATERIAL TO BE TRANSPORTED

LF = THE BASE ELEMENT FOR THE DATA SET OF EACH CROSS SECTION, GD(ARRAY). LOAD FOR THE SMALLEST GRAIN SIZE CLASS IS IN ARRAY ELEMENT (LF+1) ETC.

LFA = A VARIABLE WHICH IDENTIFIES WHETHER CORIOLIS COEFFICIENT IS TO BE CALCULATED OR SET EQUAL TO 1

LGD = IDENTIFY THE ELEMENT NUMBER IN THE SD (ARRAY) WHERE THE LAST (MOST COARSE) GRAIN SIZE DIAMETER TO BE CONSIDERED IS STORED

LGS = LAST (FINAL, LARGEST) GRAIN SIZE CLASS TO CONSIDER.

LHN = NUMBER OF VALUES IN TABLE, LAURSEN RELATIONSHIP, UPPER PORTION OF CURVE

LIMDO = COUNTER/LIMIT, NUMBER OF STRIPS IN THIS REACH (EITHER NSS OR NSSO WHICHEVER IS LARGER).

LL = A TEMPORARY STORAGE VARIABLE

LLN = NUMBER OF VALUES IN TABLE, LAURSEN RELATIONSHIP, LOWER PORTION OF CURVE

LNS = IDENTIFIES THE LARGEST GRAIN SIZE OF NON-COHESIVE MATERIAL TO BE TRANSPORTED

LQ = THE NUMBER OF DISCHARGES IN THE SEDIMENT INFLOW RATING TABLE

LSGS = IDENTIFIES THE LARGEST GRAIN SIZE OF SILT MATERIAL THAT

	WILL BE TRANSPORTED
LSS	= LOCATOR (ARRAY), LOCATES ELEMENT NUMBERS IN X AND Y ARRAYS WHERE A STRIP LINE INTERSECTS A CROSS SECTION.
LTGM	= LOCATOR, TRIBUTARY ENTRY POINT IN GEOMETRIC MODEL
LTI	= CONTROL, THE TOTAL NUMBER OF INTEGRATION INTERVALS TO USE IN CALCULATING SEDIMENT MOVEMENT.
LTSR	= LOCATOR, TRIBUTARY, SEDIMENT RATING TABLE IN CAR ARRAY
MEID	= COUNTER, THE NUMBER OF D-CARDS TO BE READ.
METRIC	= VARIABLE TO INDICATE SYSTEM OF UNITS. METRIC = 1 INDICATES METRIC UNITS. METRIC = 0 INDICATES ENGLISH UNITS.
MNTL	= MAXIMUM NUMBER OF TRIBUTARY BRANCH LEVELS IN THE STREAM SYSTEM
MNQ	= LIMIT, THE MAXIMUM NUMBER OF VALUES ON A Q CARD.
MOD2	= SUBROUTINE MOD2 INPUTS SEDIMENT DATA
MTC	= IDENTIFIER, TRANSPORT CAPACITY FUNCTION TO USE IN THIS JOB.
MTCL	= IDENTIFIES THE METHOD FOR TRANSPORTING THE CLAY LOAD
MTNC	= IDENTIFIES THE METHOD TO BE USED FOR TRANSPORTING THE NON-COHESIVE LOAD
MTSL	= IDENTIFIES THE METHOD TO BE USED FOR TRANSPORTING THE SILT LOAD
N	= THE ELEMENT NUMBER IN THE Q(ARRAY) OF THE DISCHARGE CURRENTLY BEING USED
NAP	= POINTER VARIABLE LOCATING THE BASE ELEMENT OF THE N-VALUE CORRECTION COEFFICIENTS IN THE CAR (ARRAY)
NAQ	= POINTER VARIABLE LOCATING THE BASE ELEMENT OF THE SEDIMENT DISCHARGE RATING TABLE IN THE CAR (ARRAY)
NCH	= COUNTER, THE NUMBER OF E-CARDS TO BE READ.
NCV	= NUMBER OF CONTROL VOLUMES FOR WHICH TRAP EFFICIENCY IS TO BE CALCULATED. A TYPICAL EXAMPLE: WHEN SEVERAL RESERVOIRS ARE IN THE SYSTEM EACH CAN BE CONSIDERED A ''CONTROL VOLUME'', SO ITS TRAP EFFICIENCY WILL BE CALCULATED
NDS	= THE ELEMENT NUMBER OF THE SLOPE OR DEPTH*SLOPE FOR DISCHARGE NO. 1 AT THE FIRST (MOST DOWNSTREAM) CROSS SECTION IS NDS+1.
NEB	= LOCATOR, ABSOLUTE LOCATION OF BASE ELEMENT FOR THE EQUILIBRIUM BED ELEVATION IN GD(ARRAY).
NEC	= THE MAXIMUM NUMBER OF ELEVATION COORDINATES FOR ANY ONE CROSS SECTION WHEN STORING DATA IN THE UPPER 8K MEMORY OF THE 200 SERIES GE COMPUTERS
NED	= THE ELEMENT NUMBER FOR THE EFFECTIVE DEPTH FOR DISCHARGE NO. 1 AT THE FIRST (MOST DOWNSTREAM) CROSS SECTION IS NED+1.
NEQ	= THE MAXIMUM NUMBER OF N-VALUES PLUS ELEVATION OR DISCHARGE VALUES ON EACH E-CARD. PRESENTLY SET EQUAL TO 10 VALUES OR 5 COORDINATE POINTS
NGS	= THE NUMBER OF GRAIN SIZES BEING ANALYZED
NIS	= NUMBER AT IMMOBILE SUPPLY - LOCATES THE BASE ELEMENT IN THE CAR ARRAY FOR DISTRIBUTION OF GRAIN SIZE FRACTIONS BY VOLUME (TONS) PRESENT IN THE PORTION OF THE BED THAT DOES NOT MOVE.
NK	= THE NUMBER OF ELEMENTS IN THE GD (ARRAY) THAT ARE REQUIRED FOR STORING A COMPLETE SET OF DATA FOR ONE CROSS SECTION
NMD	= A SPECIAL PROGRAM VARIABLE THAT MATCHES SUBSECTIONS OF THE DOWNSTREAM CROSS SECTION WITH THE CORRECT STRIP THROUGH THE REACH
NMDR	= THE INPUT VARIABLE NAME FOR NMD
NMU	= PERFORMS FOR THE UPSTREAM CROSS SECTON LIKE NMD DOES FOR THE DOWNSTREAM SECTION
NMUR	= THE INPUT VARIABLE NAME FOR NMD
NNV	= THE ELEMENT NUMBER OF THE N-VALUE FOR DISCHARGE NO. 1 AT THE FIRST (MOST DOWNSTREAM) CROSS SECTION IS NNV+1.
NPAR	= THE STRIP NUMBER FOR WHICH DATA ON AN E-CARD APPLIES
NPTSR	= NUMBER OF COORDINATE POINTS IN A TRIBUTARY, SEDIMENT RATING TABLE
NQ	= THE TOTAL NUMBER OF DISCHARGES READ INTO THE Q (ARRAY)
NR	= THE TOTAL NUMBER OF CROSS SECTIONS IN THE GEOMETRIC MODEL
NR1	= THE NUMBER OF CROSS SECTIONS MINUS 1.
NSE	= THE NUMBER OF ELEMENTS IN THE GD(ARRAY) RESERVED FOR SINGLE PIECES OF DATA AT EACH CROSS SECTION.
NSFR	= NUMBER OF SEDIMENT FRACTION GROUPS (IE CLAY SILT OR SAND)
NSL	= THE ELEMENT NUMBER IN THE LSS (ARRAY) WHICH POINTS TO THE FINAL CROSS SECTION COORDINATE TO BE CONSIDERED IN

		CALCULATING HYDRAULIC ELEMENTS
NSS	-	COUNTER/LIMIT, NUMBER OF SUBSECTION STATIONS AT UPSTREAM CROSS SECTION.
NSSO	-	COUNTER/LIMIT, NUMBER OF SUBSECTION STATIONS AT DOWNSTREAM CROSS SECTION.
NTCV	-	NUMBER OF TRIBUTARY ENTRY POINTS IN EACH CONTROL VOLUME
NTEL	-	NO. OF TRIBUTARY ENTRY POINTS PER LEVEL
NTW	-	LOCATOR, ABSOLUTE LOCATION OF BASE ELEMENT FOR EFFECTIVE WIDTHS IN GD(ARRAY).
NU	-	DYNAMIC VISCOSITY
NVA	-	THE ELEMENT NUMBER FOR THE AVERAGE VELOCITY FOR DISCHARGE NO. 1 AT THE FIRST (MOST DOWNSTREAM) CROSS SECTION IS NVA+1.
NVE	-	THE NUMBER OF ELEMENTS RESERVED IN THE CAR (ARRAY) FOR STORING MISCELLANEOUS DATA FOR LINKAGE BETWEEN VARIOUS SUBROUTINES
NVS	-	NUMBER AT VOLUME SHAPE - LOCATES THE BASE ELEMENT IN THE CAR ARRAY WHERE THE VOLUME VS SHAPE FACTOR IS STORED.
NWS	-	LOCATOR, ABSOLUTE LOCATION OF BASE ELEMENT FOR WATER SURFACE ELEVATIONS IN GD(ARRAY).
NXS	-	A VARIABLE THAT COUNTS THE NUMBER OF CROSS SECTIONS ENTERED FOR COMPARISON WITH NR AND POSSIBLY EXTENDING THE GEOMETRIC MODEL
NXY	-	THE NUMBER OF CROSS SECTION COORDINATES ENTERED FOR THE CURRENT CROSS SECTION
NYU	-	NUMBER AT (Y,V) - LOCATES THE BASE ELEMENT FOR DEPTH OF DEPOSITS VS VOLUME OF DEPOSITS COEFFICIENTS IN THE CAR ARRAY.
NYV	-	THE POINTER VARIABLE LOCATING THE BASE ELEMENT OF THE DEPTH VS VOLUME OF DEPOSIT DATA STORED IN THE CAR (ARRAY)
PED	-	PERCENT FINER VALUE FOR WHICH EFFECTIVE DIAMETER IS NEEDED.
PI	-	THE FRACTION OF BED MATERIAL COMPOSED OF EACH GRAIN SIZE CLASSIFICATION.
Q	-	WATER DISCHARGE, CFS.
QS	-	INFLOWING SEDIMENT LOAD FOR A PARTICULAR WATER DISCHARGE IN THE SEDIMENT LOAD RATING TABLE.
QTEP	-	WATER DISCHARGE AT EACH TRIBUTARY ENTRY POINT
QTD	-	WATER DISCHARGE * CONSTANT THAT CONVERTS UNITS OF LAURSEN RELATIONSHIP TO TONS/DAY
R	-	HYDRAULIC RADIUS OF EACH SUBSECTION AT THE CURRENT CROSS SECTION
RE(I)	-	CURRENT VALUE OF REYNOLDS NUMBER
RHO	-	DENSITY OF WATER
RL	-	REACH LENGTH BETWEEN THE CURRENT AND PREVIOUS CROSS SECTIONS
RO	-	HYDRAULIC RADIUS OF EACH SUBSECTION AT THE PREVIOUS CROSS
RRP	-	RATIO OF GRAIN SIZE TO D50 FOR EACH SIZE CLASSIFICATION IN THE LAURSEN RELATIONSHIP FOR TRANSPORT CAPACITY
RX	-	A RATIO TO MULTIPLY TIMES THE CROSS SECTION STATION VALUES OF THE PREVIOUS SECTION TO OBTAIN A CURRENT CROSS SECTION
SA	-	AREA OF EACH SUBSECTION AT THE CURRENT CROSS SECTION
SAE	-	SURFACE AREA EXPOSED TO SCOUR.
SE	-	SPECIAL ELEVATION VARIABLE.
SE	-	SILL (OR CREST) ELEVATION FOR A WEIR
SGC	-	SLOPE OF GRADATION CURVE BETWEEN ANY TWO DISCRETE POINTS (FIGURE B-9).
SGNP	-	SPECIFIC GRAVITY OF INDIVIDUAL NON-COHESIVE PARTICLES
SGSP	-	SPECIFIC GRAVITY OF INDIVIDUAL SILT PARTICLES
SHIFT	-	SHIFT FOR A RATING CURVE.
SHV	-	SHEAR VELOCITY
SL	-	SPECIAL LENGTH (OR SKEW) VARIABLE.
SL	-	SILL (OR CREST) LENGTH FOR A WEIR
SLUE	-	SUBROUTINE SLUE DETERMINES WHEN TO SKIP TO A NEW PAGE AND PRINTS COLUMN HEADINGS
SPGR	-	SPECIFIC GRAVITY OF SEDIMENT GRAINS.
SPI	-	SPECIFY PERCENTAGE FOR INTEGRATION - SPECIFIES THE PERCENTAGE OF TOTAL ITERATIONS TO BE USED IN CALCULATING THE INFLUENCE OF GRAIN SIZE DISTRIBUTION ON TRANSPORT CAPACITY THROUGH EACH REACH.
SQRT	-	A LIBRARY SUBROUTINE FOR EXTRACTING SQUARE ROOTS
STA	-	CROSS SECTION STATIONS DIVIDING THE SECTION INTO SUBSECTIONS FOR CALCULATING HYDRAULIC ELEMENTS

STCL	= SCOUR THRESHOLD TRACTIVE FORCE FOR CLAY MATERIAL
STHB	= BASE X FOR VALUES IN TABLE, LAURSEN RELATIONSHIP, UPPER PORTION OF CURVE
STLB	= BASE X FOR VALUES IN TABLE, LAURSEN RELATIONSHIP, LOWER PORTION OF CURVE
STLL	= SEDIMENT TRANSPORT FUNCTION ARRAY FOR THE LAURSEN RELATIONSHIP FOR TRANSPORT CAPACITY
STSL	= SCOUR THRESHOLD TRACTIVE FORCE FOR SILT MATERIAL
STST	= THE FIRST CROSS SECTION STATION TO CONSIDER WHEN COMPUTING HYDRAULIC ELEMENTS
SUBK	= THE SUBSECTION CONVEYANCES AT THE CURRENT CROSS SECTION
SUBW	= THE SUBSECTION WIDTH AT THE WATER SURFACE AT THE CURRENT CROSS SECTION
SUMA	= THE TOTAL AREA BENEATH THE WATER SURFACE AT THE CURRENT CROSS SECTION
SUMAO	= THE TOTAL AREA BENEATH THE WATER SURFACE AT THE PREVIOUS CROSS SECTION
SUMK	= THE TOTAL CONVEYANCE AT THE CURRENT CROSS SECTION
SUMW	= THE TOTAL WIDTH AT THE WATER SURFACE AT THE CURRENT CROSS SECTION
SUMWO	= THE TOTAL WIDTH AT THE WATER SURFACE AT THE PREVIOUS CROSS SECTION
TAB	= N=VALUE VS ELEVATION OR DISCHARGE TABLE, (ARRAY),
TAN	= LONGITUDINAL SLOPE OF THE GEOMETRIC MODEL WHEN EXTENDING IT PAST THE LAST CROSS=SECTION ENTERED
TBL	= TOTAL BED LOAD
TDF	= TEMPERATURE, DEGREES FAHRENHEIT,
TEFF	= TRAP EFFICIENCY (INFLOW=OUTFLOW)/INFLOW EXPRESSED AS A FRACTION
TEMP	= COMPUTATION VARIABLE
TEMP2	= A TEMPORARY VARIABLE
TFC	= THE BOUNDARY SHEAR DUE TO SEDIMENT PARTICLES/ CRITICAL TRACTIVE FORCE FOR BEGINNING OF MOVEMENT RATIO, LAURSEN RELATIONSHIP
TFP	= ((D/EFD)**(7/6))*(TFC=1), LAURSEN RELATIONSHIP
TH	= THE TRIAL HEAD LOSS BETWEEN THE PREVIOUS AND CURRENT CROSS SECTIONS FOR THE FIRST APPROXIMATION FOR CALCULATING THE WATER SURFACE ELEVATION
T1H	= INCREMENT LONG X=AXIS FOR VALUES IN TABLE, LAURSEN RELATIONSHIP, UPPER PORTION OF CURVE,
TOG	= A CONSTANT, 64,4
TRD	= A CONSTANT, ,66667
TWO	= A CONSTANT, 2,
TWS	= TEMPORARY STORAGE VARIABLE FOR THE NEWLY CALCULATED TRIAL WATER SURFACE ELEVATION PENDING THE DECISIONS OF WHETHER TO USE OR REJECT THE VALUE
UWCD	= UNIT WEIGHT OF CLAY DEPOSITS AT TIME DEPOSITION OCCURS
UWD	= UNIT WEIGHT OF SAND DEPOSITS EXPRESSED IN POUNDS PER CUBIC FOOT,
UWND	= UNIT WEIGHT OF NON=COHESIVE DEPOSITS AT TIME DEPOSITION OCCURS
UWSD	= UNIT WEIGHT OF SILT DEPOSITS AT THE TIME DEPOSITION OCCURS
V1	= ACCUMULATED VOLUME BENEATH THE WATER SURFACE PROFILE IN ACRE=FEET
VEL	= SUBSECTION VELOCITY OF THE FINAL (CONVERGED) WATER SURFACE ELEVATION AT THE CURRENT CROSS SECTION
VH1	= AVERAGE VELOCITY HEAD AT THE DOWNSTREAM CROSS SECTION, INCLUDING CORRECTION BY CORIOLIS COEFFICIENT
VH2	= AVERAGE VELOCITY HEAD AT THE UPSTREAM CROSS SECTION, INCLUDING CORRECTION BY CORIOLIS COEFFICIENT
VPRIME	= VARIABLE TO COMPUTE INTERMEDIATE VELOCITY IN ITERATION PROCESS
VSF	= VOLUME SHAPE FACTOR,
VTEMP	= DUMMY VARIABLE TO SIMPLIFY VELOCITY COMPUTATIONS
WS	= THE WATER SURFACE ELEVATION, VALUES ARE CONTINUOUSLY UPDATED AS CALCULATIONS MOVE UPSTREAM
WSR	= THE STARTING WATER SURFACE ELEVATION
WT	= WATER TEMPERATURE IN DEGREES FAHRENHEIT
X	= CROSS SECTION COORDINATE (STATIONS), (ARRAY),
XCH	= INPUT VARIABLE NAME FOR NCH
XDF	= INPUT VARIABLE NAME FOR IDF
XEID	= INPUT VARIABLE NAME FOR MEID

XFA	= INPUT VARIABLE NAME FOR LFA
XFD	= CROSS SECTION STATION TO STOP DREDGING,
XFM	= CROSS SECTION STATION TO STOP THE MOVEABLE BED PORTION OF THE MODEL.
XI	= INDEPENDENT VARIABLE FOR INTERPOLATION ALONG LAURSEN RELATIONSHIP TO GET TRANSPORT FUNCTION
XLIM	= NOT USED, REMOVE
XLL	= INPUT VARIABLE NAME FOR NR
XMD	= CROSS SECTION COORDINATE POINT STATION HAVING HIGHEST ELEVATION IN DREDGED CHANNEL PORTION OF THE SECTION,
XNV	= MANNING'S N-VALUE FOR USE IN CURRENT CONVEYANCE CALCULATIONS
XNVR	= INPUT VARIABLE FOR XNV
XPI	= AN ARBITRARY VALUE, PROBABLY ABOUT 95 PERCENT, THAT DESCRIBES THE UPPER BREAK POINT ON A GRADATION CURVE SO A STRAIGHT LINE TO THE 100 PERCENT POINT IS A GOOD REPRESENTATION OF THE CURVE, ALSO, A STRAIGHT LINE TO THE PERCENT FINER POINT FOR THE GRAIN SIZE CLASSIFIED BY LGS SHOULD BE ON, OR CLOSE, TO THE CURVE,
XQCH	= INPUT VARIABLE FOR KQCH
XSD	= CROSS SECTION STATION TO START DREDGING,
XSM	= CROSS SECTION STATION TO START THE MOVEABLE BED PORTION OF THE MODEL.
XSXY	= INPUT VARIABLE FOR ISXY
XXY	= INPUT VARIABLE FOR NXY
Y	= CROSS SECTION COORDINATE (ELEVATIONS), (ARRAY),
YXY	= INPUT VARIABLE FOR KXY

EXHIBIT 5

GEOMETRIC MODEL IN ALTERNATE
FORMAT

EXHIBIT 5

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GEOMETRIC MODEL IN ALTERNATE FORMAT

Basically, the alternate format is designed so that eventually, perhaps, a pseudo two-dimensional approach can be implemented for solving sediment transport problems. This format utilizes hydraulically similar strips in the direction of flow. The final step in implementing a pseudo two-dimensional solution technique would be to transfer water and sediment from one strip to another in such a manner that continuity and momentum flux are preserved. There are no immediate plans to implement such a technique.

In the alternate format, GR cards remain unchanged but data coded on the X1 card is reorganized onto A, B, and C-cards. X3 data is coded on the D-card and NC or NV data is coded on E-cards.

a. Strips and Subsections. Normally the entire width of flood plain can be described by dividing the section into three parts: left overbank, main channel and right overbank. These are considered to be strips in the direction of flow and they divide each cross section into subsections for assigning n-values and reach length. (The area and hydraulic radius is calculated for each subsection.) Three subsection stations (B-card) are needed in this case. One at the end of the left overbank strip to separate that from the main channel; one at the end of the main channel strip to separate it from the right overbank; and one at the end of the right overbank. The program will automatically interpolate if the specified subsection values do not coincide with a coordinate point. Figure 5-1 illustrates coding of the B-card.

Some problems may require more than three strips, and up to seven can be used. Each strip must have an n-value and a reach length. Strip 1 should be coded in field 1 of the B-card, strip 2 in field 2, etc., up to strip 7 in field 7. If a strip stops, leave its field blank on the B-card. This is called a transition reach.

b. The Transition Reach. The transition reach is illustrated in figure 5-1.

There are two possible solutions for increasing or decreasing the number of strips. Using the example in figure 5-1, if from the beginning of the study the transition was recognized, strip 3, MCH, could be coded in field 3 of the B, C, D and E0 cards, strip 1 in field 1 and strip 4 in field 4 and field 2 could be left blank up through section d-d. Section u-u would be coded by putting strip 2, defined by STA_2 in field 2 of the B-card and supplying C, D and E-card data. On the other hand, if the data deck is set up without recognizing this transition, the MCH would need to be shifted from strip 2 at section

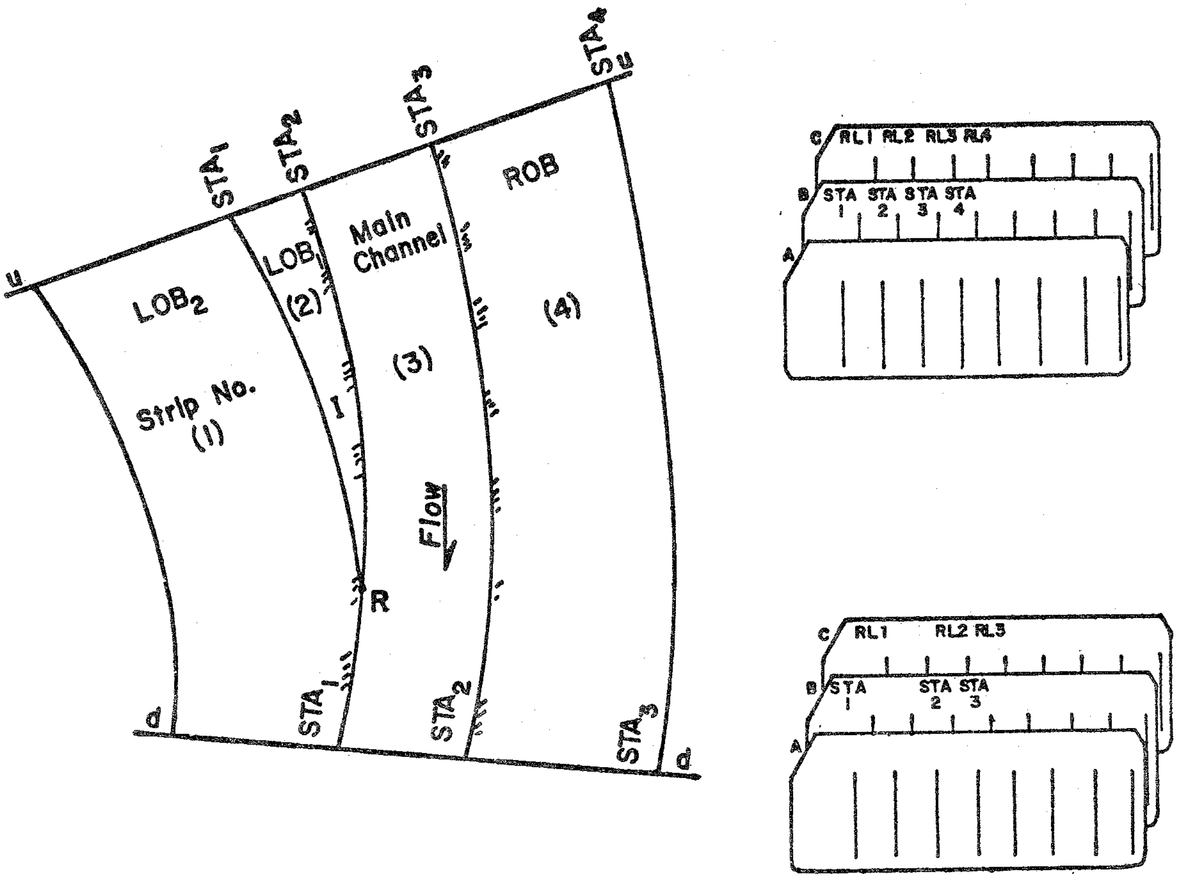


Fig. 5-1. Strips in the transition reach

d-d to strip 3 at section u-u. Code section u-u by entering STA_1, 2, 3, and 4 into fields 1, 2, 3, and 4 of the B-card and renumber strips by using variables NMD and NMU, (C-8) and (C-9), at station u-u. (For example, NMU = 1234, and NMD = 134.) Reach lengths, n-values and ineffective area information for MCH and ROB must be shifted over one field and data for LOB_2 inserted into field 2 beginning at section u-u.

c. Reach Length: The third dimension for forming the geometric model is the distance between cross sections. It is called reach length and is entered on C-cards. Each strip must have a reach length, and it is always entered at the upstream end of the reach. The first cross section (i.e., the downstream end) does not use a reach length, but a C-card must always be provided.

When a strip ends before reaching the next cross section, the distance to that intermediate point becomes the reach length. For example, in figure 5-1 strip 2 ends at point R. (It is necessary in order to assign a high n-value to dense willow growth.) A representative distance for that portion of cross section u-u between STA_1 and STA_2 is estimated to be down to point I. Therefore, that distance is used for the reach length of strip 2 for section u-u.

d. Manning n-Value. The n-value is specified for a strip at the first cross section where that strip is defined. A value is required for each strip, and it should be representative of the reach between cross sections rather than at the section or half-way on either side of the section. It is applied from the section where entered to the downstream end of that reach.

Corrections for water temperature, viscosity, grain size, changes in the bed and changing bed forms are not automatically made to n-values. If bed forms change with discharge, this influence on roughness can be associated with n-value by using a table in which n varies with discharge. Variable n-values may be used in all strips, but in this example only the channel was a problem. The negative value in field 1 identifies that an n-Q table is being used rather than n-elevation.

A table in which n varies with elevation can be used, also, but not at the same cross section as the N-Q table. The n-elevation is identified by the positive n-value in field 1, whereas the N-Q option would have a negative sign on the n-value in field 1.

e. Ineffective Area. When high ground or some other obstruction prevents water from flowing into a subsection, the area up to that point is ineffective for conveying flow and should be suppressed until the water surface exceeds the top elevation of the obstruction. An elevation can be established to identify the point below which overbank area is ineffective. The program automatically tests the first and last points in the movable bed to ascertain if natural levees are forming during the computations. If so, these override ineffective area elevations specified by input data. In fact, natural levees formed by the movable bed are always considered to establish ineffective areas even if that option were not selected by input data. If desired, the ineffective area can be related to a discharge, and all flows less than the specified discharge will recognize the area as ineffective whereas all flows larger than the specified discharge will utilize the entire area. A different value can be specified for each subsection, and the constraint can change from section to section but at a given section either discharge or elevation must be used--not both.

f. Restricted Flow Area. Some studies involve restricting flood plains with levees or transverse embankments and require successive approximations in the analysis to design the proper flow width. To avoid repunching cross section data each time a trial is made, a pair of variables, STST and ENST, are provided on the B-card, and flow will be restricted between these when they are specified. The use of STST and ENST does not change the requirements mentioned previously for subsection stations, strips, reach lengths, ineffective area or n-values for the entire cross section even though some portions are outside the limits set by STST and ENST.

*

INPUT DATA DESCRIPTION
ALTERNATE FORMAT
GEOMETRIC MODEL

The user has a choice of using the input data format for HEC-2, Water Surface Profiles, program number 723-X6-L202A, or this alternate data format for the sediment routing program which allows for future expansion of the capability of this program. If the HEC-2 format is used, only the T1, T2, T3, NC, NV, QT, X1, X3, X5, GR and EJ cards may be present in the deck. In addition, an H-card must be inserted for each cross section. It follows the GR cards.

There is no optional data format for the SEDIMENT and HYDROLOGIC MODELS.

INPUT DATA BY SEDIMENT PROGRAM FORMAT

* CARD — Comment and Title Information Required

Five comment cards are required for the geometric model. They have * in column 1 and the card sequence number in column 2. The following "Print" options are available by entering B or C in column 3 of the *1 card.

Column	Variable	Value	Description
3	ISI(1)		Normal output lists comment card, P card and cross section number.
		B	This shows initial conditions of the model and causes a Data Edit to be made.
		C	Trace printout through subroutine GMOD.

Columns 9 through 80 — Comment (or title) information.

P CARD | Job Parameters | Required

Job parameters; one card required.

Field(1)	Variable	Value(2)	Description
0		P	Card identification in column 1.
1	ALER		Allowable error between assumed and computed Water Surface Elevations. It is used to control the accuracy of the computed water surface elevation.
		+	Any positive value is acceptable.
		0,-	Program assigned +0.05.
2	ASEL		Approximate Slope of Energy Line. It is multiplied times Reach Length to get first trial fall for assumed water surface elevation.
		+	Any positive value is acceptable, but a slope that estimates slightly high is usually best. (A slope that is too flat can cause critical depth to be calculated which increases computation time for the computer run.)
		0	Program uses 0 for first reach and the previously calculated value thereafter.
3	CE		Coefficient of Expansion; used to account for energy loss at expansions.
		0	Usually sufficient; CE is set to zero.
		+	Sometimes 0.3 is used. Possible range is from 0 to 1.0. The value should not exceed 1.0.
		-	Same as below for CC.

(1) Each input card is divided into 10 fields of 8 columns each except field 1 which has 6 or 7 columns. Field 0 refers to column 1.

(2) Values shown as 0 may be left blank, but values shown as blank are not the same as 0.

P CARD (Continued) Job Parameters Required

Field	Variable	Value	Description
4	CC		Coefficient of Contraction; used to account for energy loss at contractions.
		0	Recommended; CC is set to zero.
		+	Sometimes 0.1 is used. Possible range is from 0 to 1.0; value should not exceed 1.0.
		-	Never use a negative value except to fool the computer into ignoring velocity head by using -1.0.
5	LFA		Identifier, Functional Relationship for ALPHA.
		0	Recommended; causes Alpha (Coriolis Coefficient) to be calculated.
		1	Causes Alpha to be set equal to 1.0.
6	NR	+	Number of cross sections in Geometric Model. If NR is larger than the number of cross sections coded on G cards the program will automatically extend the model by reusing the last cross section. See (P-7, 8) also.
		0	The number of cross sections read in will be used.
7	TAN		Slope of Model Bottom. (3)
		+	Desired bottom slope for extending the geometric model.
		-	If the model bottom is on an adverse slope.
8	CRL	+	Constant Reach Length for Extending Model. (3)

(3) Even if this value is specified, it will not be used unless the model requires extension (P-6) and then only to those cross sections inserted by the program in extending the model.

A CARD | Reach Parameter Card | Optional

The A card is used to identify the cross section following on G or GR cards, to select the Manning, bridge equation, weir equation or specified operating rule for use at this section and to tell the program what type of cards will be read in this cross section's data set and how many of each type are present.

Field	Variable	Value	Description
0		A	Card identification in column 1.
1	AVGS		Average section identification number.
		+	Any positive number but miles above mouth is recommended.
		0	No influence on computations.
		ABC+$@	Cannot use alpha or special symbols.
2	IDF		Identifier; Functional relationship for energy loss calculations.
		1	Manning Equation.
		2	Subcritical Flow Thru Contractions Equation (for flow thru bridges).
		4	Identifier, RI card follows with operating criteria for this water surface elevation.
3	NXY		Number of (X,Y) Coordinates describing cross section (i.e., station, elevation points on G Cards).
		4 to 100	Recommend as few as possible and still adequately describe the cross section. Code points on G-Cards, Station first then Elevation.
		-4 to -100	Same as above except code points on GR cards, Elevation first then Station.
		0	Program will reuse previous cross section. This does not involve TAN (P-7) or CRL (P-8).

(4) Cards A through H are repeated for each cross section except:
-Optional cards can be omitted when desired.
-When program extends the geometric model automatically.

A CARD (continued) Reach Parameter Card Optional

Field	Variable	Value	Description
4	MEID		Minimum Elevation Identifier for ineffective area.
		0	No D-Card is present.
		1	Program will read a D-Card and test each computation for ineffective area at this cross section.
5	NCH		Number of n-value cards (E-Cards) present for this cross section.
		0	No E-Cards present.
		1-7	Up to seven cards are permitted.
6	SE		Special Elevation
		0	Program assigns zero.
		+	If head loss at a weir is being calculated (IDF=3), enter crest elevation here. If cross section elevations are being raised or lowered for use in Manning's equation, (IDF=1), enter amount of change.
7	SL		Special Length.
		0,1	Program assigns 1.0.
		+	If head loss at a weir is being calculated, (IDF=3), enter the net crest length here. If cross sections are being corrected for skew for use in Manning's equation, (IDF=1), enter the ratio here.
		-	Never.
10	KQCH	0	No tributary is present.
		1	Tributary enters here; be sure to include a water-sediment rating table and a discharge hydrograph.

RI CARD | Rating Imposed | Optional

Omit this card if IDF (A-2) is not equal to 4.

Field	Variable	Value	Description
1		RI	Card identification.
2	OPR+	+	Operation Rule specified (water surface elevation).
3	HLOS+	+	Head loss criteria, feet when tailwater is higher than OPR.

B CARD — Subsection Station Card — Required

This data is used to subdivide this cross section into subsections for assigning n-values, reach lengths of ineffective areas.

Often only three subdivisions are needed at a cross section, left overbank (LOB), main channel (MCH), and right overbank (ROB). The variable definitions presented below define LOB in field 1, MCH in field 2 and ROB in field 3. Other cases require more subdivisions; so this data set permits up to seven. The procedure is shown by example in fig. 5-1.

Field	Variable	Value	Description
0		B	Card identification in column 1.
1	STA(1)		End of left overbank subsection. Used to tell program where left overbank strip intersects the cross section ends. (In this case it separates LOB and MCH strips.)
		+	Enter the value of the cross section station at the end of LOB subsection. Any positive station is permitted. It does not have to coincide with a coordinate point.
		0	If there is no left overbank at this section.
2	STA(2)		End of channel station. Used to tell program when the channel portion of the cross section ends. (Note: STA(2) does not have to be the main channel - it can be assigned to any strip but it should stay in that strip to the end of the model.)
		+	Enter the cross section station at the end of the main channel. Any positive station is permitted. It does not have to coincide with a coordinate point.
		0	Never.
3	STA(3)		End of right overbank.
		+	Enter the cross section at the end of the ROB subsection. Must be less than or equal to final station on G (or GR) card.
		0	Leave blank if no ROB is present.

B CARD | Subsection Station Card | Required

Field	Variable	Value	Description
4-7	STA(4) thru(7)		Subsection stations for strips 4-7. (Note: The channel does not have to be in strip 2)
		+	Enter the cross section station at the end of each strip.
		0	If strip is not being used.
8	STST		Starting station. The cross section is ignored from the beginning up to STST (for example, if a levee is being aligned only STST need be changed, not the entire set of cross section coordinates.)
		0	The first station coded on G or GR cards will be assigned by the program.
		+	The value does not have to coincide with a coordinate point coded on G or GR cards.
9	ENST	+	Ending station. All of the cross section past this station is ignored (counterpart to STST).
		0	Final cross section station coded on G or GR card will be assigned by program to ENST.
10	CHST		Channel station. The right bank station of the main channel.
		0	Program will assign the channel to strip 1 and use the first reach length on C card to calculate trial head loss, volume of sediment deposited, and slope of energy line; and the first n-value in the E0 or the E1 card to calculate sediment transport capacity.
		+	Should correspond exactly to value for STA for end of channel.

C CARD | Reach Length | Required

Enter a positive value for each strip between this and the previous (downstream) section. In cases where a strip ends before reaching the next section, show the true length of the strip. This is true regardless of which end of the reach the strip exists on.

Field	Variable	Value	Description
0		C	Card identification in column 1.
1	RL(1)	+	Enter the distance in feet to previous (downstream) cross section for the LOB strip.
		0	Only if there is no left overbank at this and the downstream section (STA value in this field on B cards) can this reach length be left blank.
2	RL(2)		Reach length that goes with STA(2), (B-2), the main channel station.
		+	Enter distance to previous (downstream) cross section in main channel.
		0	Never, only the main channel is considered to transport sediment.
3	RL(3)		Reach length that goes with STA(3) (B-3).
		+	Enter the distance to previous (downstream) cross section.
		0	Only when there is no Right Overbank (SAT(3) is blank, at this and the previous downstream cross section.)
4-7	RL(4) through RL(7)		Reach length for strips 4 through 7.
		+	Enter the distance to the previous downstream section or end of strip, whichever comes first.
		0	If these strips are not being used.

C CARD (continued) Reach Length Required

Field	Variable	Value	Description
8	NMD	blank	Normally this variable is left blank and the program assigns it. That is - when the same number of strips are present at the upstream and downstream ends of the reach.
		+	In the transition reach, see fig. 3. The user can specify this variable. Enter with a decimal point for example 1345.
9	NMU		Counterpart to NMD applied to the upstream end of the reach. If either one of these variables is specified, the other must be also.

D CARD | Ineffective Area | Optional (A-4)

Optional for each cross section. Enter a positive value of elevation below which the area of that subsection will be considered ineffective by the computer for conveying flow. The elevation does not have to exist at this subsection.

Discharge rather than elevation, may be used by entering the value as a negative number.

Field	Variable	Value	Description
0		D	Card identification in Column 1.
1	EMIN(1)		Minimum water surface elevation at which water can enter into subsection 1 or minimum discharge which can enter into subsection 1.
		+	Enter the elevation below which cross sectional area is ignored.
		0	Program assigns zero elevation and will use all area above zero.
		-	Enter the discharge below which cross sectional area is ignored.
2-7	EMIN(2) thru EMIN(7)		The minimum elevation may be specified for some or all strips at a cross section. Treat these the same as EMIN(1).

EO CARD n-Values Optional (A-5)

Enter one n-value per strip.

Field	Variable	Value	Description
0		EO	Card identification. The 0 in column 2 is a zero and must be punched to instruct the program that an n-table is not being used.
1	XNV(1)		n-value for strip 1.
		+	Enter a positive value to define n and redefine only as needed at subsequent sections.
		0	When there is no strip 1 defined at this or the previous section (B-1).
		-	Never.
2	XNV(2)... XNV(7)		n-value for strips 2 through 7.

E1-E7 CARDS

A table of n-values may be specified for each strip.

Field	Variable	Value	Description
0		E1	Card identification. The strip number (1-7) must be punched in column 2. Use one card for each strip.
1	TAB(1)	+	Enter the n-value corresponding to highest elevation. (Note. This value is also used for all elevations above table.)
		blank	Never.
		-	When using n-value versus water discharge, enter the first n-value on each card as a negative.
2	TAB(2)	+	Enter elevation or discharge corresponding to n-value in field 1. Code from highest to lowest elevation or discharge.
		blank	If n does not vary in this strip enter n in field 1 and leave remainder of card blank.
		-	Never.
3	TAB(3)		n-value for this strip for next lower elevation or discharge.
4	TAB(4)		Elevation or discharge for the n-value in field 3.

G CARD — Cross Section Coordinates — Optional (A-3)

Field	Variable	Value	Description
0		G	Card identification.
1,3,5,7,9	X	0,+	Cross section station for coordinate points.
2,4,6,8,10	Y	-,0,+	Cross section elevation for coordinate points. Enter values across the card leaving no blank fields. Enter the number of points in (A-3).

GR CARD

Field	Variable	Value	Description
		option GR	Coordinate points may be coded elevation and station on GR cards. Enter the number of points in (A-3) as a negative number.

END OF GEOMETRIC DATA

The end of geometric data is identified by coding -1 in field 2 of an A-card. The remainder of the card is blank.

EXHIBIT 6

INPUT DATA DESCRIPTION

EXHIBIT 6

TABLE OF CONTENTS

INPUT DATA FORMAT

The data format for HEC-2, "Water Surface Profiles," can be used to describe the geometric model by including an H-card after each cross section as shown in the following table. The program translates data from this format at input time. There are some limitations--for example, only T1, T2, T3, NC, NV, QT, X1, X3, GR and EJ cards are permitted. A special form of the X5 card can be used as explained in this exhibit. Any others will cause a FATAL ERROR.

EXHIBIT 6

INPUT DATA DESCRIPTION

GEOMETRIC DATA

T CARD

Three title cards are required. The program expects a T in column 1. The amount of printout of Geometric Data is optional.

Field	Variable	Value	Description
0		T1	Card identification in Columns 1 and 2 is T1, T2 and T3 for the first, second and third title card, respectively.
Column 3	ISI(1)		Normal printout lists data from comment cards and the NC-card. Only the cross section identification number is listed for cards X1 through EJ.
		B	This printout option shows the initial conditions of the model and causes a Data Edit to be made.
		C	Trace printout through subroutine GMOD.

REQUIRED CARD FOR FIRST CROSS SECTION

NC CARD

Manning's "n" and the expansion and contraction coefficients for transition losses are entered for starting each job, or for changing values previously specified.

Field	Variable	Value	Description
0	IA	NC	Card identification characters.
1	XNL	0	No change in Manning's "n" value for the left overbank.
		+	Manning's "n" value for the left overbank.
2	XNR	0	No change in Manning's "n" value for the right overbank.
		+	Manning's "n" value for the right overbank reach length which is half way between the previous and current and future and current cross sections.
3	XNCH	0	No change in Manning's "n" value for the channel.
		+	Manning's "n" value for the channel.
4	CCHV	0	No change in contraction coefficient.
		+	Contraction coefficient used in computing transition losses.
5	CEHV	0	No change in expansion coefficient.
		+	Expansion coefficient used in computing transition losses.

OPTIONAL CARD FOR ROUGHNESS DESCRIPTION*

NV CARD

Used to change the channel roughness coefficient "n" based on water surface elevations or discharge. Program interpolates between points in the table. Either the highest or lowest table value is used when the range falls outside the table. Code from highest to lowest elevation, ELN.

Field	Variable	Value	Description
0	IA	NV	Card Identification characters.
1	NUMNV	+	Total number of Manning's "n" values entered on NV cards (maximum five). If more than one NV card is used, field 1 on the other cards would contain an EL(N) value.
2,4,6... 10	VALN(1)	+	Manning's "n" coefficient for area below ELN(N). The overbank "n" values specified on CARD NC will be used for the overbank roughness regardless of the values in this table.
		-	Manning's "n" value versus water discharge. Code only the first n on the card as negative.
3,5,7... 11	ELN(N)	+	Elevation of the water surface corresponding to VALN(N) in increasing order.

Note: This card is different from the NV-card in HEC-2.

REQUIRED CARD FOR EACH CROSS SECTION

X1 CARD

This card is required for each cross section (150 cross sections can be used for each profile) and is used to specify the cross section geometry and program options applicable to that cross section.

Field	Variable	Value	Description
0	IA	X1	Card identification characters.
1	SECNO	+	Cross section identification number.
2	NUMST	0	Previous cross section is used for current section. Next GR cards are omitted.
		+	Total number of stations on the next GR cards.
3	STCHL	0	May be omitted if NUMST(X1.2) is 0.
		+	The station of the left bank of the channel. Must be equal to one of the STA(N) on next GR cards.
4	STCHR	0	May be omitted if NUMST (X1.2) is 0.
		+	The station of the right bank of the channel. Must be equal to one of the STA(N) on GR cards and equal to or greater than STCHL.
5	XLOBL	+	Length of reach between current cross section and next downstream cross section of the left overbank. Zero for first cross section if IDIR=0 (Subcritical flow).
6	XLOBR	+	Length of reach between current cross section and next downstream cross section for the right overbank. Zero for first cross section if IDIR=0.
7	XLCH	+	Length of reach between current cross section and next downstream cross section for the channel. Zero for first cross section if IDIR=0.

X1 CARD (continued)

Field	Variable	Value	Description
8	PXSECR	0	Cross section stations will not be changed by the factor PXSECR.
		+	Factor by which all cross section stations, except the first station, will be multiplied by to increase or decrease area. The factor can apply to a repeated cross section or a current one. A 1.1 would increase area by 10 percent not considering any change by PXSECE.
9	PXSECE	0	Cross section elevations will not be changed.
		+ -	Constant to be added (+) or subtracted (-) from all cross section elevations (either previous or current).

SPECIFICATION OF INEFFECTIVE FLOW AREAS

X3 CARD Optional

Field	Variable	Value	Description
0	IA	X3	Card identification characters.
1	IEARA	0	Total area of cross section described on GR cards below the water surface elevation is used in the computations.
		10	Only the cross sectional area confined by levees below the water surface elevation is used in the computations, unless the water surface elevation is above the top of levee (elevations corresponding to STCHL(X1.3) and STCHR(X1.4), in which case flow areas outside the levee will be included.

GROUND PROFILE

GR CARD

This card specifies the elevation and station of each point in a cross section used to describe the ground profile, and is required for each X1 card unless NUMST (X1.2) is zero. The points outside of the channel determine the subdivision of the cross section which corrects for the nonuniform velocity distribution.

Field	Variable	Value	Description
0	IA	GR	Card identification characters.
1	EL(1)	+ -	Elevation of cross section point 1 at station STA(1). May be positive or negative.
2	STA(1)	+	Station of cross section point 1.
3	EL(2)	+ -	Elevation of cross section point 2 at STA(2).
4	STA(2)	+	Station of cross section point 2.

Continue with additional GR cards using up to 100 points to describe the cross section. Stations should be in increasing order.

QT CARD

This card identifies the location of a tributary or a diversion. The card identification "QT" in columns 1 and 2 is all that should be punched on the card.

X5 CARD

This card identifies the presence of a weir so the upstream, operating pool elevation can be specified. This is different from HEC-2.

Field	Variable	Value	Description
0	ICG,IDT	X5	Card identification.
2	UPE	+,0,-	Minimum pool elevation upstream from the weir.
3	HLØS	+,0	Head loss at the weir when the tailwater elevation equals or exceeds the minimum pool elevation (X5-2).

H CARD | Limits of Movable Bed | Required

Field	Variable	Value	Description
0		H	Card identification in column 1.
1	ASN		Average section number identifies data on this H card with proper cross section.
		+	Should be exactly the same as AVGS on X1 card.
		0	Not recommended; but it will not affect the computations.
2	EMB		Elevation of model bottom. It is used to calculate the depth of sediment material at this cross section of the model. It is completely arbitrary unless needed to define top of rock elevations that will restrict depth of scour.
		0	Program assigns 10 feet.
		+	Enter the desired elevation. Program will not scour bed below this elevation.
3	XSM		Cross section station at change from fixed to movable bed boundary; counterpart to XFM (H-4).
		+	Enter the station, left side of channel, where the movable bed begins. Elevations at subsequent, cross section coordinates will be adjusted for scour and deposition. This station does not have to coincide with a cross section coordinate point. No interpolated point will be inserted since none is required in computations.
		0	Never.

H CARD (continued) Limits of Movable Bed Required

Field	Variable	Value	Description
4	XFM		Cross section station at change from movable to fixed boundary, counterpart to XSM (H-3).
		+	Enter the station, right side of channel, of the last movable bed point. Elevations at subsequent cross section coordinates will not be adjusted for scour or deposition.
		0	Never.
5	DLYR	0	Normally. No change to cross section bed, initially.
		+	In restarting a run it is necessary to enter DLYR unless the final calculated value is equal to initial conditions.
		-	Never negative. Always measure positively above model bottom.
6	EDC	+	Elevation of bottom of dredged channel. Do not include overdredging here. (See H-10).
		0	Program will not dredge at this cross section.
7	XSD		Cross section station to start dredging; counterpart to XFD.
		+	Enter the station of the cross section coordinate point on the left side, bottom, of dredged channel, so that elevations at subsequent coordinates of this cross section can be corrected for dredging.
		0	Either no dredging is required or XSD = XSM, (H-3).

H CARD (continued) Limits of Movable Bed Required

Field	Variable	Value	Description
8	XFD		Cross section station beyond which no dredging is performed, counterpart to XSD.
		+	Enter the station of the cross section coordinate point at the bottom of dredged channel, so that elevations at subsequent coordinate points of this cross section will not be corrected for dredging.
		0	Either no dredging is required or XFD = XFM, (H-4).
9	XMD		Cross section station of highest elevation within the portion of cross section that will be dredged. It is used to test the elevation of that point against the elevation of dredged channel to determine whether or not dredging is required.
		+	Enter the x-coordinate having the highest elevation within the portion of channel to be dredged.
		0	Program assigns first station within dredged channel portion of section.
10	DOD		Depth of overdredging. Used to establish some extra depth below required bottom elevation.
		+	Enter the amount of overdredging desired at this cross section.
		0	Leave blank if no dredging is required.

Repeat cards X1 through H as required to complete the geometric model.

EJ CARD

End of geometric model data is established by a card with EJ in columns 1 and 2. The remainder of the card should be blank.

SEDIMENT MODEL

T4 CARD | Comment Cards | Required

Five comment cards are required. They have T in column 1 and the card sequence number in column 2. The number 4 is suggested for the first sequence number. The following Print Option is available.

Column	Variable	Value	Description
4	ISI(2)	B	The Data File is printed out for initial conditions of the model.

I1 CARD Job Parameter Card Required

Card I1 is required. It contains sediment parameters for the job.

Field	Variable	Value	Description
0	ICG & IDT	I1	Card identification in columns 1 and 2.
1		Comment	
2	SPI		Specify iterations.
		0	Program calculates the value.
		+	Specify the number of times during each discharge event for the program to recalculate the composition of material in the bed. NOTE: As much as any other input variable SPI affects computation time. When possible specify 1. If a larger value is needed, calculations will display oscillations in the amount of sediment being transported and in the bed profile. The value can be increased to 20, 50, etc., until values are essentially the same as those calculated with SPI left blank.
3	IBG		Program variable, instructs program to calculate gradation in surface layer based upon transport capacity required to just transport the inflowing sediment load with no scour or deposition - if possible. Note: Do not use with 0-cards (armor layer specified).
		0	Program uses gradation on N-Card to calculate transport capacity.
		+3	Program calculates gradation of surface layer based on inflowing load and sediment transport theory. Iterative process performed in three iterations (i.e., "IBG" iterations.

I1 CARD (Continued) — Job Parameter Card — Required

Field	Variable	Value	Description
4	MNQ	+	Maximum number of discharges that will be analyzed in parallel. Any number up to 10 is permissible when tributaries or diversions are not present. Otherwise use 1. (See table 1 for maximum size.)
		0	Program assigns 1.
5	SPGF		Specific gravity of fluid. It is used with density and acceleration of gravity to calculate unit weight.
		+	Enter value for temperature of fluid.
		0	Program assigns 1.0000 (Fresh water at 39.2° F.).
6	ACGR	+	Acceleration of gravity.
		0	Program assigns 32.174 (standard 45° latitude, sea level).

I2 CARD — Job Parameter Card for CLAY

The presence of an I2-Card instructs the program that the mixture of sediment to be analyzed contains clay size particles.

Field	Variable	Value	Description
0	ICG & IDT	I2	Columns 1 and 2 identify card group and data type as job parameter data for CLAY.
1	Comment		Any Alpha or Numeric Comment.
2	MTCL	1	Method for calculating transport capacity for CLAY (only 1 is currently available).
		0	Default = 1.
3,4	ICS, LCS		Identifies smallest and largest grain size fractions of CLAY to be transported. "Only 1 size presently available" and that includes all grain sizes up to .004 mm.
		0	Default = 1. and 1. respectively.
5	SPGC	+	Specific gravity of clay particles.
		0	Default = 2.65.
6	DTCL	+	Deposition threshold for clay. This is the average bed shear stress in lbs/ft^2 above which clay will not be deposited.
		0	Default = 0.02 lb/ft^2
7	STCD	+	Scour threshold for clay deposits. This is the shear stress in lbs/ft^2 above which great hunks of clay material are ripped from the bed.
		0	Default = 0.02. (For lack of better data.)

I2 CARD (continued) Job Parameter Card for CLAY

Field	Variable	Value	Description
8	PUCD	+	Unit weight of fully consolidated clay deposits in the stream bed in lbs/ft^3.
		0	Default = 78 lbs/ft^3.
9	UWCL	+	Unit weight of clay material at the moment it is deposited on the stream bed.
		0	Default = 30 lbs/ft^3.
10	CCCD	+	Compaction coefficient for clay deposits for the equation γ_{clay} = UWCL+CCCD$\cdot\log_{10}$(Time where time is expressed in years.
		0	Default = 16.

I3 CARD — Job Parameter Card for SILT

The presence of an I3-Card instructs the program that the mixture of sediment to be analyzed contains SILT size particles.

Field	Variable	Value	Description
0	ICG & IDT	I3	Columns 1 and 2 identify card group and data type as job parameter data for SILT.
1	Comment		Any alpha or numeric comment.
2	MTSL	1	Method for calculating transport capacity for SILT. (Only 1 is currently available.)
		0	Default = 1.
3,4	IASL, LASL		Identifies smallest and largest grain size fractions of SILT to be transported. (Shown in the following table.) Program automatically includes all sizes between IASL and LASL.
		0	Default IASL = 1, LASL = 4.
		+	(see table below)
5	SGSL	+	Specific gravity of silt particles.
		0	Default = 2.65.
6	DTSL	+	Deposition threshold for silt. This is the average bed shear stress in lbs/ft^2 above which silt material will not be deposited.
		0	Default = 0.02 lb/ft^2 (for lack of better data).

	Classification	Grain Size mm	Geometric Mean mm
1	Very fine silt	.004-.008	.005
2	Fine	.008-.016	.011
3	Medium	.016-.031	.022
4	Coarse	.031-.0625	.044

I3 CARD (continued) Job Parameter Card for SILT

Field	Variable	Value	Description
7	STSL	+	Scour threshold for silt deposits. This is the shear stress in lbs/ft^2 above which great hunks of silt material are ripped from the bed.
		0	Default = 0.02 lb/ft^2 (for lack of better data).
8	PUSD	+	Unit weight of fully consolidated silt deposits in lbs/ft^3.
		0	Default = 82 lb/ft^3.
9	UWSL	+	Unit weight of silt material at the moment it is deposited on the stream bed.
		0	Default = 65 lb/ft^3.
10	CCSD	+	Compaction coefficient for silt deposits for the equation $\gamma_{silt} = UWSL+CCSD \cdot \log_{10}(Time)$ where time is expressed in years.
		0	Default = 5.7.

I4 CARD Job Parameter Card for SAND

The presence of an I4-Card instructs the program that sand sizes present in the mixture of sediment material are to be analyzed.

Field	Variable	Values	Description
0	ICG & IDT	I4	Columns 1 and 2 identify card group and data type.
1		Comment	
2	MTC		Identifier, transport capacity relationship.
		0	Program uses Einstein's Method as programmed by Toffaleti.
		2	User must supply his own transport relationship in the form of DS vs transport coefficients (on cards J and K) (where DS is the depth slope product).
		3	Madden's modification of Laursen's relationship.
3	IGS		Identifier, smallest grain size fraction of sand to be transported in the calculations. (See table below.) IGS must always be less than LGS.
		0	Default = 1.
4	LGS		Identifier, largest grain size fraction to be transported in the calculations.
		0	Default = 10.

The following table of grain sizes is built into the Program. IGS and LGS must be selected from this table. All sizes between IGS and LGS will be transported.

I4 CARD (continued)

Job Parameter Card for SAND

	Classification	Grain Size (mm)	Metric Geo. Mean
1	Very Fine Sand	.062 - .125	.088
2	Fine Sand	.125 - .250	.177
3	Medium Sand	.250 - .500	.354
4	Coarse Sand	.500 - 1.000	.707
5	Very Coarse Sand	1.000 - 2.000	1.414
6	Very Fine Gravel	2.000 - 4.000	2.828
7	Fine Gravel	4.000 - 8.000	5.657
8	Medium Gravel	8.000 - 16.000	11.314
9	Coarse Gravel	16.000 - 32.000	22.627
10	Very Coarse Gravel	32.000 - 64.000	45.255

Field	Variable	Value	Description
5	SPGS	+	Specific gravity of sand particles. (Not the unit weight of deposit material.)
		0	Program assigns 2.65.
6	GSF	+	Grain shape factor.
		0	Program assigns .667.
7	BSAE	+	B coefficient in surface area exposed function. Equation is as: $FSAE = ASAE(SAE)^{BSAE}+CSAE.$
		0	Program assigns 0.5.
8	PSI	+	The letter ψ from Einstein's method is used to approximate ψ^* for calculating equilibrium bed elevation.
		0	Program assigns 30.
9	UWD	+	Unit weight of deposited sediment. Specify in lbs/ft^3.
		0	Program assigns UWD = 93 lbs/ft^3, a reasonable value for sand. Program does not change this value with time.

J CARD Special Transport Function Optional

Coefficients of Special Transport Capacity function expressed in (tons/day/foot of width) by the equation $GP = ((DS-C)/A)^B$ where DS is depth-slope product and A, B and C are coefficients. A separate J-card is required for each grain size fraction being evaluated. Stack cards from fine to coarse.

Field	Variable	Value	Description
0		J	Card identification in column 1.
1		Comment	Comment information such as name of grain size fraction. It can be letters or numbers.
2	CAR(NTC+1)	+	Coefficient corresponding to A in above equation.
3	CAR(NTC+2)	+	Coefficient corresponding to B in above equation.
4	CAR(NTC+3)		Coefficient corresponding to C in above equation.

K CARD Special Transport Function Optional

Coefficients of function correcting above transport capacity function for variation in n-value have the following general form: $ST\emptyset = E/(D^n)$. Only 1 K card is permitted for each job.

Field	Variable	Value	Description
0	ICG	K	Card identification in column 1.
1		Comment	Comment information.
2	CAR(NNV+1)		Coefficient corresponding to D in above equation.
3	CAR(NNV+2)		Coefficient corresponding to E in above equation.

L CARD | Inflowing Sediment Load | Required

The inflowing sediment load is related to water discharge, (table 3). An array of values is required in which row 1, (first L card), is water discharges and the remaining rows are sediment loads in tons/day by grain size fraction, and each field is associated with the water discharge in row 1. Each card describes one grain size fraction and cards should be stacked from fine to coarse.

Field	Variable	Value	Description
0	ICG	L	Card identification in column 1.
1		Q	Comment field.
2	CAR(NBS+1)	+	Water discharge in cfs from water vs. sediment load rating curve. If the range of table is exceeded, the extreme value is used.
3 to 10	CAR(NBS+2) up to CAR(NBS+9)		If more than one water discharge is required then enter values across this card. Up to 9 values are permitted (fields L-2 through L-10). They can be in either ascending or descending order.
0	ICG	L	Card identification goes in column 1. A separate L card is required for each grain size classification present. Stack the cards from fine to coarse.
1		VFS→VCG	Comment field; any number, letter or special character is permitted, but grain size pneumonic is recommended (i.e., VFS, FS ...).
2	CAR(NBS+LQ+1) up to CAR(NBS+LQ+9)		Enter the sediment load in tons/day corresponding to the water discharge on the first L card. Always begin in Field 2.

M CARD Volume Coefficients Optional

Omit M-cards and the program calculates the required coefficients. When using M-cards, enter one for each cross section. Stack M Cards from downstream to upstream direction.

Field	Variable	Value	Description
0		M	Card identification goes in column 1.
1		ASN	Comment information (cross section number should be used here).
2	VSF		Volume Shape Factor. It is used to average upstream and downstream cross section end areas so volume of deposits can be calculated by multiplying resulting average end area times reach length.
		blank	Program assigns 0.5 which is the recommended value for general application.
		+	If cross sections are triangular in shape 0.3 is recommended for VSF.
3	CYV		Width of movable bed. It is used to calculate end area of deposits from depth of deposits. CYV is approximately XFM minus XSM (H-card).
		+	Enter one value for each cross section and use a new M-card for each.

N CARD Bed Material Gradation Required

Bed material composition by grain size fraction is required for each cross section. Up to four size fractions can be entered on one card. If more than four grain sizes are present, use a continuation N card to finish coding size fractions. Stack cards from downstream to upstream direction.

Field	Variable	Values	Description
0		N	Card identification in column 1.
1			Comment field (recommend cross section number always be used here).
2	SAE		Surface Area of bed that is not covered by armor layer at this cross section. Divide the surface area exposed to scour by total surface area.
		blank	Program used 1.0 for initial value.
		0 to +1	Program uses whatever value is entered as the initial value rather than 1.0.
		-1.0	Program redefines SAE to 1.0 for every calculation which is the same as ignoring all armoring.
3	DMAX		MAXIMUM Grain Size at this Cross Section. Obtain from gradation curve-diameter for which 100 percent is finer.
		0	Program assigns SD(LGS) (I1-4).
		+	Enter grain size in feet.
		-	Never.
4	DXPI		Grain size in 80 to 95 percent finer range.
		0	Program assigns SD(LGS) (I1-4)
		+	Enter grain size in feet that is approximately 95 percent size on gradation curve. It should define the upper breakpoint in the gradation curve.
		-	Never.

N CARD (continued) Bed Material Gradation Required

Field	Variable	Value	Description
5	XPI		Percent finer for DXPI (N-4) expressed as a decimal.
		0	Program assigns 1.0.
		+	Range is from 0 to 1.00.
		-	Never.
6	CAR(K5)		Total of grain size fractions in the bed.
		0	Program sums all values that follow for individual grain sizes.
		1.0	Program considers CAR(K5) to equal 100 percent of inactive deposits irregardless of what the sum of individual values equals.
		-	Never.
7	CAR(KF+1)	0 to 1.0	Enter the fraction of the total amount of bed material composing the smallest size classification present in the bed.
		0	If this grain size is not present in bed.
		-	Never.
8	CAR(KF+2)		If more than one grain size is present in the bed, enter fractions across the card, from finest to coarsest, for each size classification. Continue in field 2 of a second N-Card if needed.

O CARD | Bed Material Data Active Layer Optional

Omit "O-Cards" normally. These cards are used in order to continue from the end of a previous computer run. The same number and order of cards are required as for N-Cards and the O-Card group follows the last N-Card in the data deck. (Enter card $PCH O-Cards in hydrologic data deck at time when O-Cards are desired and program will punch automatically.)

Field	Variable	Value	Description
	O		Card identification in column 1.
1		ASN	Comment field (recommend cross section number always be used here).
2	SAE		Surface Area Exposed.
		+	This entry overrides SAE on N-Cards if a positive number is entered.
		blank	Program assigns zero.
3	GAL		Minimum grain size in stable armor layer.
		+	This is the minimum grain size that the program calculated to be stable in the armor layer.
		0	Never - when O-Cards are used.
4	EBE		Equilibrium Bed Elevation.
		+	The elevation that separates the active from inactive storages in the bed material. (Calculated from Water Surface Elevation minus the DEQ in SRMØD5).
5	XPI		Percent finer for DXPI (N-4) express as decimal.
		+	The value here overrides the value on (N-4).
6	CIMBE	+,0,-	Change from initial Model Bed Elevation.

0 CARD (continued) Bed Material Data Active Layer Optional

Field	Variable	Value	Description
7	GD(LF+1)	+	Tons of smallest size fraction in the active layer of the bed in the reach described by this (Ø-1) cross section.
8-10	GS(LF+NGS)	+	Data that follows is tons of each size of material present up to largest size being transported.

HYDROLOGIC MODEL

$HYD Required

Field	Variable	Value	Description
			Program command card. (Begin in column 1.)

*

* CARD | Comment Card | Required

One comment card is required for each Q card in the discharge histograms.

Field	Variable	Value	Description
0	IDC	*	Card identification is required in column 1.
column 5	ISI(3)		Optional output from water surface profile computations can be obtained by specifying the following code in column 5.
		blank (4)	Discharge, starting water surface elevation, water temperature and flow duration in days.
		A	Water surface, energy line elevations, velocity head, alpha, top width, average bed elevation, velocity in each subsection are printed for each discharge at each cross section.
		B	Cross section coordinates at current time and distribution of hydraulic data across the section for the final calculated water surface are printed.
		D	Trace information.
		E	Detailed Trace Information. All of above information plus coordinates, area and wetted perimeter for each trapizoidal area in cross section and for each trial elevation at each cross section.
column 6	ISI (4)		Optional output from sediment movement program.
		blank	No printout except at end of job
		A	A table showing volume of sediment in and out and the resulting trap efficiency.
		B	In addition to A, the bed change from initial elevations in feet, water surface elevation in feet, bed thalweg elevation in feet, sediment load passing in tons/day for CLAY, SILT and SAND.

(4) Leave blank column - not zero.

*

* CARD (continued)			Comment Card	Required
Field	Variable	Value	Description	
		C	A detailed printout of calculations	
		D	Values from Toffaleti's program showing the detailed distribution by grain size fraction from bed surface at each cross section before the values are corrected by percentage present in the bed.	
		E	Detailed trace for debugging purposes.	
column 7	ISI(5)		Optional controls for dredging/no dredging.	
		N	Perform no dredging during this discharge even though the bottom elevation may be greater than bottom of dredge channel elevation.	
2 - 10			Comment data for discharge-elevation-duration data that follows.	

Q CARD — Water Discharge in CFS — Required

Field	Variable	Value	Description
0		Q	Card identification in column 1.
1	Q_1	+	Outflow from downstream boundary of geometric model.
	IF TRIBUTARIES OR DIVERSIONS ARE PRESENT IN THE GEOMETRIC DATA		
2	Q_2	+	Tributary discharge of first tributary from downstream boundary of geometric model. For remaining tributaries, enter the discharge from each across the card in the sequence of the tributaries as you proceed toward the upstream end of the geometric model. Up to 20 tributaries can be entered in this manner. Use field 1 for tributary flow on continuation cards.
		-	Diversion flows are identified by a negative discharge. Otherwise, diversions and tributaries are subject to the same coding rules. They may be mixed or they both may occur at the same point as a function of time. However, both may not occur at the same time at the same cross section.
		0	Treated as +.
	IF TRIBUTARIES AND DIVERSIONS ARE <u>NOT</u> PRESENT IN THE GEOMETRIC DATA		
2-10	Q_2-Q_{10}	+	Up to MNQ (I1-Card) discharges may be entered across the Q-Card.

R CARD — Starting Elevation for WS — Optional

If the water surface does not change from that of the previous discharge, omit this card.

Field	Variable	Value	Description
0	R		Card identification in column 1.
1	WS(1)	+	Enter the value that goes with Q(1). Once this value is entered it will be retained for the Q in field 1 until a new R card is read to change it. Also, R cards override the rating curve entered with $ rating. That is, if an R card is encountered in the data deck it will be used even though a rating curve is present. Computations revert back to the rating curve until another R card is encountered.
2	WS(2)	+	The starting water surface elevation that goes with Q(2) when tributaries are not present. Note: If an R card is present all starting water surface elevations will be changed as indicated on that card. A blank will be considered zero.
3-10	WS(3)...WS(10)	+	Enter 1 starting elevation for each downstream boundary Q and put it in the same card fields as that Q occupies.
		0	Leave fields blank after final Q field.

S CARD | Rating Shift | Optional

If no shift is needed, omit this card.

Field	Variable	Value	Description
0		S	Card identification goes in column 1.
1	SHIFT	+	Enter the shift for starting water surface elevations in field 1. All starting elevations will be shifted by this amount for this and subsequent Q's until a new shift value is read from an S card. To return to zero shift a blank S card must be inserted.

T CARD — Water Temperature — Optional

If water temperature does not change from previous value (T or I cards), omit this card.

Field	Variable	Value	Description
0		T	Card identification goes in column 1.
1	WT(1)	+	Water temperature for Q(1), enter only if a change from the value previously entered on I or T card, use degrees Fahrenheit.
2-10	WT(2)...WT(10)	+	Enter a value in each field for each Q that exists on the Q card.

W CARD Duration Required

Field	Variable	Value	Description
0		W	Card identification goes in column 1.
1	DD(1)	+	Enter the duration in days or fraction thereof that the Q(1) flow will last.
2-10	DD(2)...DD(10)	+	Enter the duration for each Q on Q card.

$$END

LAST card in this run, normal exit.

Exhibit 7, Summary of Input Data Cards, shows the location of command cards in the data deck.

$ARMOR

Causes the CIMBE on O-Cards to be set to zero so the bed is considered armored at its initial elevation.

$DREDGE

Causes dredging to be calculated. (See **$NO** DREDGE below).

$JOB

Permits stacking one job behind another provided the entire geometric model, sediment model and hydrologic model are present in each job.

$NO DREDGE

Causes dredging calculations to cease.

$PCH O-Cards

Causes N and Ø Cards to be punched out.

$RATING

The rating curve option permits the user to enter a rating curve at any point where the * comment card would normally be encountered in the hydrologic model. The proper card sequence is the $RATING card followed by R cards as: See Summary of Input Data Cards, page **7-3**.

R CARD

Rating Curve.

Field	Variable	Value	Description
0		RC	Card identification in columns 1 & 2.
2	MIN	+	The number of water surface values that will be read. (Should be less than 41.)
3	INT	+	The discharge interval between water surface values in cfs. Use as small an interval as desired, but it must be a constant for the full range of water surface elevations that follow.
4	QBASE	+	If the first discharge in the table is not zero enter its value here in cfs.
5	GZRO	+	If the rating table is a stage-discharge curve rather than elevation-discharge, enter gage zero here.
6	RAT(1)		Lowest water surface elevation, or stage, goes here.
7	RAT(2)...all		Enter up to 40 points using all 10 fields on subsequent cards. Put R in column 1 on all cards after first.

$TRIB

Identifies the presence of rating table(s) for water-sediment discharge from tributaries (LT Cards).

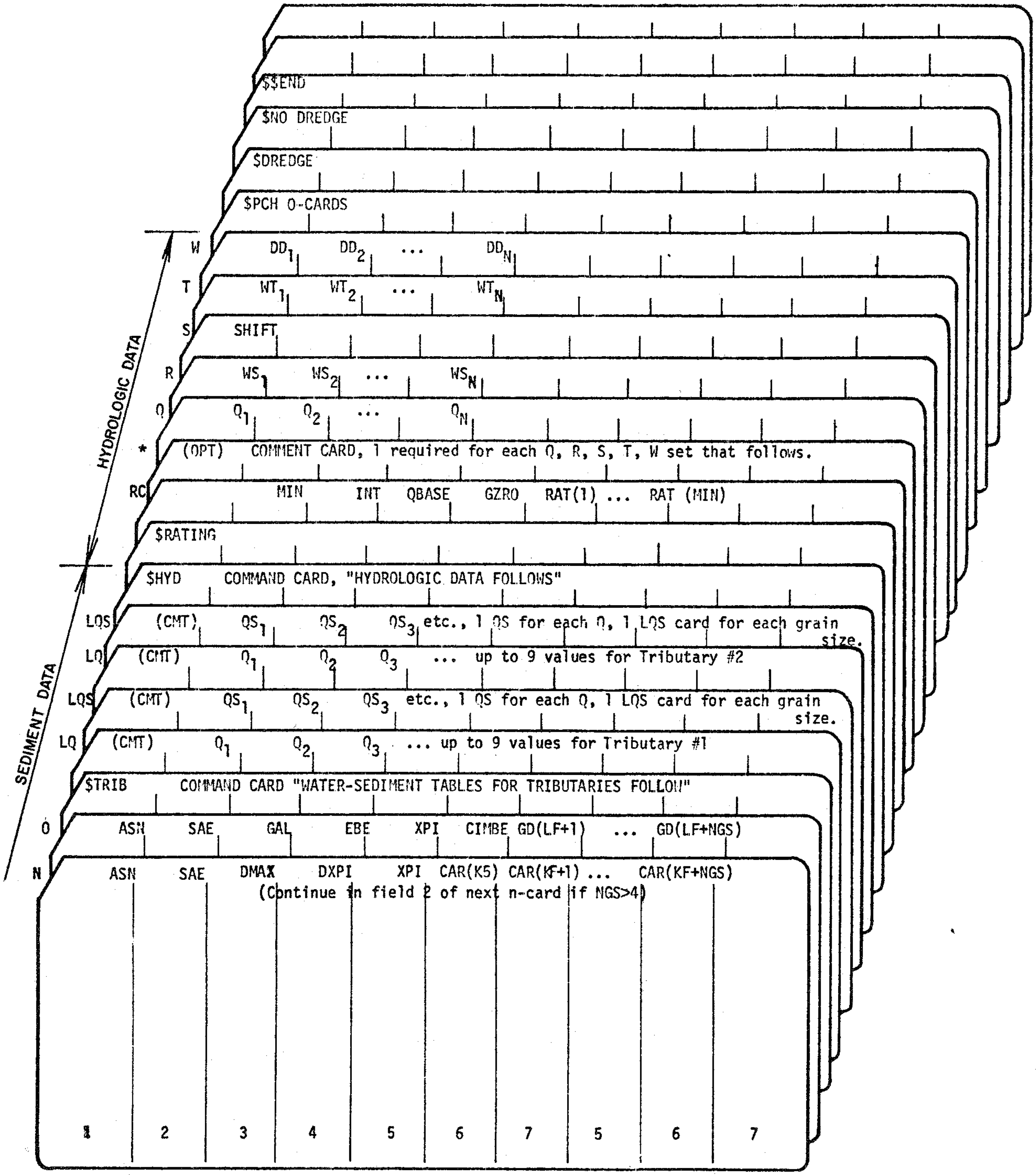
$UPDATE

Causes all sediment deposits above the bottom of dredged channel to be removed and cross section coordinates to be adjusted permanently in storage.

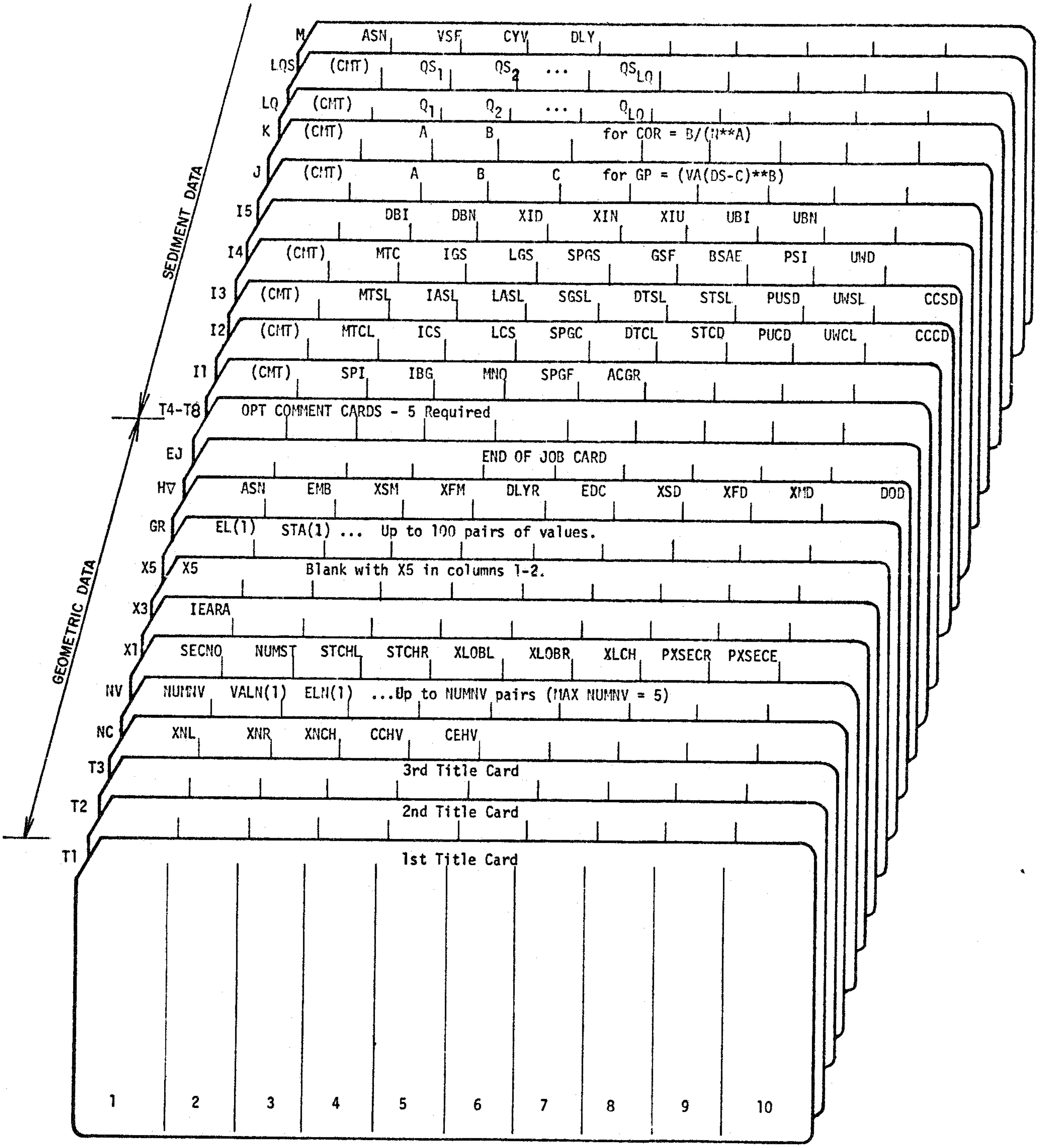
EXHIBIT 7

SUMMARY OF INPUT DATA CARDS

GPO 689-992/5612



$$END
$NO DREDGE
$DREDGE
$PCH O-CARDS
W DD1 DD2 ... DDN
T WT1 WT2 ... WTN
S SHIFT
R WS1 WS2 ... WSN
Q Q1 Q2 ... QN
* (OPT) COMMENT CARD, 1 required for each Q, R, S, T, W set that follows.
RC MIN INT QBASE GZRO RAT(1) ... RAT (MIN)
$RATING
$HYD COMMAND CARD, "HYDROLOGIC DATA FOLLOWS"
LQS (CMT) QS1 QS2 QS3 etc., 1 QS for each Q, 1 LQS card for each grain size.
LQ (CMT) Q1 Q2 Q3 ... up to 9 values for Tributary #2
LQS (CMT) QS1 QS2 QS3 etc., 1 QS for each Q, 1 LQS card for each grain size.
LQ (CMT) Q1 Q2 Q3 ... up to 9 values for Tributary #1
$TRIB COMMAND CARD "WATER-SEDIMENT TABLES FOR TRIBUTARIES FOLLOW"
O ASN SAE GAL EBE XPI CIMBE GD(LF+1) ... GD(LF+NGS)
N ASN SAE DMAX DXPI XPI CAR(K5) CAR(KF+1) ... CAR(KF+NGS)
(Continue in field 2 of next n-card if NGS>4)
1 2 3 4 5 6 7 5 6 7
HYDROLOGIC DATA
SEDIMENT DATA


SEDIMENT DATA
GEOMETRIC DATA
M ASN VSF CYV DLY
LQS (CMT) QS1 QS2 ... QSLQ
LQ (CMT) Q1 Q2 ... QLQ
K (CMT) A B for COR = B/(N**A)
J (CMT) A B C for GP = (VA(DS-C)**B)
I5 DBI DBN XID XIN XIU UBI UBN
I4 (CMT) MTC IGS LGS SPGS GSF BSAE PSI UWD
I3 (CMT) MTSL IASL LASL SGSL DTSL STSL PUSD UWSL CCSD
I2 (CMT) MTCL ICS LCS SPGC DTCL STCD PUCD UWCL CCCD
I1 (CMT) SPI IBG MNQ SPGF ACGR
T4-T8 OPT COMMENT CARDS - 5 Required
EJ END OF JOB CARD
H∇ ASN EMB XSM XFM DLYR EDC XSD XFD XMD DOD
GR EL(1) STA(1) ... Up to 100 pairs of values.
X5 X5 Blank with X5 in columns 1-2.
X3 IEARA
X1 SECNO NUMST STCHL STCHR XLOBL XLOBR XLCH PXSECR PXSECE
NV NUMNV VALN(1) ELN(1) ...Up to NUMNV pairs (MAX NUMNV = 5)
NC XNL XNR XNCH CCHV CEHV
T3 3rd Title Card
T2 2nd Title Card
T1 1st Title Card
1 2 3 4 5 6 7 8 9 10

Hydrologic Engineering Methods for Water Resources Development