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HEC-6 SCOUR AND DEPOSITIONS

IN RIVERS AND RESERVOIRS

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(190)

HEC-6, Scour and Deposition in Rivers and Reservoirs

For the Maricopa County Flood Control District

David T. Williams, President
WEST Consultants Inc., Carlsbad, CA

DAY 1

8:00 - 8:15 am	Introduction and Administration
8:15 - 9:15 am	Sediment Transport in Natural Rivers
9:15 - 9:30 am	Break
9:30 - 10:00 am	Properties of Non-Cohesive Sediment
	Shape factors, specific gravity, settling velocities, initiation of motion, types of loads, cohesive sediments.
10:00 - 11:30 am	Introduction to HEC-6 and Basic Data Requirements
	History, basic principles, capabilities and limitations, computational sequence, distinction between run data and calibration data, data sources.
11:30 - 12:30 pm	Lunch
12:30 - 1:15 pm	Interpretation of HEC-6 Output and Results
	Explanation of input and output information, control of output, interpretation of results, accuracy assessment, procedures of running HEC-6 in fixed and mobile bed conditions.
1:15 - 3:00 pm	Workshop 1, HEC-6 in Fixed Bed Mode
	Development of hydrologic data, geometric model development, hydraulic calibration.
3:00 - 3:15 pm	Break
3:15 - 3:30 pm	Workshop 1 Review

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DAY 1, cont.

3:30 - 5:00 pm	Review of Sediment Transport Functions
	Computations of sediment transport rates by several procedures, multiple transport functions, terminology, function limitations.

DAY 2

8:00 - 9:15 am	Selection of Sediment Transport Relations
9:15 - 9:30 am	Break
9:30 - 11:30 am	Development of Bed Material and Inflowing Sediment Load
	Development of the sediment boundary for HEC-6, definition of terms, sources of data and costs, sampling procedures, where to collect samples, sensitivity of results to data variability, strategy for developing a sampling program.
11:30 - 12:30 pm	Lunch
12:30 - 2:45 pm	Workshop 2, Development of Sediment Data for HEC-6
	Development of inflowing sediment load, bed gradation, program execution in moveable bed mode.
2:45 - 3:00 pm	Break
3:00 - 3:15 pm	Workshop 2 Review
3:15 - 5:00 pm	Calibration/Validation Techniques and Interpretation of Results

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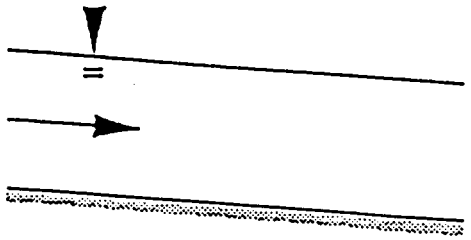
DAY 3

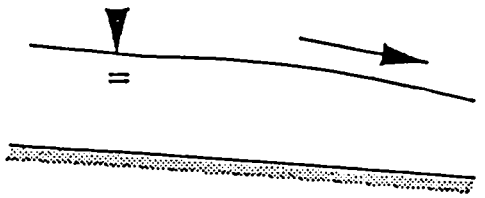
8:00 - 9:00 am	Hydrology Generation Using WATSTORE and Histogram Generator
	Use of utility program, "Sediment Weighted Histogram Generator" to develop long term HEC-6 hydrology input
9:00 - 9:15 am	Break
9:15 - 11:30 am	Workshop 3, Verification of HEC-6
	Experimentation with hydraulic and sediment parameters to assess effects on model performance, adjustments to reproduce field observations, sensitivity analysis.
11:30 - 12:30 pm	Lunch
12:30 - 1:00 pm	Workshop 3 Review
1:00 - 2:45 pm	Workshop 4, Use of Features of HEC6; Stream Network Application
2:45 - 3:00 pm	Break
3:00 - 3:15 pm	Workshop 4 Review
3:15 - 4:15 pm	Estimation of Sediment Yield
4:15 - 4:45 pm	Case Study:
	EPNG Pipeline Crossing of the Gila River near Coolidge, Arizona
4:45 - 5:00 pm	Open Discussion, Closure

WATER SURFACE PROFILE CALCULATION

1. Classifications of Open Channel Flow

a. Steady vs. Unsteady





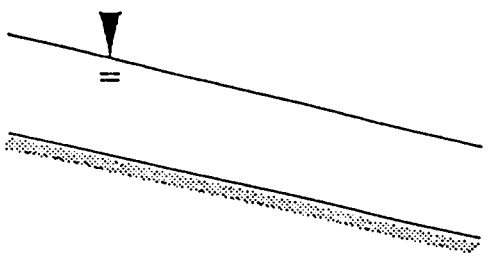
Steady Flow

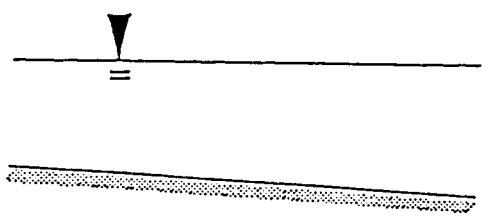
Depth and velocity at a given location do not vary with time.

Unsteady Flow

Depth and velocity vary with time at a given location

b. Uniform vs. Varied





Uniform Flow

Depth and velocity are constant with distance along the channel

Varied Flow

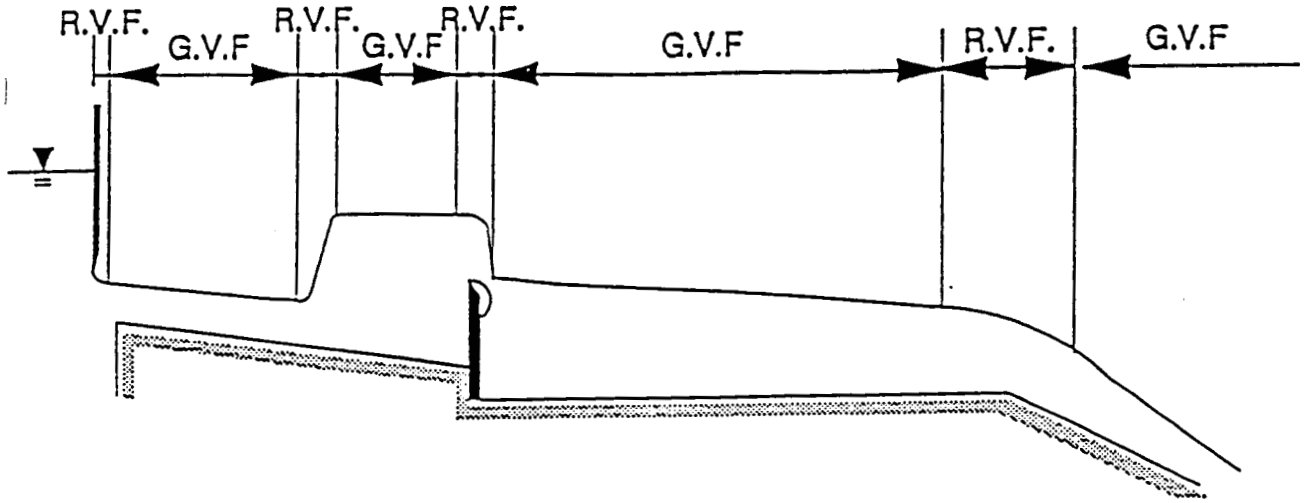
Depth and velocity vary with distance along the channel.

Gradually varied flow-

depth changes gradually over a long distance.

Rapidly varied flow-

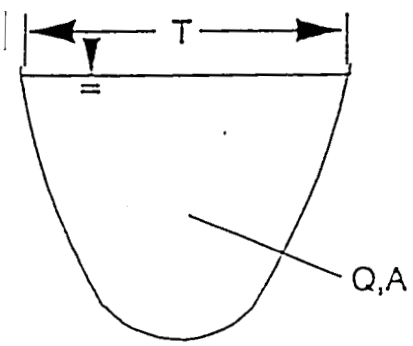
depth changes abruptly over a short distance.



c. Subcritical vs. Supercritical

Effect of gravitational forces relative to inertial forces represented by the Froude No., a dimensionless ratio.

$$Fr = \frac{V}{\sqrt{gD}}$$



where

Fr = Froude No.

V = Mean Velocity = Q/A

g = gravitational acceleration

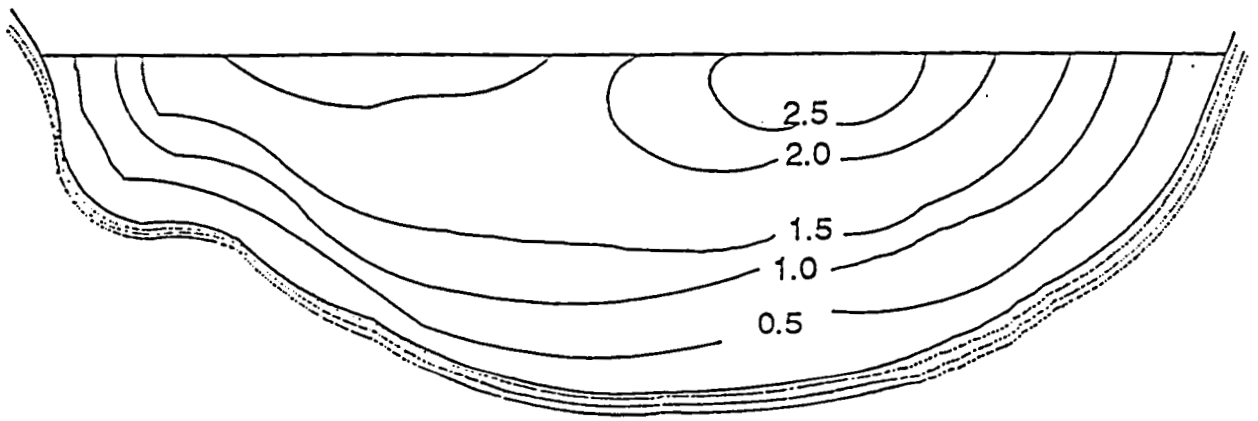
D = hydraulic mean depth = A/T

This definition of Froude No. applies only where a uniform velocity distribution can be assumed.

For	$Fr < 1$	flow is subcritical
	$Fr = 1$	flow is critical
	$Fr > 1$	flow is supercritical

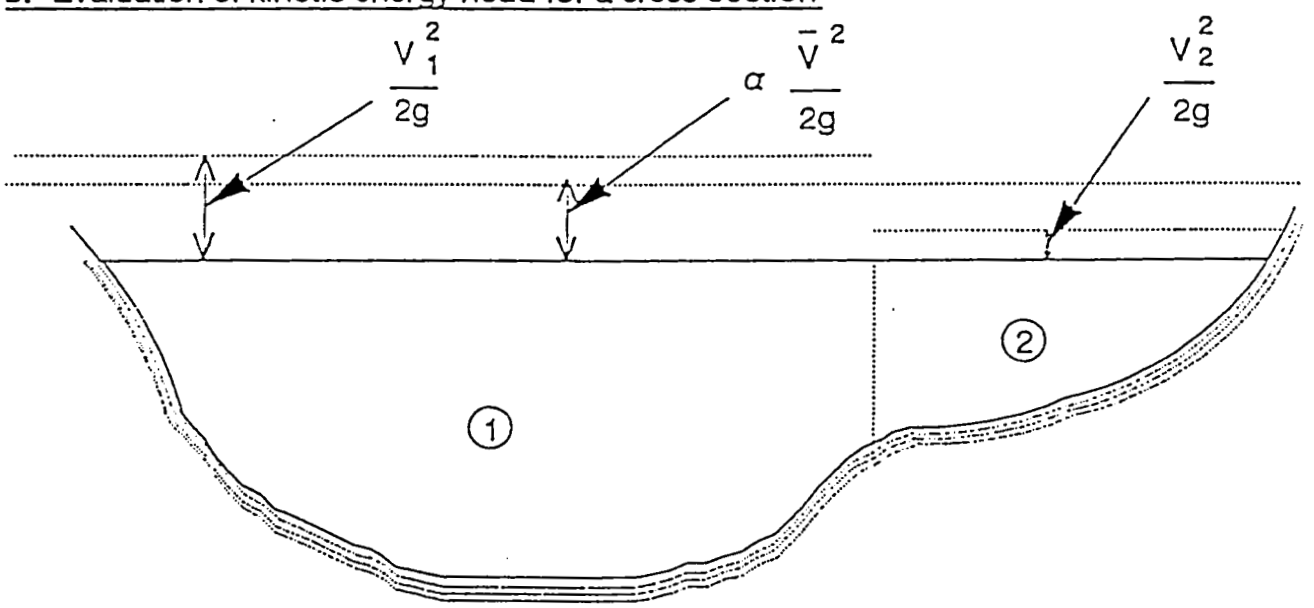
2. Velocity Distribution in a Cross Section

a. Factors influencing velocity distribution



Velocity distribution is affected by shape of cross section, roughness of boundaries, presence of bends, etc.

b. Evaluation of kinetic energy head for a cross section



V_1 = mean velocity for subarea 1

V_2 = mean velocity for subarea 2

Kinetic energy head = discharge-weighted velocity head

$$= \frac{Q_1\left(\frac{V_1^2}{2g}\right) + Q_2\left(\frac{V_2^2}{2g}\right)}{Q_1 + Q_2} \equiv \alpha \frac{\bar{V}^2}{2g}$$

$$\alpha = \frac{2g\left[Q_1\left(\frac{V_1^2}{2g}\right) + Q_2\left(\frac{V_2^2}{2g}\right)\right]}{(Q_1 + Q_2)\,\bar{V}^2}$$

$$\alpha = \frac{Q_1 V_1^2 + Q_2 V_2^2}{(Q_1 + Q_2)\,\bar{V}^2}$$

in general

$$\alpha = \frac{[Q_1 V_1^2 + Q_2 V_2^2 + Q_3 V_3^2 + \cdots + Q_N V_N^2]}{Q\,(\bar{V}^2)}$$

c. Typical values of velocity coefficient, α

Channel type	Value of α		
	Min.	Avg.	Max.
Regular channels, flumes, spillways	1.10	1.15	1.20
Natural streams	1.15	1.30	1.50
Rivers under ice cover	1.20	1.50	2.00
River valleys, overflooded	1.50	1.75	2.00

From Chow, Open Channel Hydraulics

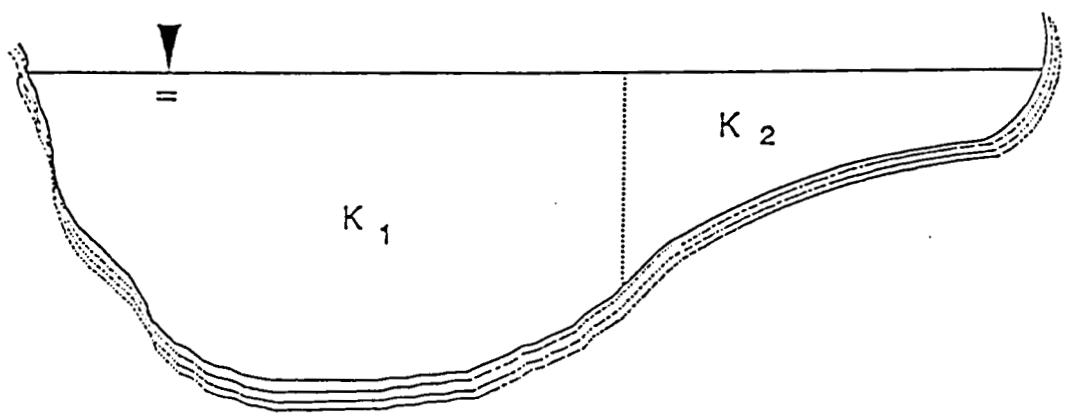
d. Determining flow distribution in a cross section

$$V = \frac{1.5}{n} R^{2/3} S_f^{1/2} \qquad \text{(Manning Eq.)}$$

$$Q = VA = \frac{1.5}{n} A R^{2/3} S_f^{1/2}$$

$$\text{Let } K = \text{conveyance} = \frac{1.5}{n} A R^{2/3}$$

$$\text{Then } Q = K S_f^{1/2}$$



For a given water surface and total discharge, determine Q_1 and Q_2

$$S_f^{1/2} = \frac{Q}{K}$$

Assume S_f is constant for a cross section

Then $\quad Q_1 = K_1 S_f^{1/2}$

$\quad\quad\quad Q_2 = K_2 S_f^{1/2}$

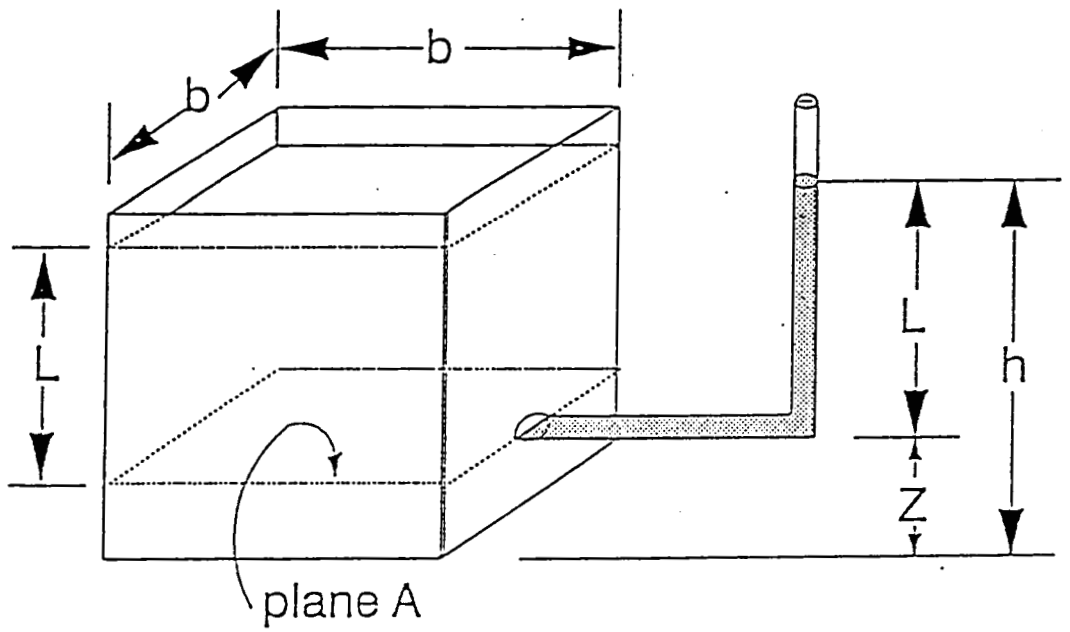
Or in general

$$Q_i = K_i S_f^{1/2}$$

where i designates subsection number. If this eq. is combined with the equation with the equation for α, there results

$$\alpha = \frac{(\Sigma A_i)^2 \Sigma(K_i^3/A_i^2)}{(\Sigma K_i^3)}$$

3. Pressure Distribution in a Channel Section



$$\text{Pressure on plane A} = \frac{b\,b\,L\gamma}{b\,b} = \gamma L \qquad \text{(+Atmos. pressure)}$$

$$\text{Pressure head} = \frac{\text{pressure}}{\gamma} = \frac{\gamma L}{\gamma} = L$$

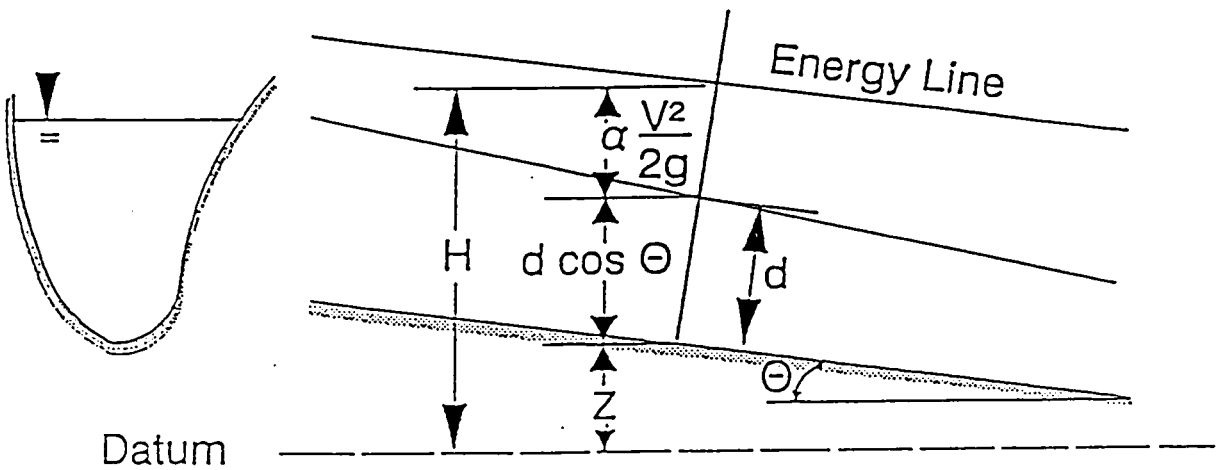
Piezometric head = Z + pressure head = Z + L = h

The pressure distribution in a still body of water is hydrostatic, which means that the pressure head is everywhere equal to the depth below the water surface.

A hydrostatic pressure distribution may be assumed to exist in a moving fluid where streamlines are approximately straight and parallel.

4. Energy Principles

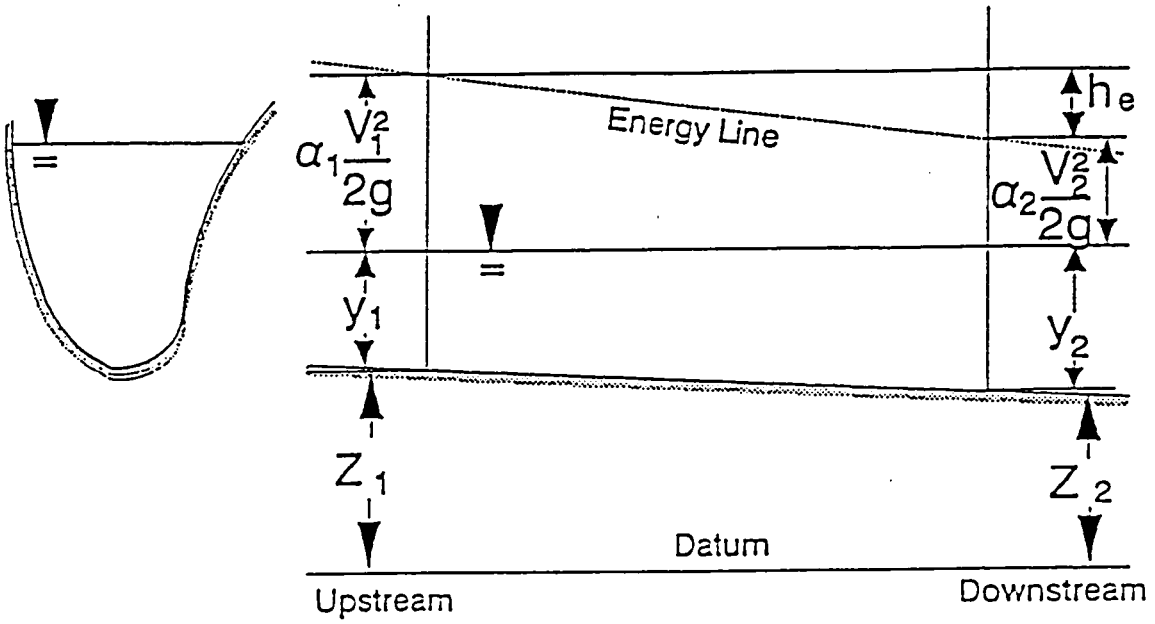
a. Total energy head for a cross section



$$H = Z + d \cos \Theta + \alpha \frac{V^2}{2g}$$

For a bed slope of 1:10, $\Theta = 5°40'$ and $\cos \Theta = 0.99$. The $\cos \Theta$ term in the energy equation is usually assumed equal to 1.

b. The energy equation



$$Z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = Z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_e$$

Let $H = Z + y + \alpha \frac{V^2}{2g}$

$H_1 = H_2 + h_e$

c. Limitations of energy equation

(1) Steady Flow

(2) One dimensional flow

(3) Gradually varied flow
(hydrostatic pressure distribution assumed)

(4) Channels of small slope (<1:10)

(5) Friction Slope S_f = Constant for a given cross section

d. Energy Losses

(1) Total Loss

$$h_e = h_f + h_o$$

where h_e = total energy loss
h_f = energy loss due to friction
h_o = other losses

(2) Contraction and expansion losses

$$h_o = C_c \left| \alpha_1 \frac{V^2_1}{2g} - \alpha_2 \frac{V^2_2}{2g} \right|$$

and

$$h_o = C_e \left| \alpha_1 \frac{V^2_1}{2g} - \alpha_2 \frac{V^2_2}{2g} \right|$$

where

C_c = Empirical Contraction Coefficient: $(V_{up}-V_{dn})$ = Negative

C_e = Empirical Expansion Coefficient: $(V_{up}-V_{dn})$ = Positive

$\alpha_1 \frac{V^2_1}{2g}$ = Upstream Velocity Head

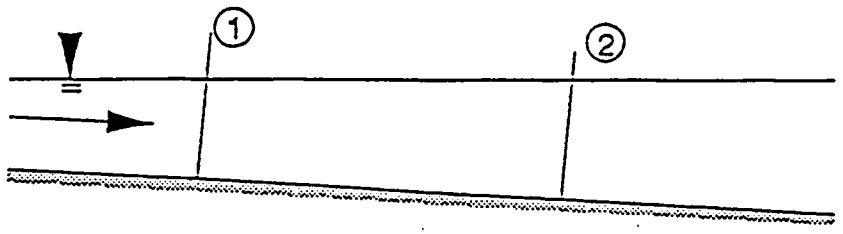
$\alpha_2 \frac{V^2_2}{2g}$ = Downstream Velocity Head

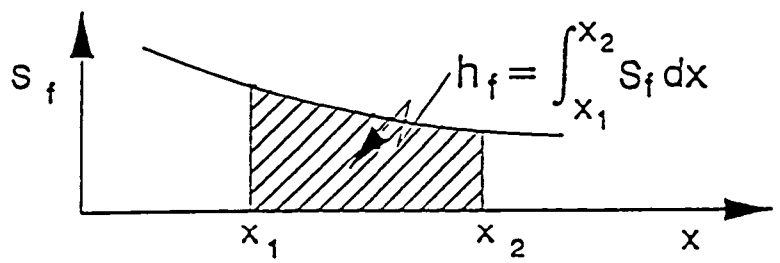
Typical Values

C_c 0.1 to 0.5

C_e 0.3 to 1.0

(3) Determining friction loss in a channel reach





Let $$\int_{X_1}^{X_2} S_f \, dx = \overline{S}_f L \qquad (1)$$

where $\overline{S}_f$ = representative friction slope
L = reach length

Approximations for $\overline{S}_f$

$$\overline{S}_f = \frac{S_{f_1} + S_{f_2}}{2} \qquad (2)$$

or

$$\overline{S}_f = \left[\frac{Q}{\left(\frac{K_1 + K_2}{2} \right)} \right]^2 \qquad (3)$$

substituting (3) in (1)

$$h_f = L \left[\frac{2Q}{K_1 + K_2} \right]^2$$

Total Energy Loss Equation:

$$h_e = c \left| \alpha_1 \frac{V_1^2}{2g} - \alpha_2 \frac{V_2^2}{2g} \right| + L \left[\frac{2Q}{K_1 + K_2} \right]^2$$

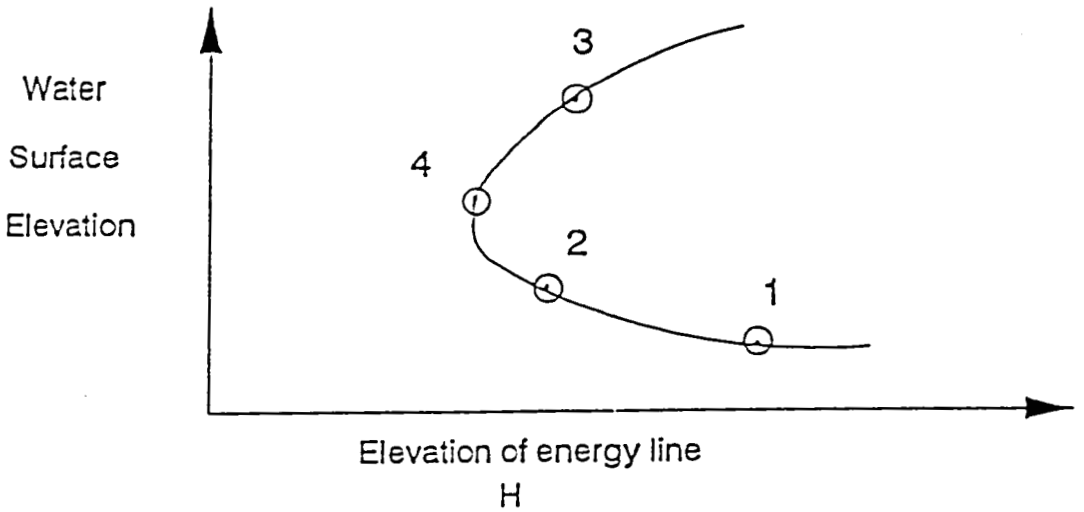
5. Critical Depth and its significance

a. Definition of critical depth

The depth at which total energy head is a minimum for a given discharge.

b. Computation of critical depth in irregular channels

Minimize $Z + y + \alpha \frac{V^2}{2g}$



c. Controls and their significance in open channel flow

References:

a. EM 1110-2-1409, "Backwater Curves in River Channels," Corps of Engineers, 1959.

b. French, Richard H., Open Channel Hydraulics, McGraw-Hill, 1985

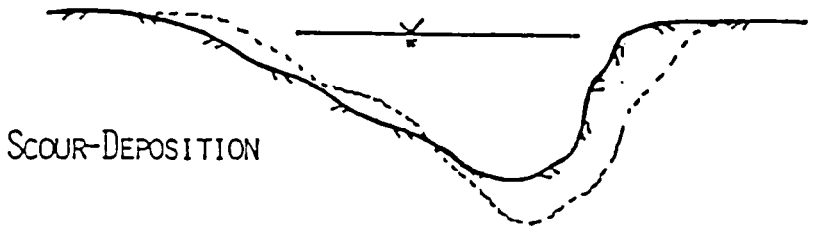
c. Henderson, F.M., Open Channel Flow, MacMillan, 1966.

d. U.S. Army Corps of Engineers, Water Surface Profiles, IHD Volume 6, The Hydrologic Engineering Center, July 1972.

e. Chow, Ven Te, Open Channel Hydraulics, McGraw-Hill, 1959.

SEDIMENT TRANSPORT IN NATURAL STREAMS

MOBILE BOUNDARY CONDITIONS



"EQUILIBRIUM SEEKING CONCEPT"

WHY WORRY ABOUT SEDIMENT?

- CAN DECREASE DEGREE OF LEVEE PROTECTION
- REMOVES VALUABLE RESERVOIR STORAGE
- INTERFERES WITH NAVIGATION
- CAN UNDERMINE CHANNEL CROSSINGS
- CAN ADVERSLY AFFECT WATER QUALITY

SEDIMENT TRANSPORT PROCESS:

- EROSION: LAND SURFACE, STREAM CHANNEL
- ENTRAINMENT
- TRANSPORTATION
- DEPOSITION
- COMPACTION

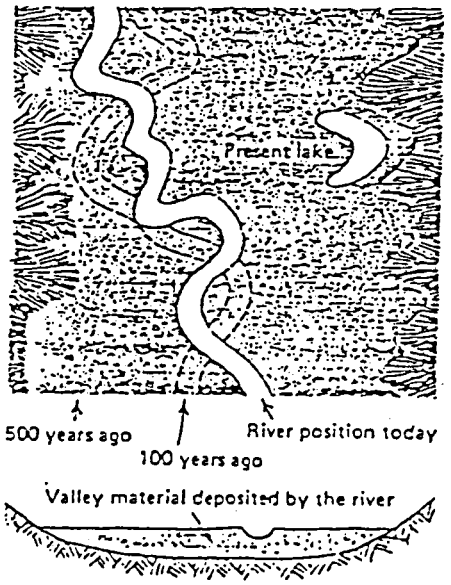
"EQUILIBRIUM SEEKING"

WHAT CAUSES EROSION?

- WATER: RAINFALL, RUNOFF, STREAMFLOW
- WIND
- GRAVITY
- ICE
- MAN

TIME SCALES FOR SEDIMENT PROCESS:

- GEOLOGIC TIME (10^4 - 10^7 YEARS)
  - BASINS FILLING, PLAINS DEGRADING, SWAMPS FORMING, ETC.
  - CAUSES: WEATHER, MOUNTAIN BUILDING, SEA LEVEL CHANGES, ETC.
- PROJECT TIME (100 YEARS AND LESS)
  - RIVER MEANDER, CHANNEL ERODES, SHOALING, ETC.
  - CAUSES: TRANSPORT CAPACITY, SEDIMENT SUPPLY, MAN'S WORKS
  - RESERVOIR SEDIMENTATION



Present and past courses of a reach, or length, of river. (U.S.G.S.)

- MAJOR FLOOD
    - CHANGES FLOODPLAIN GEOMETRY, SCOURS STRUCTURES, DEBRIS/ SEDIMENT DEPOSITS
    - CAUSES: FLOOD MAGNITUDE, SPECIFIC LOCATION, SPECIFIC REGULATION WORKS
- INSTANTANEOUS
    - SEDIMENT LOAD, EROSIVE POWER
    - CAUSES: STREAM GEOMETRY, FLOW VELOCITY, SEDIMENT GRADATION

CLASSIFICATION OF SEDIMENT

- BED LOAD
- SUSPENDED LOAD
    - SUSPENDED BED LOAD
    - WASH LOAD

SEDIMENT TRANSPORT STUDIES: BED LOAD AND SUSPENDED BED LOAD

STREAM REGIME

- UPPER: HILLY, STEEP, BOULDERS AND GRAVEL IN BED
- LOWER: ALLUVIAL PLAIN, SAND-SILT-CLAY IN BED

USUALLY CONCERNED WITH RESPECT TO LOWER REGIME

ALLUVIAL STREAMS EVOLVE TOWARD EQUILIBRIUM

$$Q_S * D_{50} = Q * S_F$$

WHERE:

Q_S = BED MATERIAL LOAD

D_{50} = AVERAGE SEDIMENT SIZE

Q = DISCHARGE

S_F = E.G.L. SLOPE

ON AN ANNUAL BASIS, D_{50} AND Q ARE APPROXIMATELY CONSTANT

$$Q_S \uparrow \downarrow, \therefore S_F \uparrow \downarrow$$

VARIES ALONG THE STREAM

SOURCES AND SINKS

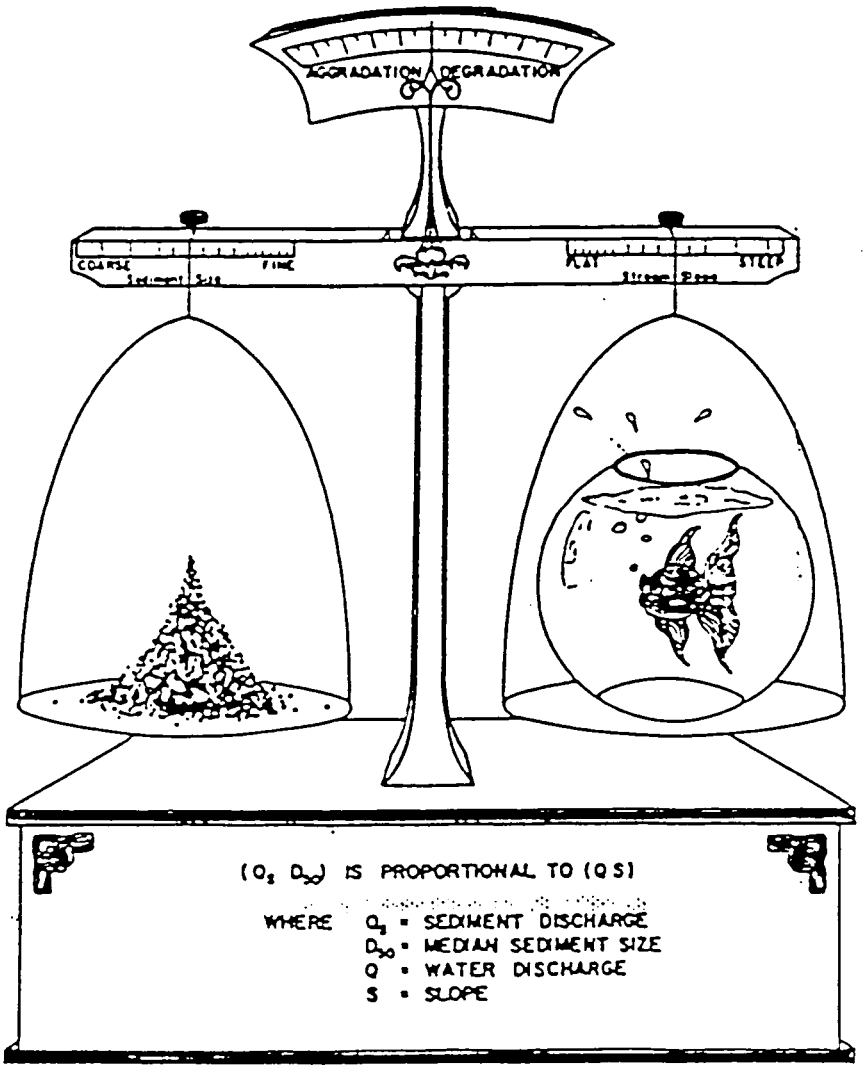


Figure 8. Schematic of the Lane relationship for qualitative analysis.

ALLUVIAL RIVER REGIMES

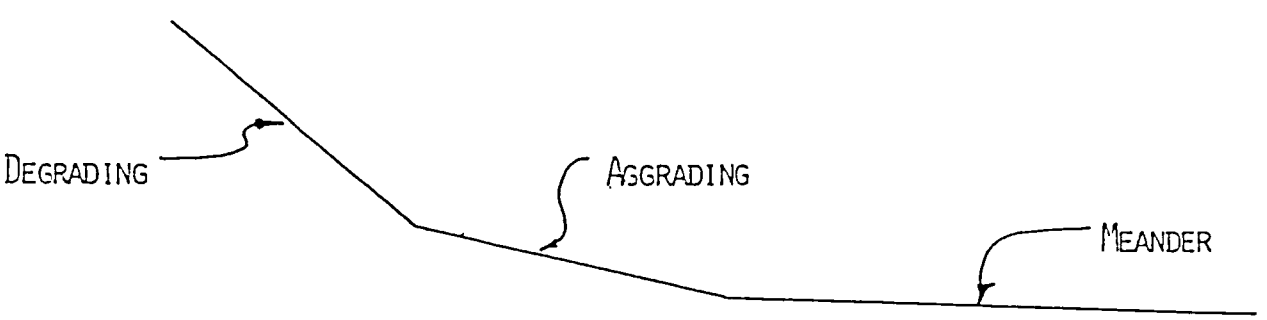
- MEANDERING: FAIRLY STABLE STREAM (EQUILIBRIUM CONDITION)
  - SEDIMENT LOAD IN IS APPROXIMATELY EQUAL TO TRANSPORT CAPACITY OUT, CAUSING BANK EROSION (MISSISSIPPI RIVER)

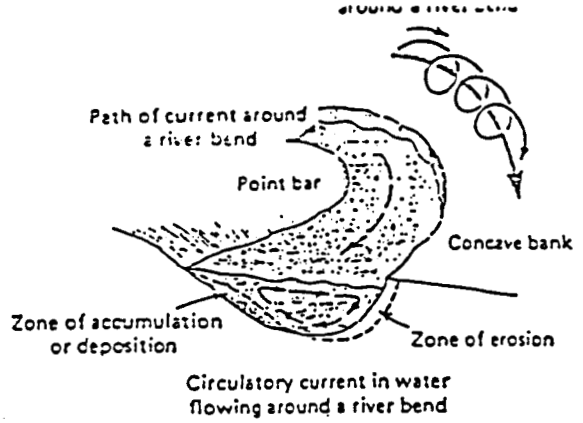
- AGGRADING: SEEKING EQUILIBRIUM
  - SEDIMENT LOAD IN IS GREATER THAN TRANSPORT CAPACITY OUT, CASUING WIDE, SHALLOW (BRAIDED) STREAMS (HIGH PLAINS RIVERS)

- DEGRADING: SEEKING EQUILIBRIUM
  - SEDIMENT LOAD IN IS LESS THAN TRANSPORT CAPACITY OUT, CAUSING DEEP, WIDE RIVERS (COLORADO RIVERS - URBANIZING STREAMS)

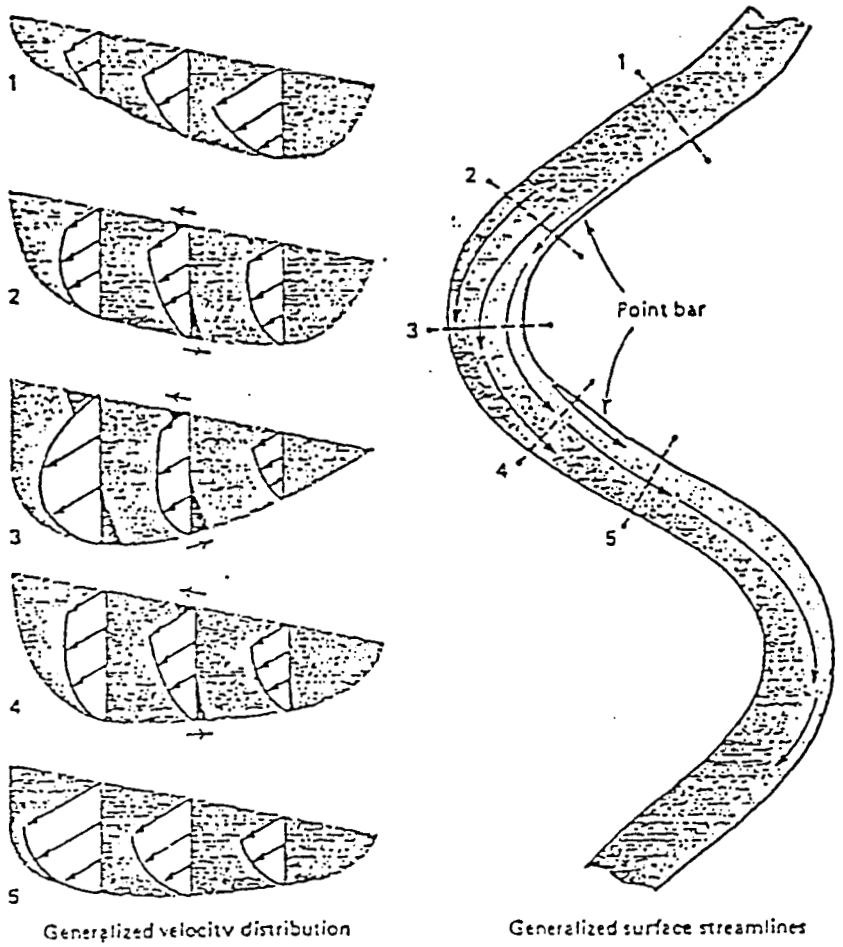
ONE RIVER CAN EXPERIENCE ALL THREE REGIMES OVER ITS LENGTH

$$Q_S * D_{50} = Q * S_F$$





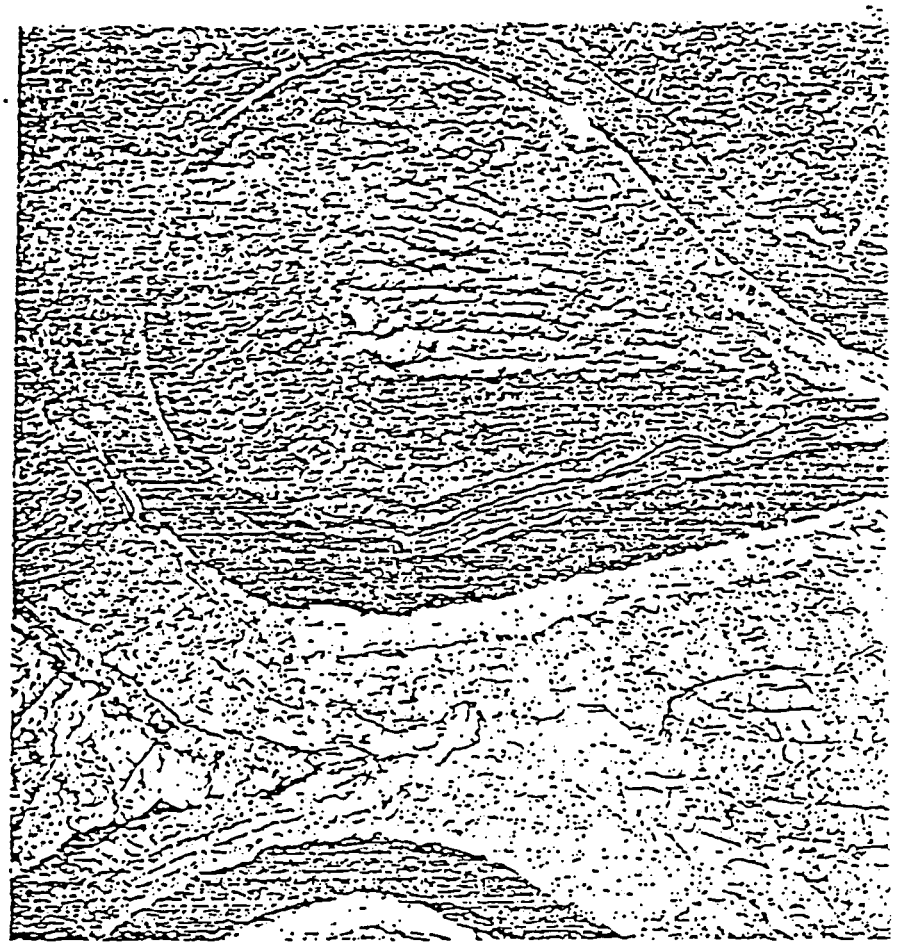
Effect of a curved channel on water flow. (U.S.G.S.)



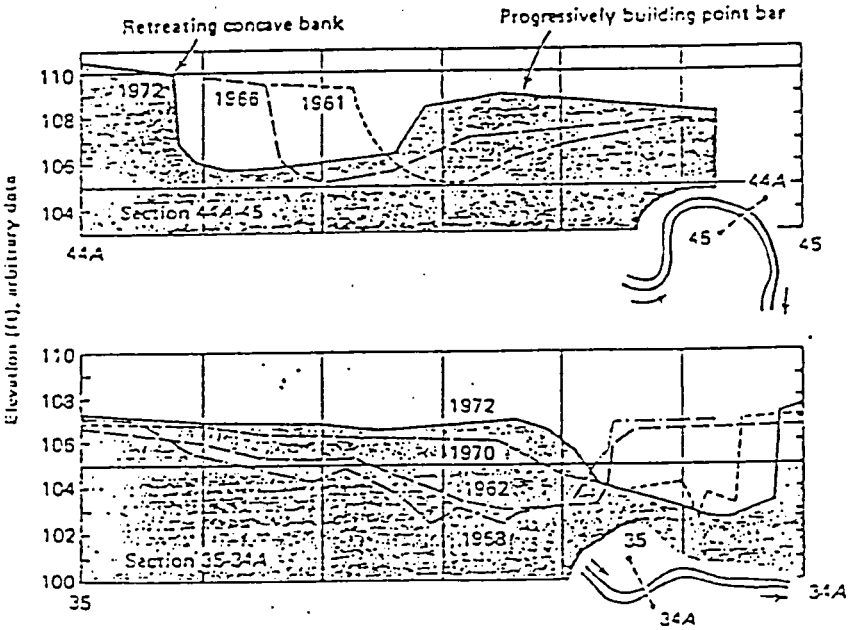
Meandering

Isometric view of generalized diagram of flow distribution in a meander; open parabolas with arrows indicate downstream velocity vectors; lateral component of velocity is shown by gray areas; all sections are viewed from a changing position to the left of and above the individual section. (From *Fluvial processes in geomorphology*, by Leopold, Wolman, and Miller. W. H. Freeman and Company. Copyright © 1964.)

Degradation



The meandering gorge of the Colorado River at the Loop, below Moab, Utah. The channel has cut downward more than 1,000 feet since the Colorado Plateau area began to rise more than 1 million years ago. (U.S.G.S.)



Aggradation

Data obtained from successive resurveys of Watts Branch near Rockville, Maryland, show lateral migration of a river channel by the building of a point bar into the stream and the concurrent erosion of the opposite bank. The continuation of such point bar building results in the development of a flood plain. Diagrams in lower right indicate position of the cross section relative to channel bends. (From Leopold, *Bull. Geol. Soc. America*, June 1973.)

GENERAL SEDIMENT TRANSPORT EFFECTS

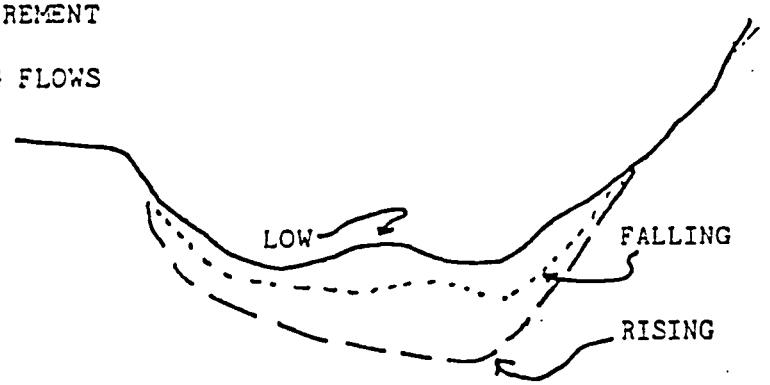
-DEVELOPING WATER SURFACE ELEVATIONS

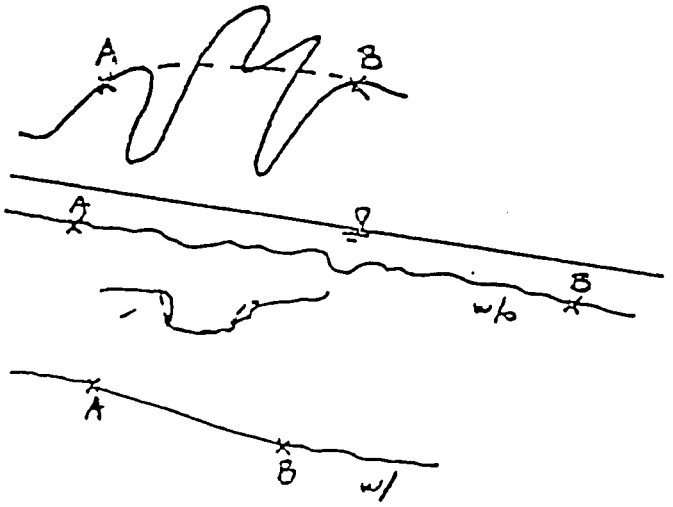
USUALLY RIGID BOUNDARY ASSUMPTION

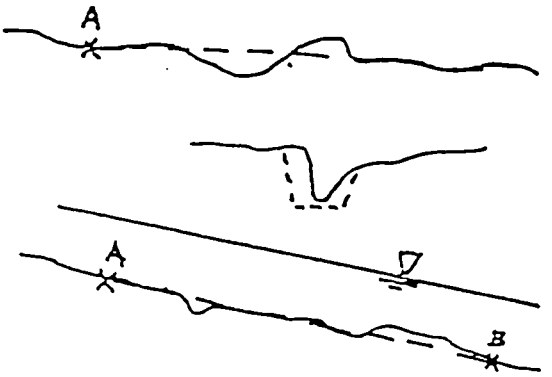
BED CHANGES DURING THE YEAR

TIMES OF MEASUREMENT

RISING/FALLING FLOWS







-CHANNELIZATION

SHORTEN, DEEPEN, WIDEN CHANNEL

STREAM WILL RESEEK EQUILIBRIUM

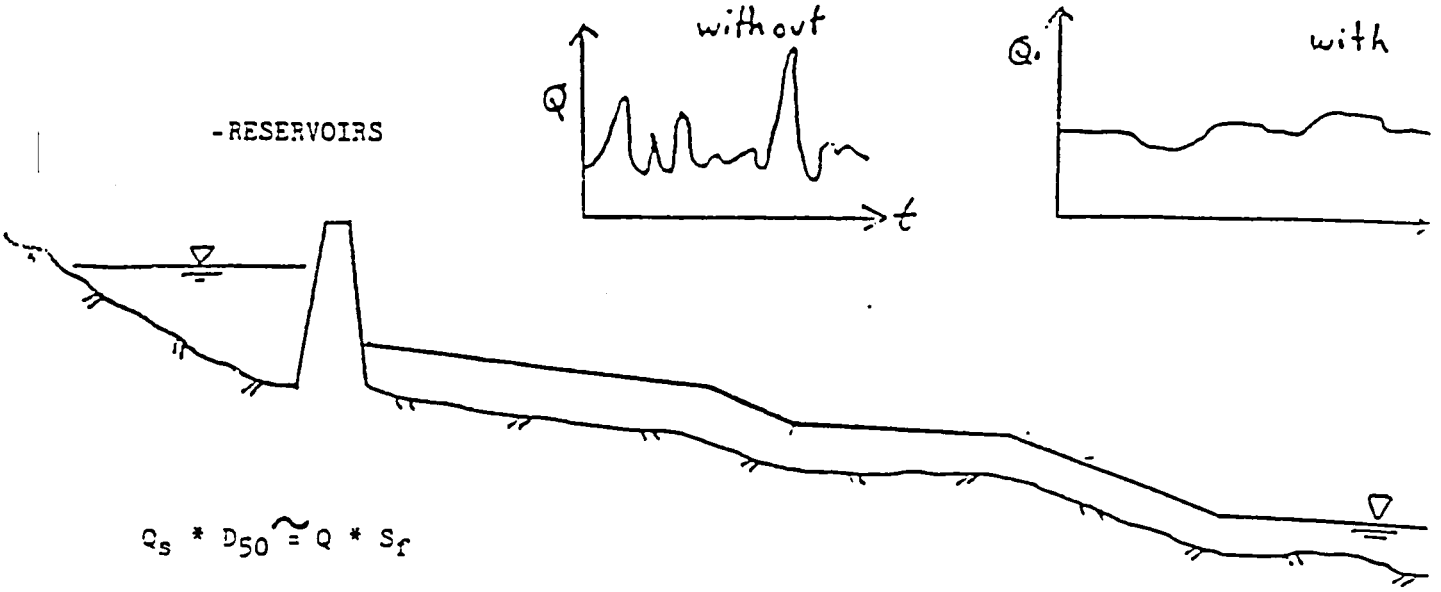
TRIBUTARY EFFECTS

-CHANNELIZATION CAN CAUSE:

_____ UPSTREAM

_____ IN IMPROVED REACH AND DOWNSTREAM

-RESERVOIRS



$Q_s * D_{50} \cong Q * S_f$

A RESERVOIR CAN CAUSE:

*_____ IN POOL

*_____ DOWNSTREAM

*HOW FAR DOWNSTREAM?

CHANGED FLOW REGIME CAUSES:

*INCREASED TRANSPORT

*DECREASED TRANSPORT

*BOTH

*TRIBUTARY EFFECTS

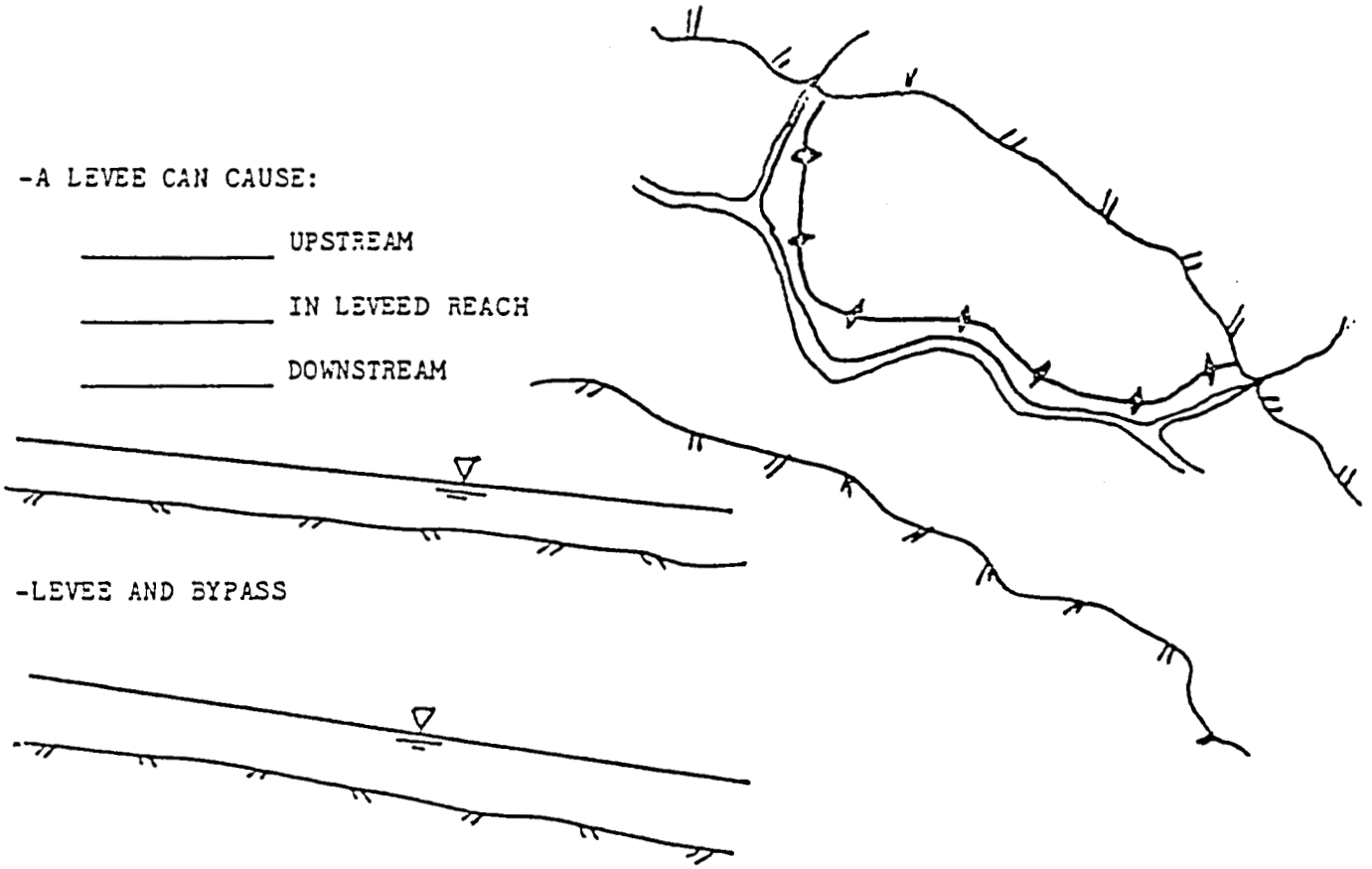
USUAL EFFECTS: IMMEDIATE DEGRADATION DOWNSTREAM, THEN DEPOSITION IN LOWER REACHES

-A LEVEE CAN CAUSE:

_____ UPSTREAM

_____ IN LEVEED REACH

_____ DOWNSTREAM

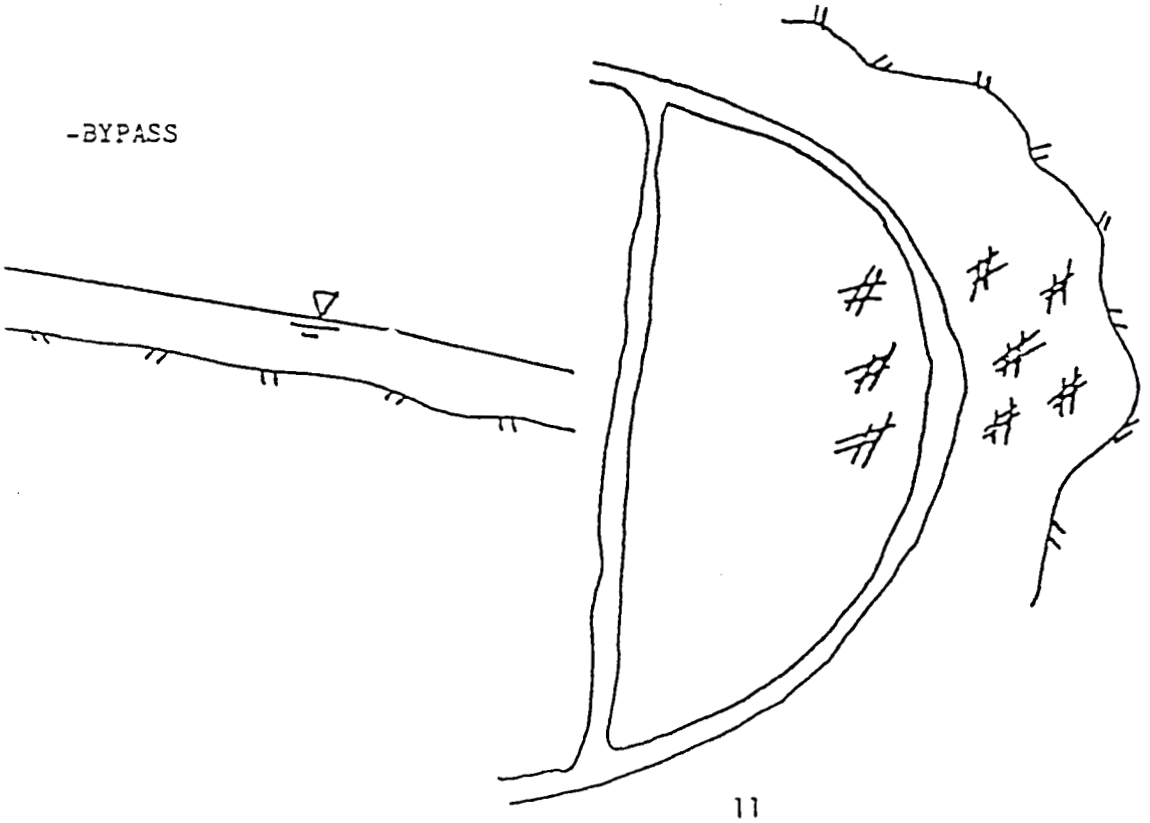


-LEVEE AND BYPASS

DIVERT FLOW THAT WOULD HAVE GONE INTO OVERBANK STORAGE

DIFFICULT TO PREDICT SCOUR-DEPOSITION

-BYPASS



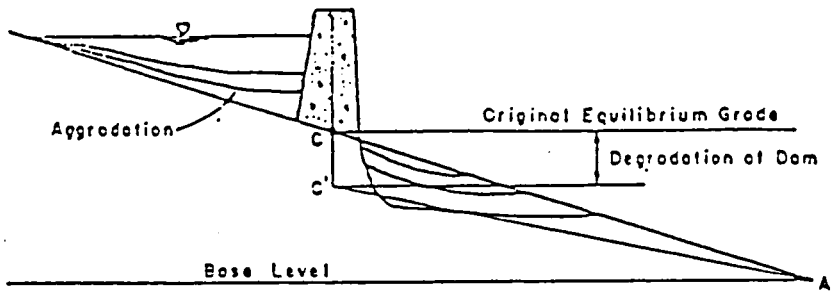


Fig. 2.12 Channel adjustment above and below a dam.

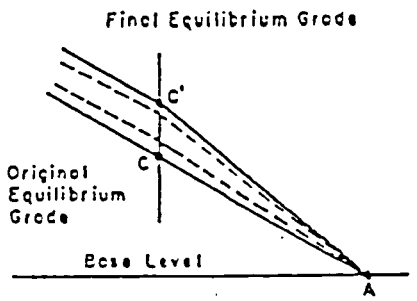
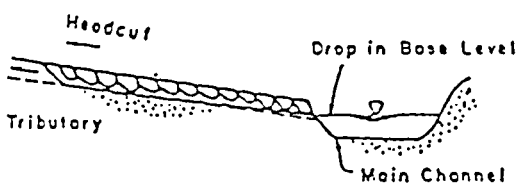


Fig. 2.13 Changes in channel slope in response to an increase in sediment load at point C .



Local Effects	Upstream Effects	Downstream Effects
1. Headcutting	1. Increased velocity	1. Increased transport to main channel
2. General scour	2. Increased bed material transport	2. Aggradation
3. Local scour	3. Unstable channel	3. Increased flood stage
4. Bank instability	4. Possible change of form of river	4. Possible change of form of river
5. High velocities		

Fig. 2.14 Lowering of base level for tributary stream.

SEDIMENT TRANSPORT REFERENCES

Sedimentation Engineering, ASCE Manual No. 54, 1975.

Hydraulics of Sediment Transport, Walter H. Graf, McGraw Hill, 1971

River Mechanics (two volumes), Hsieh Wan Shen, Editor and Publisher, 1971

Environmental Impact on Rivers (Volume 3 of River Mechanics) Hsieh Wen Shen, Editor and Publisher, 1973

Loose Boundary Hydraulics, A. J. Raudkivi, Pergamon Press, 1976

An Introduction to Fluvial Hydraulics, Serge Leliavsky, Dover, 1955

Open Channel Flow, Henderson, Macmillan 1966, Chapter 10

Mechanics of Sediment Transport, M. S. Yalin, Pergamon Press, 1972.

Sediment Transport in Alluvial Streams, Bogardi, Janos, L. 1974

Sedimentation Investigations of Rivers and Reservoirs, EM 1110-2-4000, Department of the Army, Washington, D.C., 1988.

FROM:

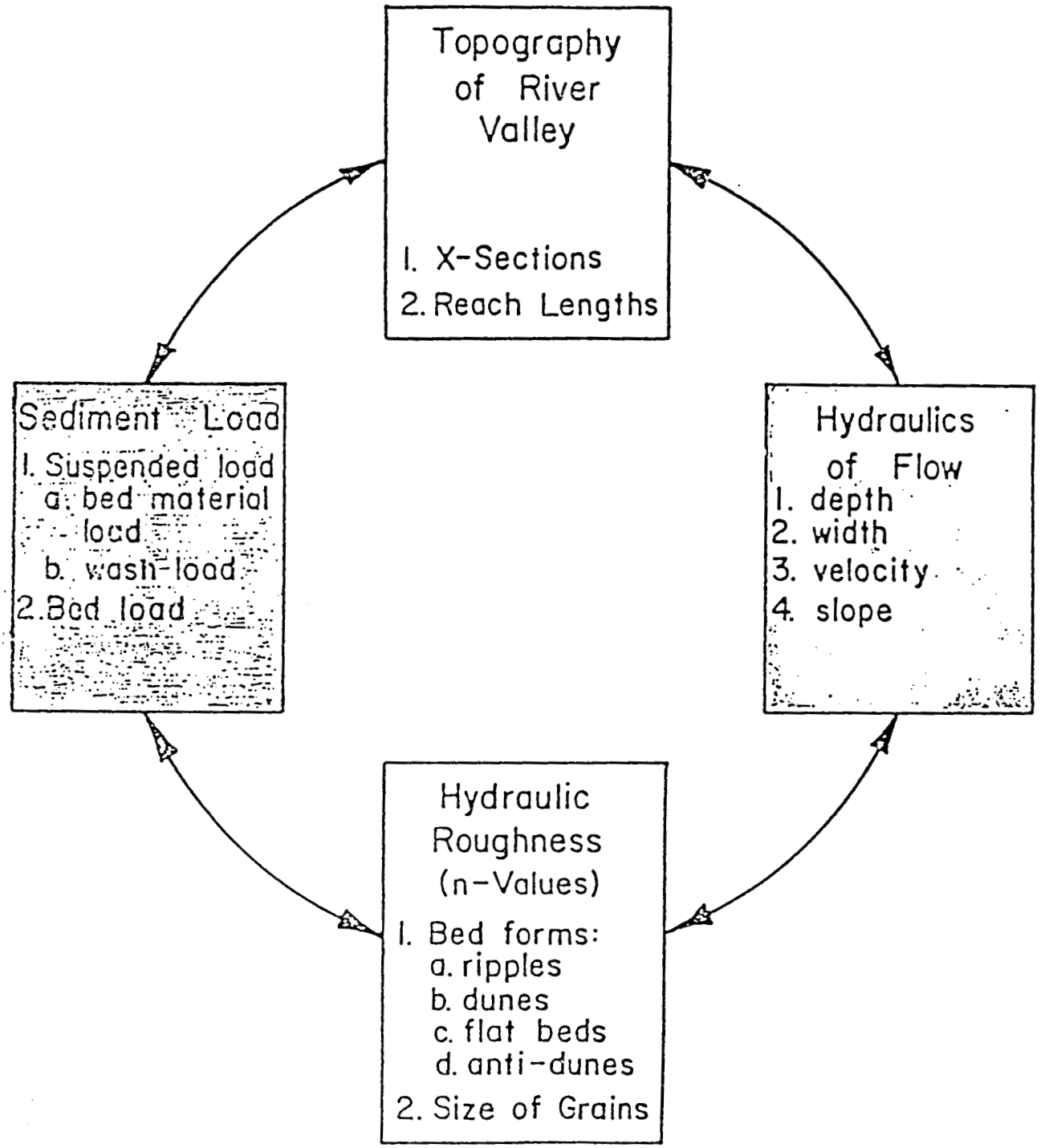
Sediment Transport in Rivers and Reservoirs Short Course Manual, HEC

Three Levels of Analysis for
Conducting Sedimentation Engineering Evaluations

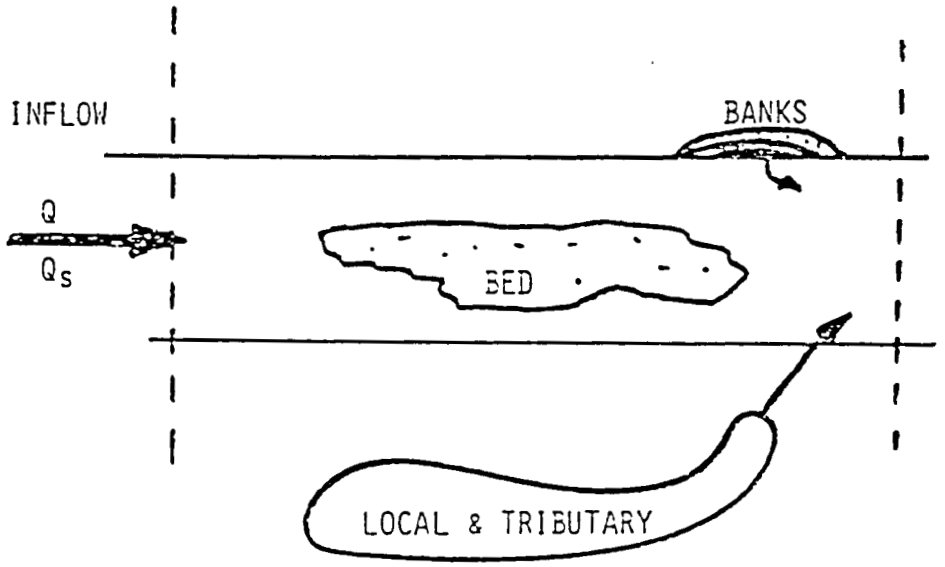
Level	Objectives	Study Components
I	Identify problems and conduct qualitative assessment.	Identify the problems and analyze them qualitatively through the application of general principles. Visit the problem site and compile and review available data. Use these data to support your qualitative assessment. Identify data needs for higher level studies.
II	Refine problem definition	Refine the definition of the problems identified during the Level I study. Obtain additional data. Conduct quantitative engineering analysis.
III	Conduct thorough quantitative analyses of the problem.	Prepare a thorough statement of the problem. Collect all necessary data. Perform intermediate and advanced analyses of the problem through the application of one or more simulation models (physical and/or numerical). Attempt to verify results.

THE ANALYSIS OF SEDIMENTATION PROBLEMS

- HISTORICAL INFORMATION
- SITE RECONNAISSANCE
- QUALITATIVE ASSESSMENT
- ANALYTICAL STUDIES
- NUMERICAL MODEL STUDIES
- PHYSICAL MODEL STUDIES



MOVABLE BED MODEL



SEDIMENT SOURCES IN A RIVER REACH

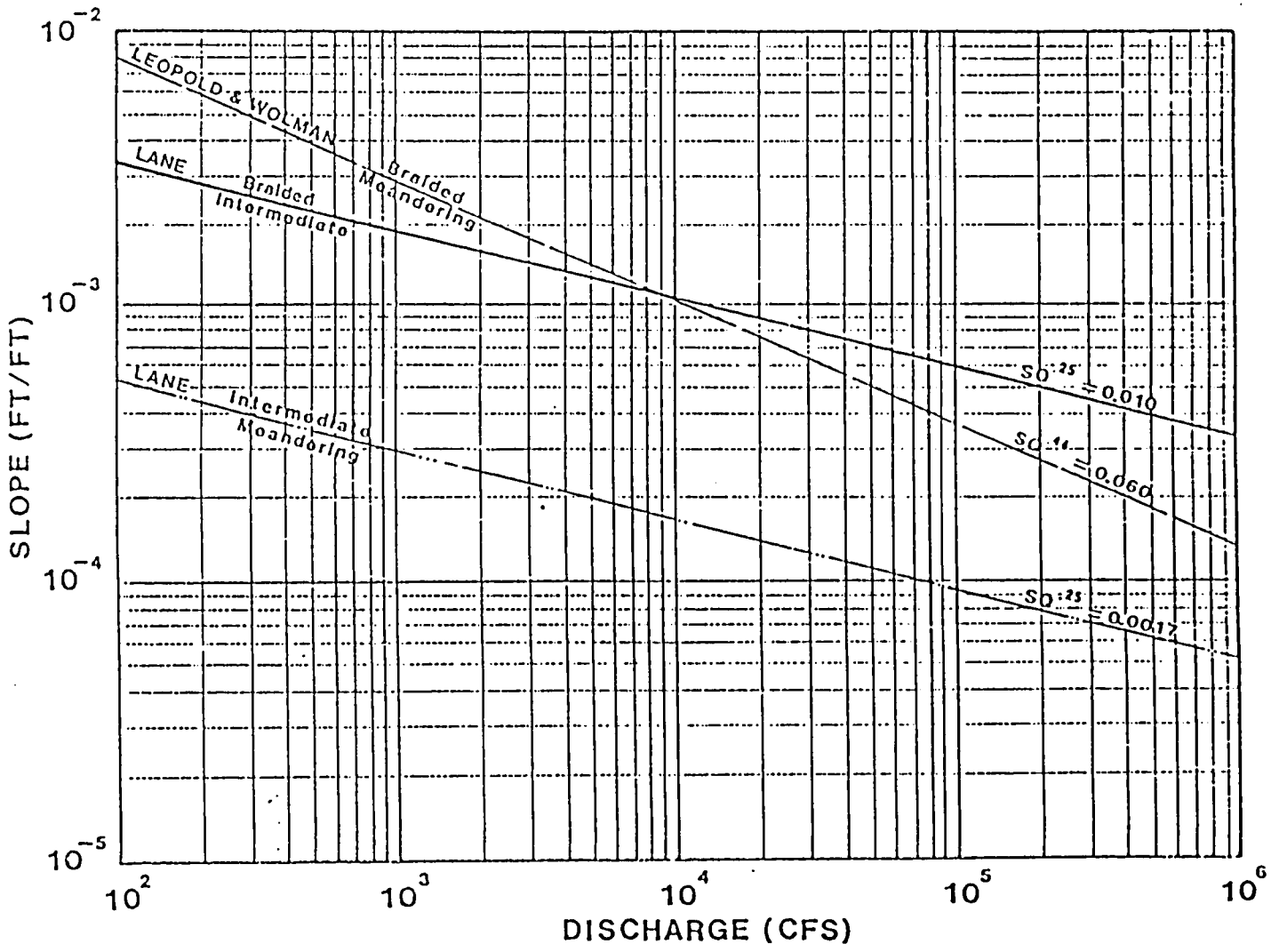


Figure 4. Slope-discharge relations.

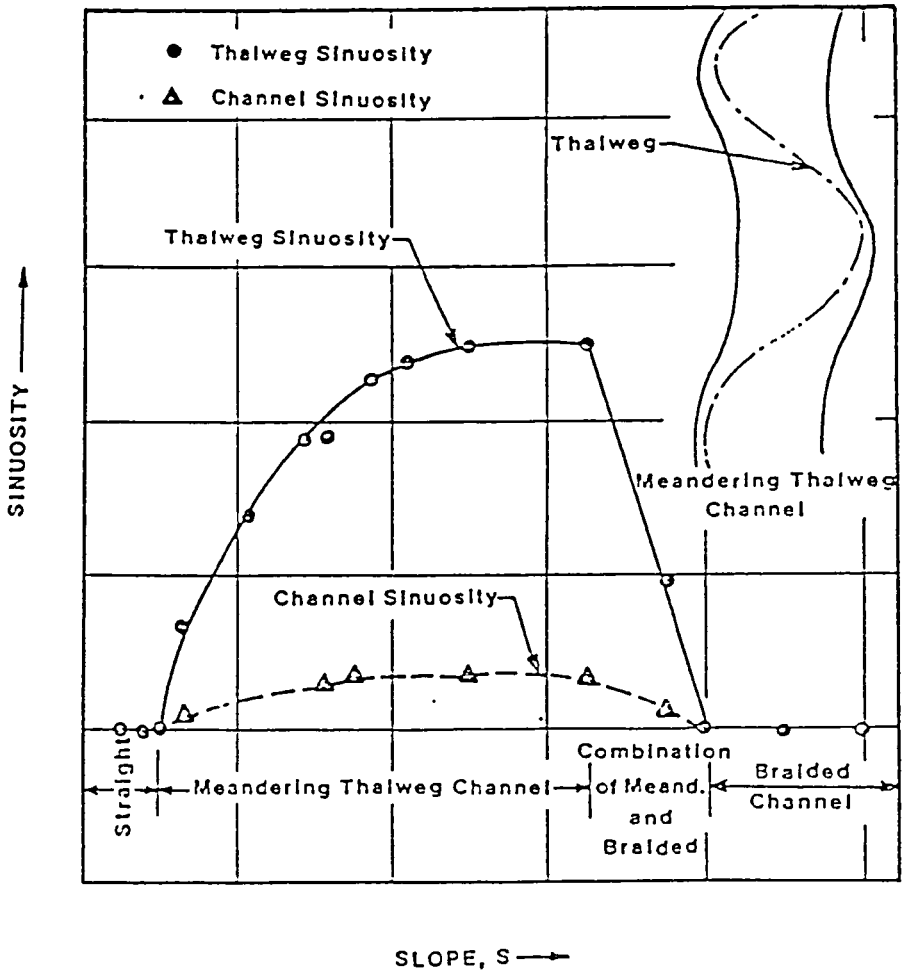


Figure 5. Channel pattern versus slope and sinuosity (Kahn, 1971)

PROPERTIES OF NON-COHESIVE SEDIMENT AND CHARACTERISTICS OF ITS MOVEMENT

Ref: Sedimentation Engineering, V. Vanoni, Ed., ASCE Manual No. 54, 1975.

I. Non Cohesive Sedimentation Materials

A. Particles that do not stick to each other. Individual particles retain their physical properties at all times.

A. Sediment Grade Scale; Shown in Attachment #1 & 2.

1. Note geometric spacing of grades
2. Note size range. Coarsest particles are transported by rolling along bed. Finest are transported in suspension.

B. Shape of Particles:

The most useful shape factor is McNown's:

$$SF = \frac{c}{\sqrt{ab}}$$

where a,b, & c are mutually perpendicular particle dimensions and a > b > c.

C. Specific gravity

The specific gravity of sediment material depends on the mineral composition of the rock from which it originated, on its weathering history and on the sorting that has occurred during its transport. Specific gravities of common individual grains range from less than 2.5 to 5.3. Quartz, a very common

mineral in sediments, has a specific gravity of 2.65.

Because the specific gravity of the particle is an important parameter in sediment transport, it is desirable that it be determined for samples of the sediment for which non-cohesive sediment loads are to be computed.

D. Settling Velocities of Single Spheres

$$w^2 = \frac{4}{3}\frac{gd}{C_D}\left(\frac{\gamma_s - \gamma}{\gamma}\right) \tag{1}$$

where w settling velocity

g acceleration of gravity

d diameter of the sphere

C_D drag coefficient

γ_s specific weight of the particle

γ specific weight of water

For $$0.1 > R = wd/\nu, \tag{2}$$

where ν is the kinematic viscosity, $C_D = 24/R$. For $R > 0.1$ the coefficient of drag needs to be determined empirically. The attached figure #3 shows such a curve. The settling velocity of a sphere can be calculated from this curve by first calculating the submerged weight

$$F = \frac{\pi d^3}{6}(\gamma_s - \gamma) \tag{3}$$

and $F/\rho\nu^2$, where ρ is the density of the fluid mass. Enter this value on the auxiliary scale in #3, follow the sloping

lines down to the curve for spheres, and read the corresponding value of R. w can then be calculated from R via equation (2).

The settling velocities for spheres having a density of 2.65 can be read from attachment #4.

E. Correction of Settling Velocity for Shape Factor.

Attachment #5 shows plots for correcting the fall velocity calculated for spheres for particle shape.

F. Correction of Fall Velocities for High Concentration of Suspended Sediment

$$w_h = w(1-\phi_p)^5 , \qquad (4)$$

where w_h is the "hindered settling velocity" and ϕ_p is the volume concentration of suspended particles: cu cm of particles per cu cm of suspension.

G. Specific Weights of Sediment Beds

Bulk densities of non-cohesive sediment beds vary widely depending on particle size distribution, particle density, and packing. Consolidation becomes a factor with finer particles (silt and clay). Attachment #6 shows variations of specific weights with particle size. Attachment #7 shows extreme variations.

It is usually advisable to measure specific weights when a conversion of weight of material deposited to deposit volume is required.

II. Initiation of Sediment Motion by Currents

A. Sediment particles are lifted from their place in the bed by pressure fluctuations. These fluctuations are random and there is a wide distribution in peak pressures. There is not, therefore, a certain current or bed shear stress that is the "threshold" of sediment transport. Most experimentors utilize "weak motion" as initiation of motion or extrapolate to zero motion from a function that is defined for higher flows. From a combination of mechanics and dimensional analysis Shields obtained

$$\frac{\tau_c}{(\gamma_s - \gamma)d} = f\left(\frac{u_{*c}\, d}{\nu}\right) \tag{5}$$

where τ_c is the bed stress necessary to initiate motion, U_{*c} is the shear velocity needed to initiate motion and the term in parenthesis is the boundary Reynolds number, R_*.

Recall that for steady, uniform flow,

$$\tau = \gamma R_h S, \tag{6}$$

where τ is the average shear stress around the wetted boundary R_h is the hydraulic radius of the channel, and S is the (energy) slope.

$$U_* = \sqrt{\tau/\rho} \tag{7}$$

so that both τ and U_* can be obtained for use in equation 5.

Equation 5 can be solved for τ_c or d by means of a Shields Diagram as shown in Attachment #8. This plot shows the relation for an artifically flattened bed under fully

developed turbulent flows. One can calculate the value of τ_c, for example, by trial, using successive values of U_* to calculate both $\tau_c/(\gamma_s-\gamma)d$ and R_* until the resulting plotted point falls on the curve.

Alternatively, the function shown above the auxiliary scale in #8 can be calculated, the corresponding value of $\tau_c/(\gamma_s-\gamma)d$ found leads directly to τ_c.

A plot of sediment size for various critical shear stresses is shown in attachment #9. This plot was calculated using a sediment particle density of 2.65 gm/cu cm.

Example Problem

What is the critical shear stress for a 1 mm uniform sand having a density of 2.65 gm/cu cm in water at 20°C?

Solution: Units given are metric, so that it is easiest to use metric values for the dimensionless numbers required.

The kinematic viscosity of water at 20°C is .0100 cm^2/S. $\gamma = \rho g$ and $\rho_s = 2.65$ gm/cm.^{3} The auxiliary function using centimeter gram second units, is

$$\frac{.1}{.01}\sqrt{0.1\left(\frac{2.65}{1.00} - 1\right) 980 \times 0.1} = 40.2$$

$$\tau_c/(\rho_s-\rho)qd = 0.033$$

$$\tau = 0.033 \times 1.65 \times 980 \times 0.1 \simeq \underline{\underline{5.34 \ \frac{\text{dynes}}{\text{cm}^2}}}$$

Check: $U_* = \sqrt{\tau/\rho} = 2.31$ cm/s

$$R_* = \frac{2.31 \times 0.1}{.01} = 23.1$$

III. Sediment Loads in Rivers

The way that non-cohesive particles are transported depends on their size and on their intensity of the currents. The bed load consists of particles that roll along the bed. The suspended load consists of particles that are carried by the waters above the bed. The coarser portion of the suspended particles--typically particles larger than .02 mm--occasionally settle to the bed and are subsequently resuspended. This process goes on continually in alluvial channels and the amount of suspended particles of these sizes tends to establish an equilibrium with the bed material. The portion of the sediment that rolls along the bed plus that portion of the suspended load that interchanges with the bed in significant amounts is collectively called the bed material load.

The remaining suspended load--that material that is comprised of particles smaller than about 20 micrometers--is called wash load. Because there is little interchange with the bed, there is not a relation between discharge and wash load is determined by the supply to the stream.

The bed material load plus the wash load is called the total load.

IV. Velocity Profiles

Turbulent momentum transport in streams results from mixing initiated by the roughnesses of the bed and banks. Dimensional considerations and intuitive models lead to a velocity profile description of

$$u = \frac{2.303\ U_*}{k} \log\ (A\ y/yo) \tag{8}$$

where u is the velocity at distance y from the bed, k is von Karman's constant, A is a constant that is experimentally found to be 30.1 for rough beds having roughness of y_o. A bed is rough when the height of the roughness elements begin to compare with the thickness of the viscous layer at the bed (i.e., 11.6 ν/U_*.)

Karman's constant is 0.4 for clear water, but at high concentrations of suspended sediment, the sediment alters the velocity profile. Attachments #10, #11 show this effect. Notice that the velocities are higher in the upper regions of the flow. Apparently the presence of high concentrations of suspended solids near the bed inhibits the upward propagation of mixing.

V. Suspended Sediment Concentration Profiles

Rouse (1937) derived a vertical concentration profile from the one-dimensional diffusion equation and a simplified model of vertical mixing in open channel flow. His equation is

$$\frac{c}{c_a} = \left[\frac{d-y}{y}\ \frac{a}{d-a}\right]^z \tag{9a}$$

$$z = w/kU_* \tag{9b}$$

where c is the suspended sediment concentration at y, and c_a is the concentration at y = a. Equation 9 shows that the concentration at any elevation above the bed increases <u>to the power proportional to w</u>. The settling velocity is therefore

a very important parameter!

COHESIVE SEDIMENTS

Ref: Mitchell, J.K. Fundamentals of Soil Behavior, J. Wiley, 1976.

I. Composition

A. Clay and silt minerals are the dominant components of cohesive sediments. Algae are the next most common constituents followed by bacteria and other organic material.

B. These particles are small. Gravitational forces are consequently small and settling velocities are low.

C. Sediment loads in typical lowland streams are largely composed of these materials: wash loads make up to 90 percent of the loads of many streams.

D. These particles can be either cohesive or non-cohesive, depending on the dissolved salt composition and concentration of the stream waters.

II. Clay Minerals

A. There are three principal clay mineral groups. Their important properties are summarized in the following table:

HEC-6: RESERVOIR SEDIMENT CONTROL APPLICATIONS[1]

<u>Caveat:</u> "*... the choice of a model at this time is arbitrary, and the choice of a modeler is probably more important than the choice of a model.*" (Dawdy and Vanoni 1986)

1. Some History of HEC-6 Development and Applications.[2] The following list summarizes efforts of the Corps' Waterways Experiment Station (WES) and Hydrologic Engineering Center (HEC). Numerous research and project applications of HEC-6 have been performed by other Corps' offices, government agencies, private consultants, universities, and foreign countries that are not reported here.

- The "Time Sequencing Method" of scour and deposition calculations was developed at the Little Rock District of the Corps of Engineers in 1967 by Tony Thomas; it lead to the development of HEC-6. The motivation for that effort was to confirm land acquisition requirements for Ozark Reservoir on the Arkansas River, recognizing potential future (50-year) sedimentation.

- The next major development was made at HEC for the Walla Walla District in the early 70's. The need was to predict future water surface elevations for levees at Lewiston ID on Lower Granite Reservoir. The incorporation of bed material sorting and armoring and expansion of transport of grain sizes up to 64mm was done at this time.

- First complete documentation published by HEC for "Scour and Deposition in Rivers and Reservoirs", 1973.

- First HEC "Sediment Transport" training course presented, 1973.

- The third major development was made in 1974 for the Fort Worth District. They needed to predict future maintenance dredging on the proposed Trinity River Navigation Project which consisted of 22 locks and dams in series. Silt and clay were the dominant sediment classes. The code was modified to handle a system of locks and dams and to transport, deposit, and consolidate clays and silts.

- Comparison of model results with laboratory flume data (Thomas and Prasuhn 1977).

- Use for analysis of scour of sediment deposits after removal of a dam (HEC 1977).

---

[1] Prepared by D. Michael Gee, Research Hydraulic Engineer, Hydrologic Engineering Center, 609 2nd St., Davis, California 95616.

[2] Contributions to this section by Tony Thomas of WES are gratefully acknowledged.

- "Scour and Deposition in Rivers and Reservoirs" is designated as "HEC-6", publication of user's manual and public release of the model, 1977.

- The next major development was made for the Walla Walla District in 1978 to handle a dendritic network of streams. This led to the "Network Version" developed by WES.

- Addition of gravel mining capability at HEC, 1980.

- Addition of graphics using HEC-HGP (Hydraulics Graphics Package), 1980.

- The next major development was made for Mt. St. Helens studies on the Toutle and Cowlitz rivers for the Portland District during 1980-1985. Several transport functions were added to the model and the capability of including the effect of high concentrations of fines on the transport of sands using Colby's correction factor was added. A normal depth approximation to supercritical flow was developed. These enhancements were made to the Network Version which was given the name "TABS-1" and became the research version of the model at WES.

- Publication of HEC Training Document No. 13, "Guidelines for the Calibration and Application of Computer Program HEC-6", 1981.

- Application to the Arkansas River, CO - simulation of irrigation diversions and use of HEC-DSS for hydrologic data management (Gee 1983).

- Release by HEC of a microcomputer (PC) version of HEC-6, 1985.

- Addition of cohesive sediment erosion algorithms. This was initially made to TABS-1 for Vicksburg District studies of the Red River Navigation Project in 1986.

- Implementation of a commercial vendor system by HEC for software distribution and support outside of the Federal Government, 1988.

- The next major development of TABS-1 was made for studies of the Richard B. Russell Reservoir pump-back hydropower project by the Savannah District. This modification changed geometry files from sequential storage to random access storage.

- A major enhancement was made to TABS-1 for dredging studies in the lower Mississippi River for the New Orleans District in 1991. The rate of dredging could be prescribed as well as the location of the out-fall discharge.

- Documentation and public release of a network version, based on TABS-1, of HEC-6 by HEC, 1991.

- Major update of TD-13, 1992.

- Update of user's manual, 1993.

- Ongoing work at WES with TABS-1 involves coupling of the sediment transport algorithms

with the UNET unsteady flow program. It is planned to include the results of this work in the HEC NexGen River Analysis System currently undergoing design and development.

2. HEC-6 Description.

HEC-6 (HEC 1991) is a one-dimensional movable boundary open channel flow and sediment movement model designed to simulate changes in river profiles due to scour and deposition over fairly long time periods (typically years, although applications to single flood events are possible). The continuous flow record is broken into a sequence of steady flows of variable discharge and duration (see Figure 1). For each flow a water surface profile is calculated (using steady flow standard-step backwater computations) thereby providing energy slope, velocity, depth, etc. at each cross section. Potential sediment transport rates are then computed at each section for the given bed material grain size distribution. These rates, combined with the duration of the flow allow for a volumetric accounting of sediment for each reach. The amount of scour or deposition at each section is then computed and the cross section shape adjusted accordingly (Figure 2). The computations then proceed to the next flow in the sequence and the computation cycle is repeated beginning with the updated geometry. The sediment calculations are performed by grain size fraction thereby allowing for the simulation of hydraulic sorting and armoring. Features of the model include: capability to analyze networks of streams (Figure 3), automatic channel dredging, various levee and encroachment options, and several options for computation of sediment transport rates.

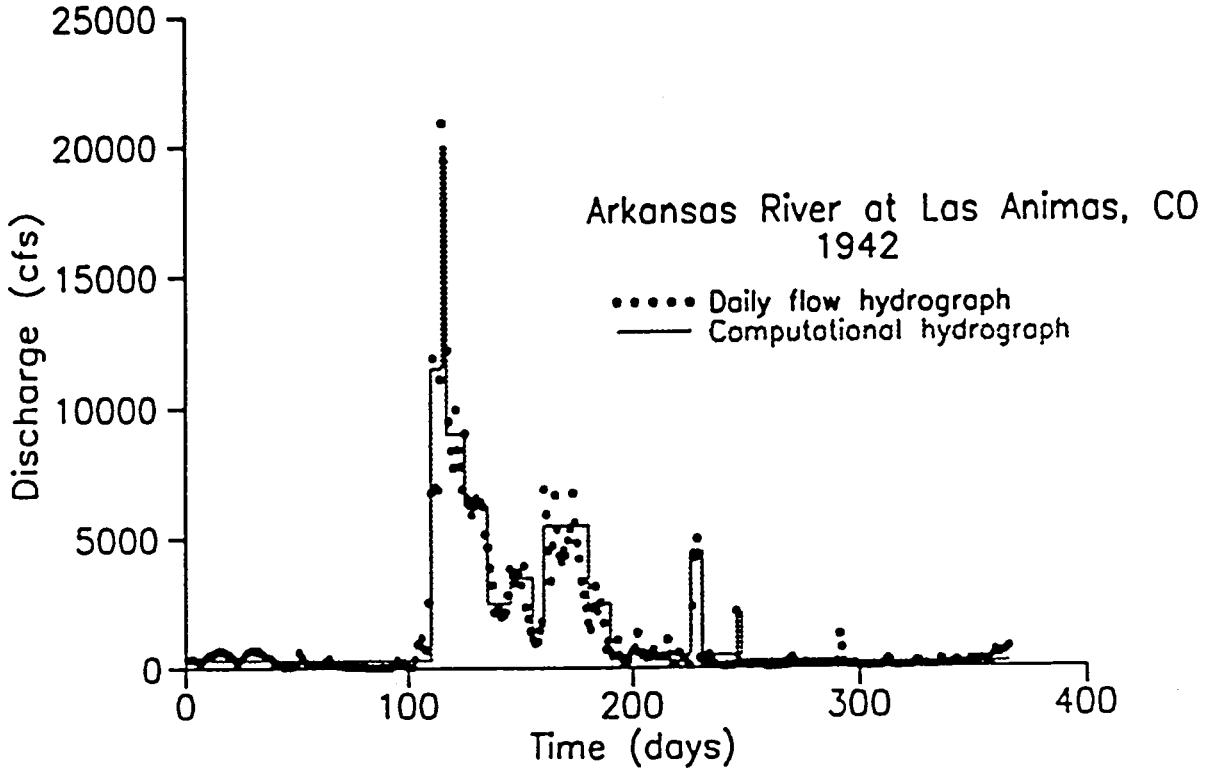


Figure 1.
Flow Data Compression.

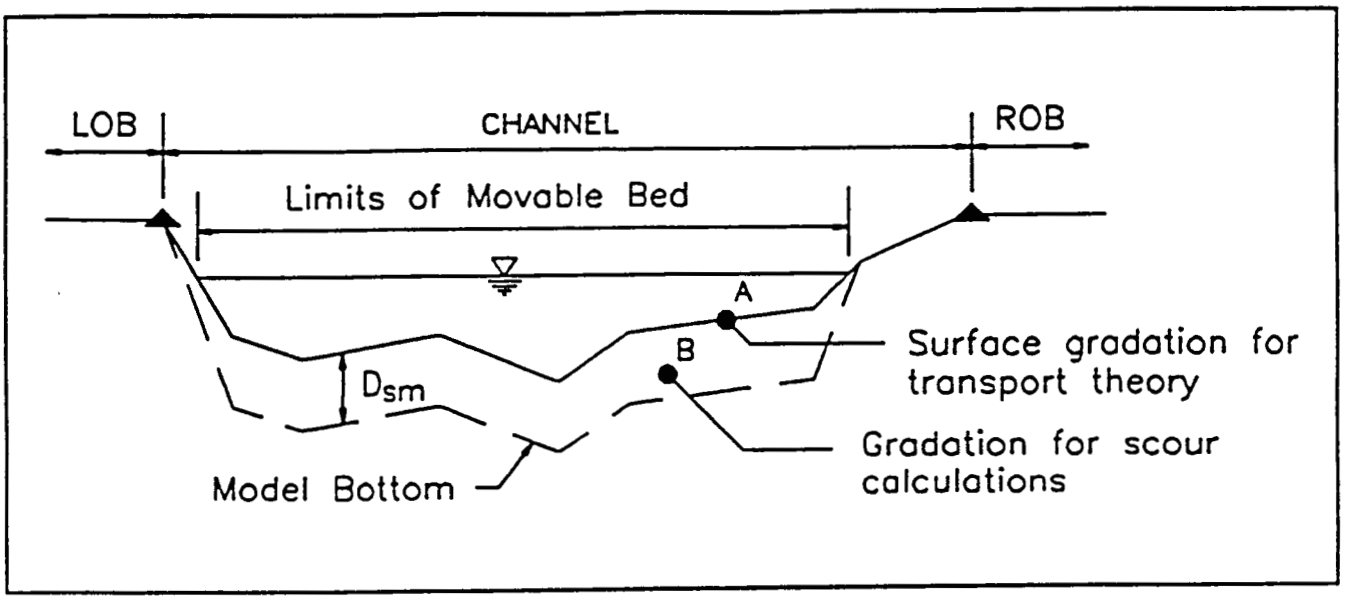


Figure 2 HEC-6 Cross Section Adjustment

HEC-6 (HEC 1991) is a movable boundary model. It was formulated around Einstein's basic concepts (Einstein 1950) of sediment transport; however, it is designed for the non-equilibrium case. Einstein did not address the non-equilibrium condition, but his "particle exchange" concept was extended in HEC-6 by noting that when sediment is in transport there will be a continual exchange between particles in motion and particles on the bed surface. The residue in the bed may be measurable, as in the case of the "bed material load", or it may be unmeasurable, as in the case of "wash load". The stability of particles on the bed surface may be related to inertia, as in the case of non-cohesive particles; or that stability may be primarily electrochemical, as in the case of cohesive particles. Energy forces acting to entrain a particle may be primarily gravity induced, as in the case of flow in inland rivers; or the forces may be combinations of energy sources such as gravity, tides, waves, and density currents, as in the coastal zone. Different types of sediment require different entrainment functions depending upon the propensity of the sediment to change hydrodynamic and physical properties of the flow and upon the sensitivity of the sediment type to water temperature and chemistry.

a. Equations of flow. The equations for conservation of energy and water mass are simplified by eliminating the time derivative from the motion equation which leaves the gradually varied steady flow equation. It is solved using the standard-step method for water surface profiles. The following terms are

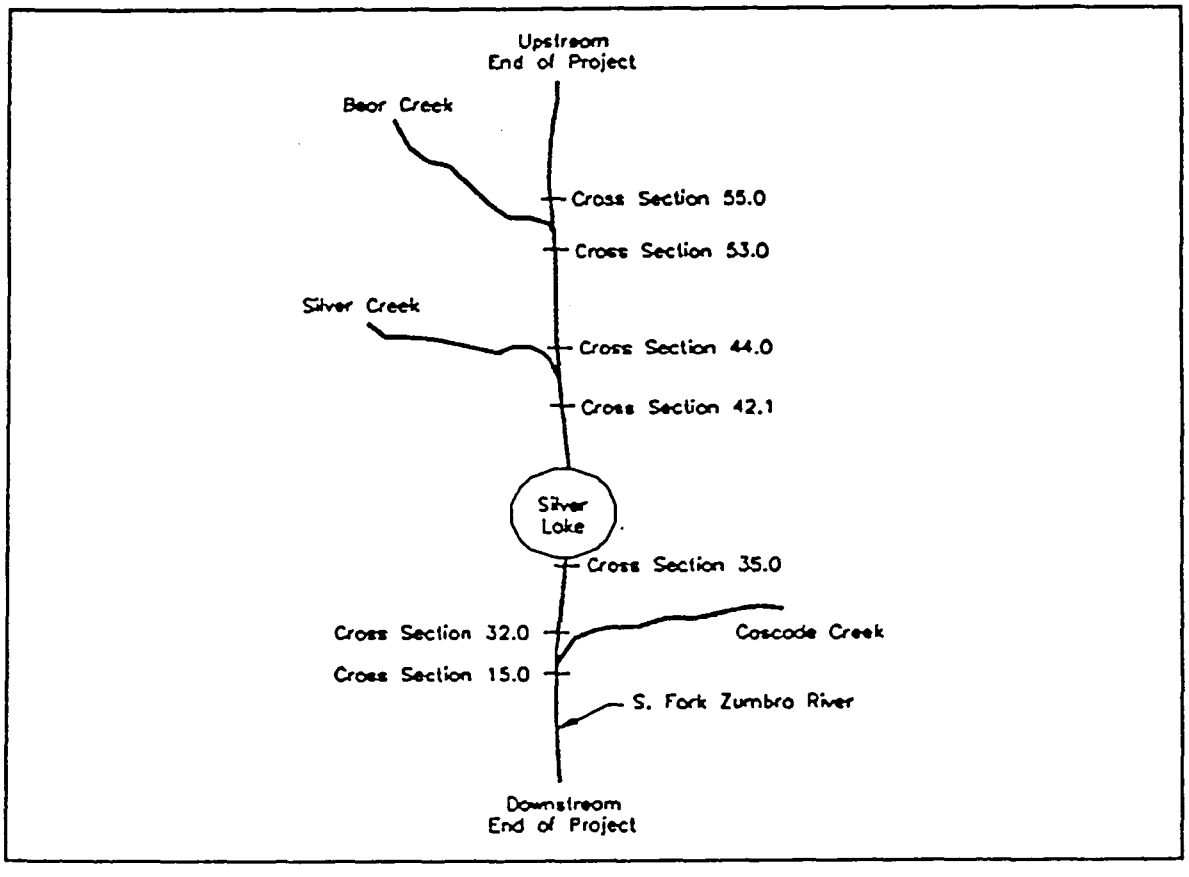


Figure 3 Example Stream System Network

included:

$$\frac{h}{x} = \frac{(U^2/2g)}{x} = S_e \qquad \text{(conservation of energy)} \quad (1)$$

where

g	=	acceleration due to gravity
h	=	water surface elevation
S_e	=	slope of energy line
U	=	flow velocity
x	=	distance in the direction of flow
□	=	correction for transverse distribution of flow velocity

$$Q = UA + Q_1 \qquad \text{(conservation of water)} \quad (2)$$

where

A	=	cross-sectional area of flow
Q_1	=	lateral or tributary inflow
Q	=	main stem water discharge downstream from Q_1
U	=	main stem mean water velocity upstream from Q_1

b. Friction and form losses. Both friction and form losses are included in S_e; bed roughness is prescribed with Manning *n* values. *n* values may vary with water discharge, location, or be related to bed material size (Limerinos 1970).

c. Equation of sediment continuity. The Exner equation is used for conservation of sediment:

$$\frac{Q_s}{x} + B_s\frac{Y_s}{t} + q_s = 0 \qquad \text{(conservation of sediment)} \quad (3)$$

where

B_s	=	width of bed sediment control volume
Q_s	=	volumetric sediment discharge rate
q_s	=	lateral or tributary sediment discharge rate
t	=	time
Y_s	=	bed surface elevation

d. Equation of sediment transport. Einstein's (Einstein 1950) work is definitive and presents a complete view of the processes of equilibrium sediment transportation; it, however, has been more useful for understanding those processes than for application, partially because of the numerical complexity of the computations. Many other researchers have contributed sediment transport functions - always attempting to develop one which is reliable when compared with a variety of field data. The resulting functions are numerous, yet no single function has proved superior to the others for all conditions. Therefore, the following

functional form is presented here to show the importance of various parameters.

$$G = f\,(U,\ d,\ S_e\ ,\ B,\ D_{eff}\ ,\ SG_s\ ,\ G_{sf}\ ,\ D_{si}\ ,\ P_i\ ,\ SG_f\ ,\ T,\ \ldots) \qquad \text{(Sediment Transport)} \quad (4)$$

where:

B	=	effective width of flow
d	=	effective depth of flow
D_{eff}	=	effective particle diameter of the mixture
D_{si}	=	geometric mean of particle diameters in each size class i
G	=	total bed material discharge rate in units of weight/time (e.g., tons/day)
G_{sf}	=	grain shape factor
P_i	=	fraction of particles of the ith size class that are found in the bed
S_e	=	slope of energy grade line
SG_f	=	specific gravity of fluid
SG_s	=	specific gravity of sediment particles
T	=	water temperature
U	=	flow velocity

Sediment transport rates are calculated for grain sizes up to 64 mm (soon to be expanded to 2000 mm). Sediment sizes larger than 64 mm, that may exist in the bed, are used for sorting computations but are not transported. For deposition and erosion of clay and silt sizes up to 0.0625 mm Krone's (1962) method is used for deposition and Ariathurai's (1976) adaptation of Parthenaides' (1965) method is used for scour. The default for clay and silt allows only deposition using a method based on settling velocity.

The sediment transport function for bed material load is selected by the user. Transport functions available in the program include the following:

a. Toffaleti's (1966) transport function
b. Madden's (1963) modification of Laursen's (1958) relationship
c. Yang's (1973) stream power for sands
d. Duboys transport function (Vanoni 1975)
e. Ackers-White (1973) transport function
f. Colby (1964) transport function
g. Toffaleti (1966) and Schoklitsch (1930) combination
h. Meyer-Peter and Müller (1948)
i. Toffaleti and Meyer-Peter and Müller combination
j. Madden's (1985, unpublished) modification of Laursen's (1958) relationship
k. Parthenaides (1965), Ariathurai (1976) and Krone (1962) for cohesive sediments
l. Copeland's (1990) modification of Laursen's relationship (Copeland and Thomas 1989)
m. User specification of transport coefficients based upon observed data

e. Computational methodology. Descriptions of the computational methodology used in HEC-6 and application of the program are presented in the HEC-6 user's manual (HEC 1991).

Experience has shown that successful application of movable boundary models may require substantial effort to reproduce field observations, i.e., calibration. The general topic of application and calibration of

numerical river models is thoroughly covered in Cunge, et al. (1980).

3. **Specific Reservoir Simulation Capabilities.**

- User can specify water surface elevations (internal boundary conditions) to simulate operation and control of reservoir pool elevations as functions of time.
- Allows for deposition and compaction of cohesive sediments with time.
- Provides for reentrainment of cohesive sediments based on equations presented by Parthenaides (1965).
- Can simulate deposition at various pool levels and, therefore, compute impacts of reservoir deposits on upstream water surface profiles.
- Has a "parallel flow" capability, which means that several discharges in the time series of flows can be modeled without updating boundary geometry - achieves computational efficiency.
- Can compute trap efficiencies and perform volumetric accounting of sediment by grain size.

4. **Some Limitations of HEC-6 with Regard to Reservoirs.**

- It is a one-dimensional model.
- Density variations due to thermal stratification or sediment concentrations are not included in the hydraulics.
- Modeling of the structure is limited by what the user can do with cross sections and water surface elevations.

5. **Some Additional HEC and Corps of Engineers Software for Reservoir Analysis.**

- HEC-5 "Simulation of Flood Control And Conservation Systems" (HEC 1982).
- HEC-5Q "Simulation of Flood Control and Conservation Systems - Appendix on Water Quality Analysis" (HEC 1986).
- HEC-PRM "Prescriptive Reservoir System Analysis Model - Missouri River System Application" (HEC Technical Paper No. 136 Nov. 1991).
- HEC NexGen project.
- TABS-2 "Open Channel Flow and Sedimentation," two-dimensional flow and sediment modeling system (vertically averaged).

a. Purpose. The purpose of the TABS-2 system (Thomas and McAnally, 1985) is to provide a complete set of generalized computer programs for two-dimensional numerical modeling of open-channel flow, transport processes, and sedimentation. These processes are modeled to help analyze hydraulic

engineering and environmental conditions in waterways. The system is designed to be used by engineers and scientists who need not be computer experts.

b. Description. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation processes in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure 4.

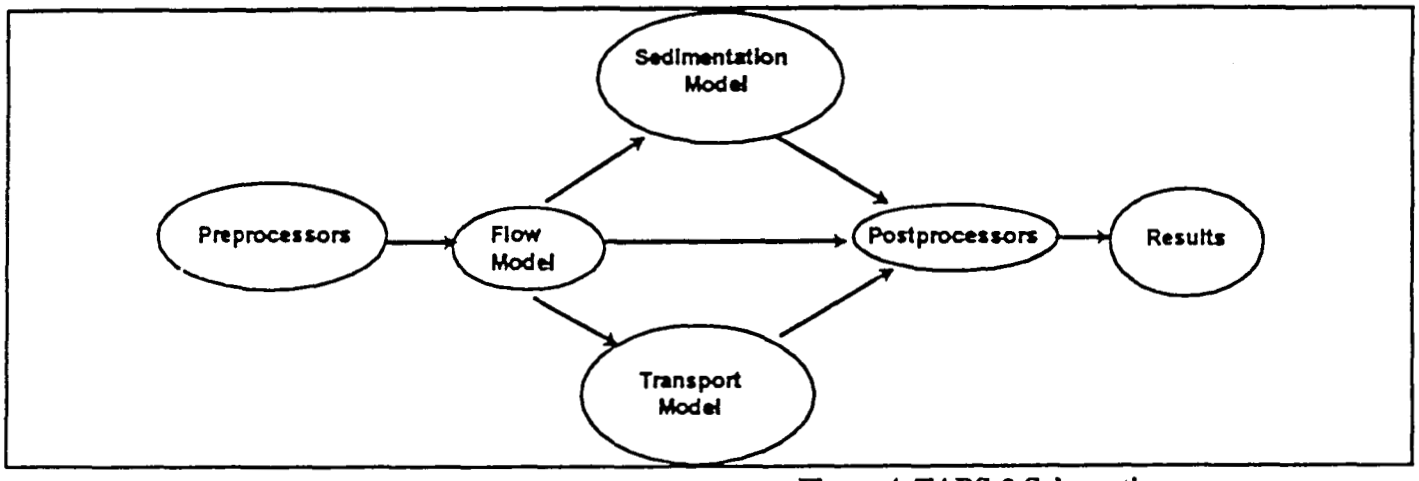


Figure 4 TABS-2 Schematic

c. Uses. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, dispersive transport, sediment erosion, transport and deposition, resulting bed surface elevations, and feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact of project designs on flows, sedimentation, and salinity. The calculated velocity pattern around structures and islands is particularly useful.

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SUMMARY OF HEC-6 CAPABILITIES AND LIMITATIONS

Capabilities

1. One-Dimensional
2. Movable Boundary
3. Steady State Open Channel Flow
4. Continuous sequence of flows segmented into a series of steady state flow events
5. Standard Step Backwater Computations
6. Sediment transport rates computed at each section
7. Volumetric accounting of each sediment size in each reach (between cross sections)
8. Amount of scour or deposition is computed for each reach and cross section geometry is adjusted after flow event
9. Sediment calculations are done by grain size fraction
10. Allows for simulation of hydraulic sorting and armoring

SUMMARY OF HEC-6 CAPABILITIES AND LIMITATIONS

Limitations

1. One-Dimensional

2. Sequence of steady state and equilibrium conditions

3. Meanders not considered

4. Bank widening not considered

5. River Network Constrains

    a. Sediment transport in distributaries not possible

    b. Flow around islands (closed loops) cannot be simulated directly

    c. Only one junction or control point is allowed between adjacent cross sections

6. Split flow cannot be simulated

7. Supercritical flow is approximated by normal depth

June 1988
Michael Gee

DATA REQUIREMENTS FOR HEC-6

Definitions:

INPUT (or RUN) DATA: The data needed to operate a computer program.

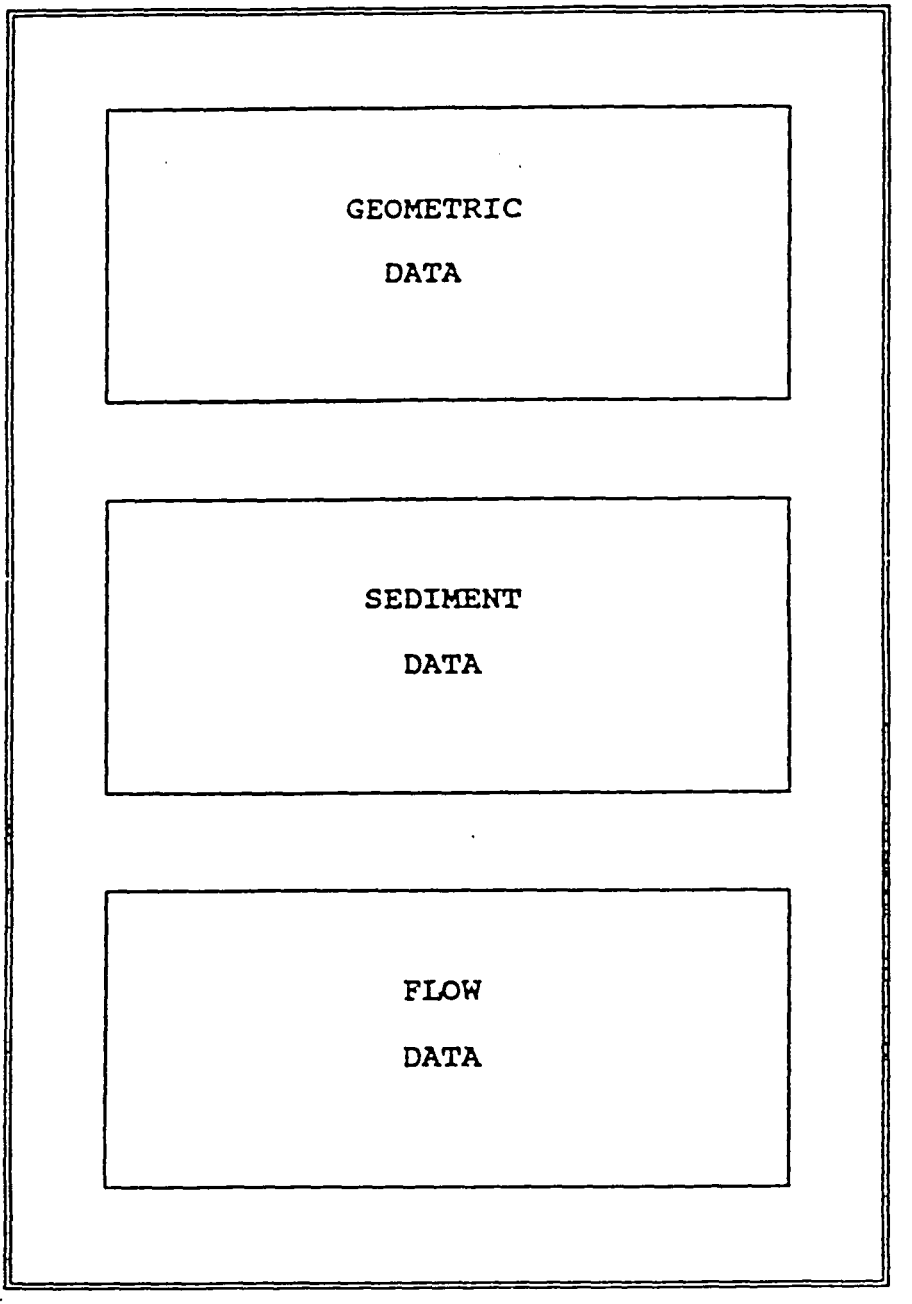
CALIBRATION DATA: Field data or observations used to evaluate the performance of a model and adjust model parameters if necessary.

VERIFICATION DATA: Additional field data, not used to calibrate the model parameters, used to verify that the model performs adequately under conditions other than those for which it was calibrated.

Objective:

The objective of this lecture is to describe the required input data for HEC-6.

HEC-6 Input Data File Structure



NOTE: The geometric and sediment data apply to time zero; that is, the beginning of the simulation.

GEOMETRIC DATA

Item:	Records:	Source(s):
Cross sections,	X1,X3,GR	Field surveys, topo maps, HEC-2 data sets.

NOTE: Cross sections selected for HEC-2 may not be optimal for HEC-6. The difference is between hydraulic conveyance controls and reach-averaged sediment transport characteristics.

Boundary roughness:	NC,NV	Field estimation and calibration.

NOTE: Boundary roughness is described by Manning's relation in HEC-6. It may vary with distance, elevation, or discharge; but is not directly coupled with the sediment transport as in the Einstein-Barbarossa approach.

Expansion-Contraction Losses:	NC	Field estimation and calibration.
Channel subdivisions:	X1	Field estimation and calibration.
Bed width:	H	Field estimation and calibration.

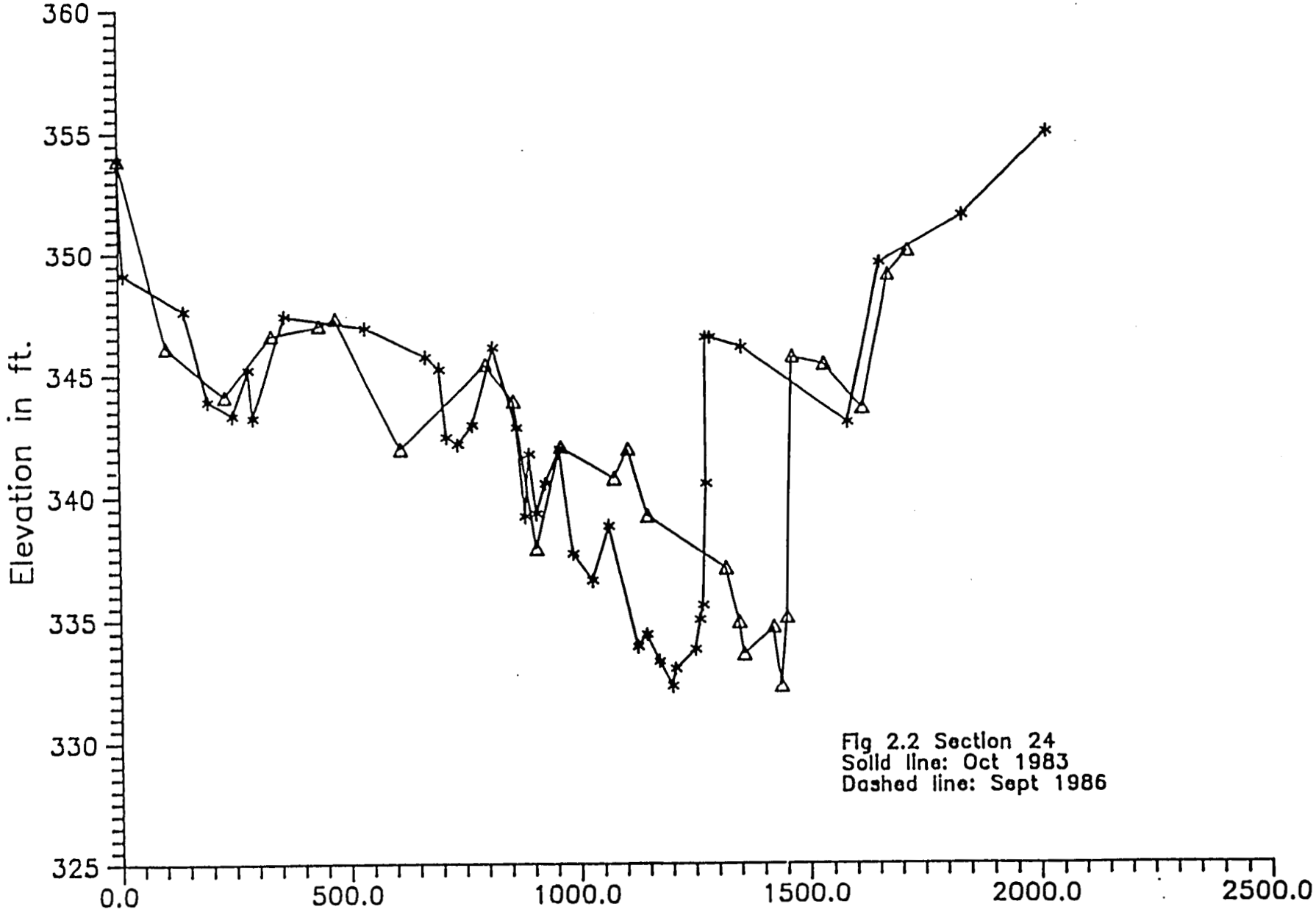


Fig 2.2 Section 24
Solid line: Oct 1983
Dashed line: Sept 1986

SEDIMENT DATA

Item:	Records:	Source(s):
Sediment properties:	I1-I4	Field estimation.
Grain sizes:	I1-I4	Determined from field samples/measurements.

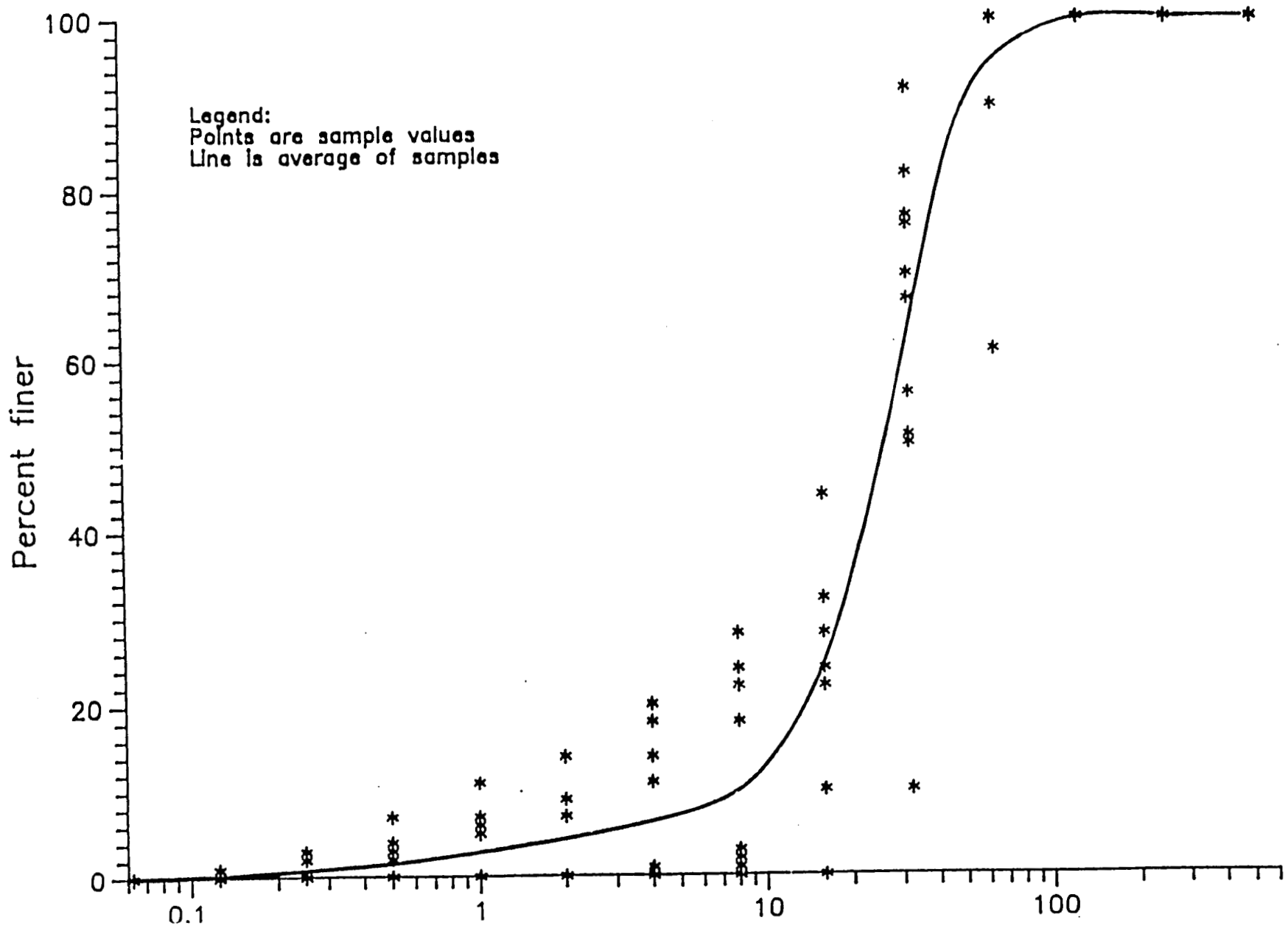
NOTE: The number of grain sizes selected on the I1-I4 records governs the L and N records.

Transport function:	I4	User selected.
Weighting factors:	I5	Computational smoothing.
Inflowing sediment:	L	Field measurements and/or calculation (e.g. use of the CORPS system), input as a function of water discharge.

NOTE: Need grain size distribution of the inflowing sediment load. Typically this is the gradation of the bed material load (not the same as that of the bed material); for open rivers wash load can be neglected, for reservoirs, however, wash load may be dominant.

Bed material gradation:	N	Field sampling.

NOTE: A bed material gradation must be supplied at each cross section; experience has shown, however, that smoothing the changes in gradation from section to section will aid the HEC-6 solution.


Legend:
Points are sample values
Line is average of samples
Percent finer
100
80
60
40
20
0
0.1
1
10
100

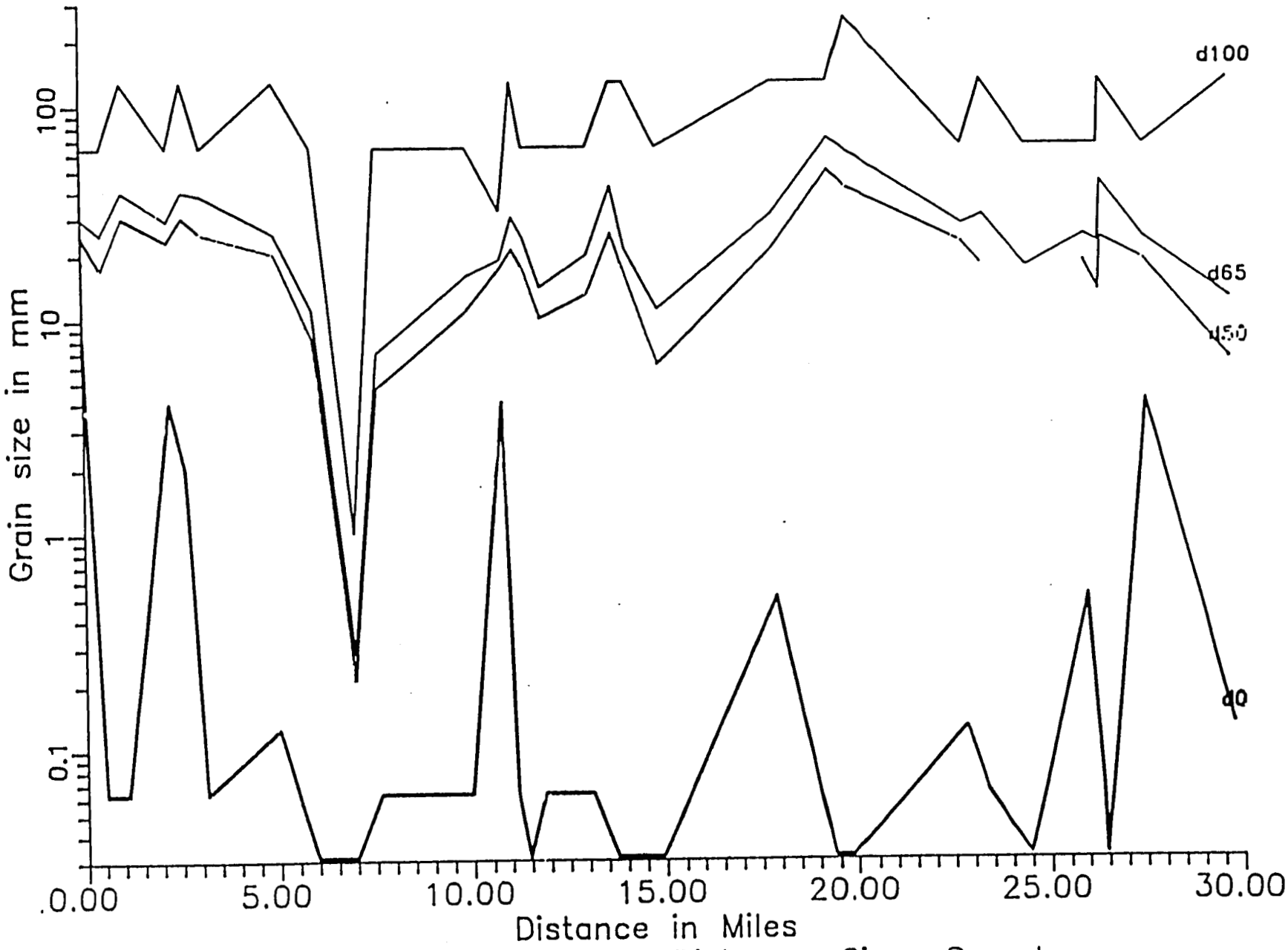
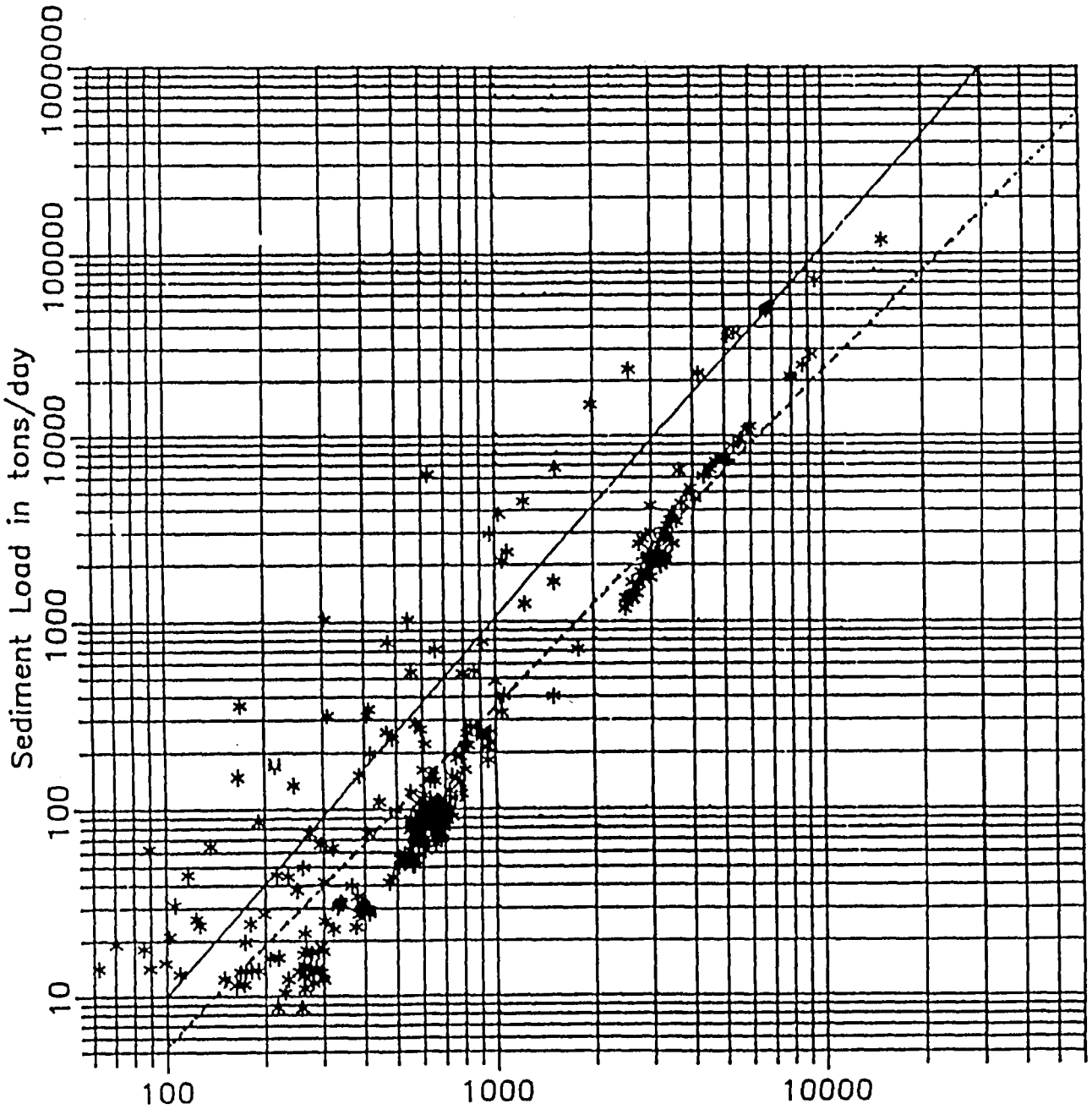


Fig. 3.1 Bed Material Size Distribution vs. Distance, Sieve Samples



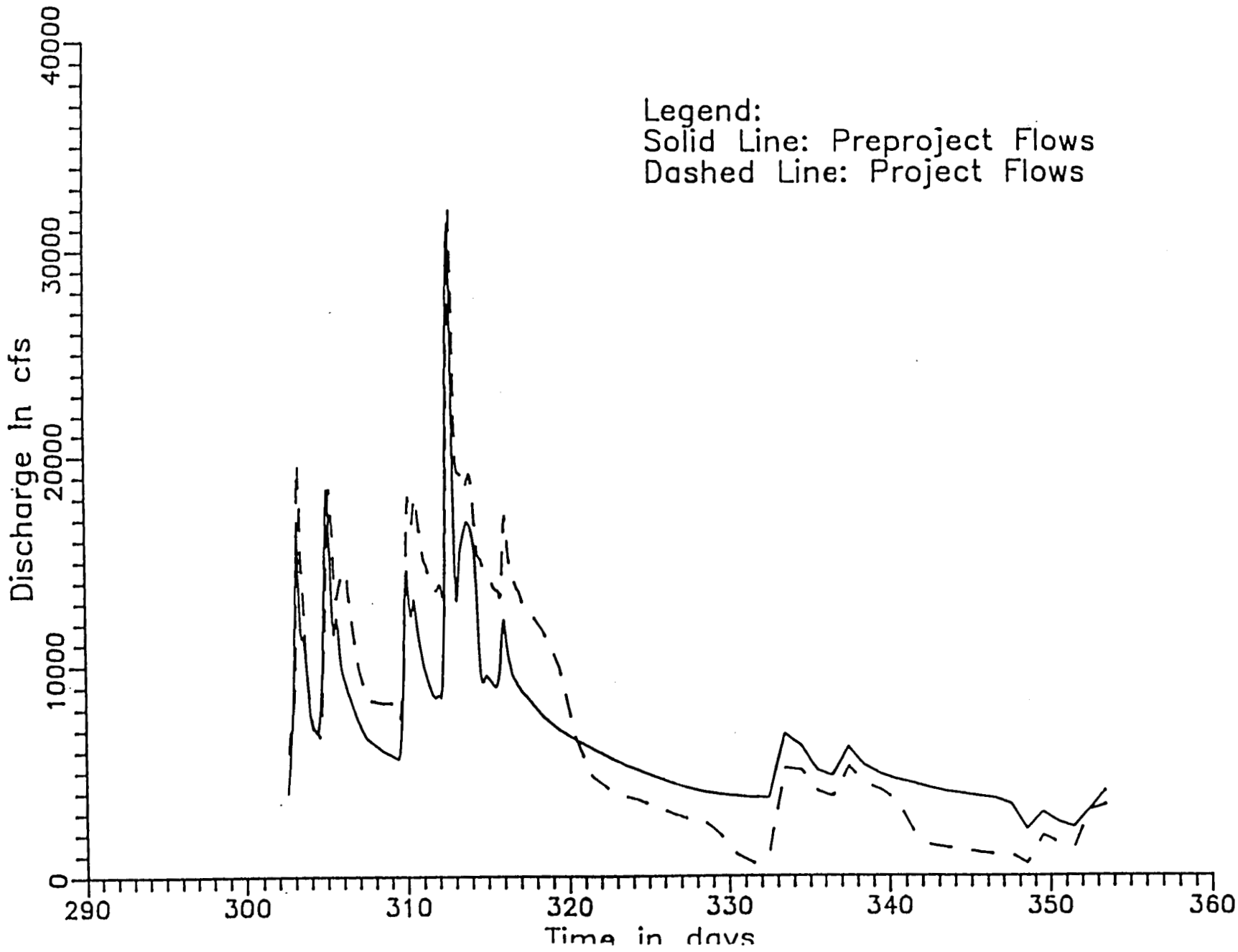
Legend:
Points are USGS samples
Line: 1977 COE relation
Dashes: 1987 HEC relation

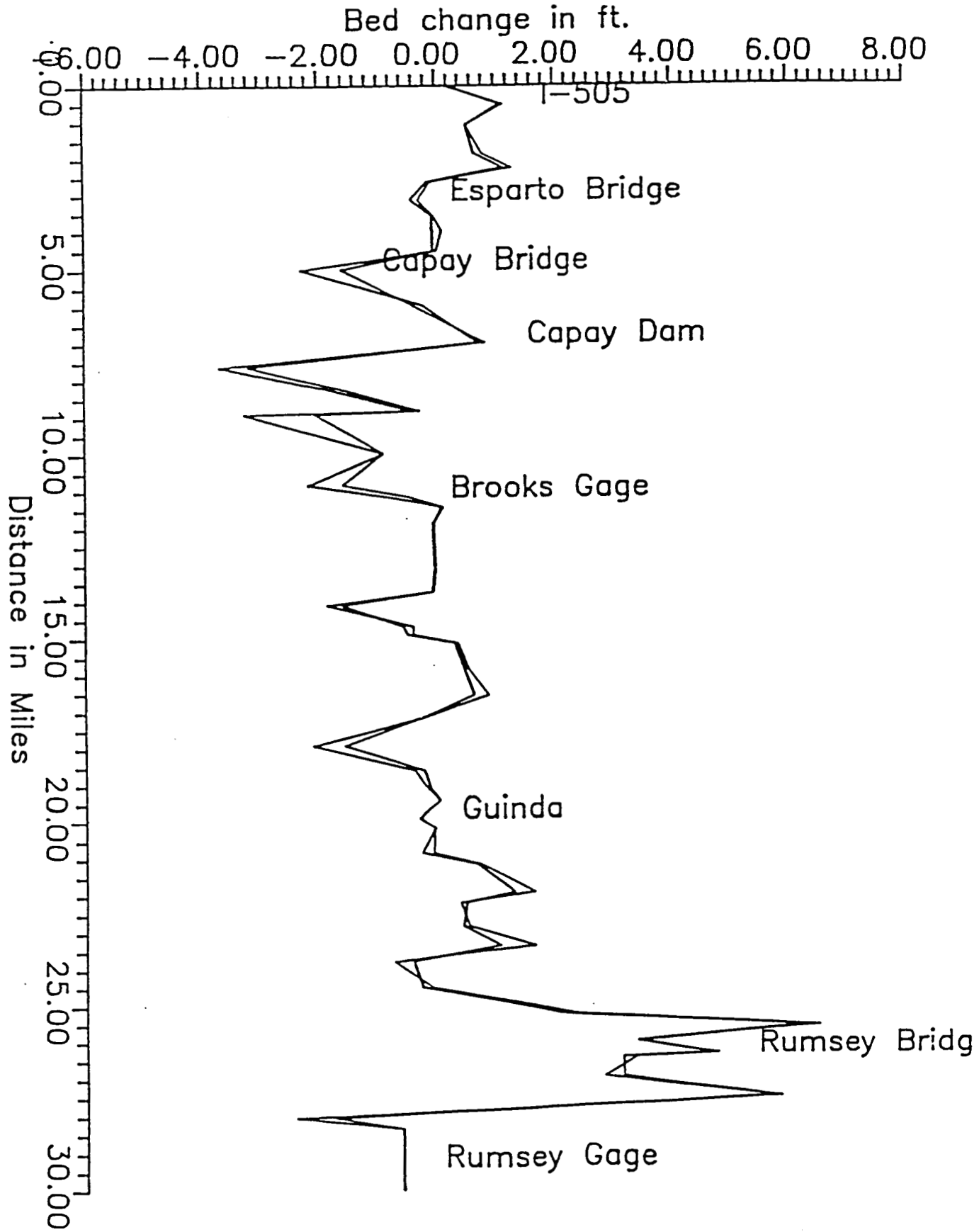
FLOW DATA

Item:	Records:	Source(s):
Print/plot control,	*	User selected; data will be saved for plotting at times that a "B" level sediment print is requested.
Water surface elevation or rating curve,	R,RC	Gage data, uniform flow computations.
Water discharge,	Q	Flow records; continuous, flow-duration, or stochastic.
Time interval	W	User developed.

NOTE: Time intervals may vary; smaller time intervals yield better results but take more computer time. Several methodologies have been developed for compression of flow records. Time intervals must be selected to preserve inflowing sediment volume.

Water temperature	T	Flow records.


Legend:
Solid Line: Preproject Flows
Dashed Line: Project Flows
Discharge in cfs
0
10000
20000
30000
40000
290
300
310
320
330
340
350
360
Time in days


Bed change in ft.
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00
8.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Distance in Miles
I-505
Esparto Bridge
Capay Bridge
Capay Dam
Brooks Gage
Guinda
Rumsey Bridg
Rumsey Gage

SUMMARY OF RECORD SEQUENCE FOR HEC-6

1. TITLE RECORDS (required): T1-T3

2. GEOMETRIC DATA

   A. Manning's n (required unless repeated) - NC, NV (also can adjust by $KI and $KL - see Hydrologic data)

   B. QT - (optional) used for tributary discharges

   C. X1 - (required) start of a cross section

   D. X3 - (optional) ineffective flow - note: similar but not the same as X3 of HEC-2

   E. X5 - (optional) internal boundary condition specification; adjusts water surface elevations - note: not the same as X5 of HEC-2

   F. XL - (optional) conveyance limits

   G. GR - (required unless repeated) ground stations and elevations

   H. H or HD (required) sediment reservoir determination, dredging limits

   I. EJ - (required at end of segment geometric data) end of geometry

   J. $TRIB - (optional unless simulation of tributaries) identifies start of tributary geometry

   K. CP - (required if $TRIB is used) indicates location of tributary within network

SUMMARY OF RECORD SEQUENCE FOR HEC-6 (continued)

3. SEDIMENT DATA

A. T4-T8 - (required) title records

B. I1 - (required) sediment properties and selection of transport method

C. I2 - (required for clay transport) clay properties

D. I3 - (required for silt transport) silt properties and number of size fractions

E. I4 - (required for sand transport) sand properties and number of size fractions

F. I5 - (optional) weighing factors for computations

G. J and K - (optional) user specified transport relation

H. LQ - (required) discharge for inflowing load

I. LT - (required) total load for inflowing load

J. LF - (required) fraction of total load for each grain size

K. PF (or N) - (required) bed gradation

L. $LOCAL - (optional) identifies inflowing load records for local inflows or diversions

M. LQL, LTL, LFL - (optional) same as LQ, LT, and LF but for local inflows and diversions

SUMMARY OF RECORD SEQUENCE FOR HEC-6 (continued)

4. HYDROLOGIC DATA (continued)

L. VJ, VR - (optional) used in conjunction with $VOL, specifies elevation intervals for computations

M. * - (required) indicates a set of information is to follow for a single discharge

N. Q - (required) discharge

O. R - (required if rating curve is not specified) downstream water surface elevation for specified discharge

P. S - (optional) shifts water surface elevation

Q. T - (required for first discharge) water temperature

R. W - (required unless X record is used) duration of discharge

S. X - (optional) discharge duration and computational increment

T. $$END - (required) end of hydrologic data

INTERPRETATION OF RESULTS FROM HEC-6

Objective: to present the types of information which may be printed out and to illustrate how to interpret the calculated results.

1. Geometric data

   A. Normal printout

   B. B-level printout

   C. D-level printout (trace)

   D. END OF GEOMETRIC DATA

2. Sediment data

   A. Normal printout

   B. B-level printout

   C. C-level printout (trace)

   D. END OF SEDIMENT DATA

3. Hydrologic data

   A. The desired level of printout must be specified - the default is "NO PRINTOUT".

B. Hydraulic calculations. Request an A-level printout on the first event to aid in debugging the data deck.

C. Sediment calculations. Request an A-level printout for volumes. If bed change and sediment loads are desired, request a B-level. All values are calculated whether or not a printout is requested.

D. END OF JOB

4. Interpretation of calculated results

The most common printout levels are "none" in hydraulic calculations and B-level in sediment calculations. However, when debugging a new data deck it is useful to have an A-level printout in hydraulic calculations. For this reason both are described below.

A. "N" is the discharge number when making parallel calculations

B. "Discharge" is the prescribed water discharge

C. "Water surface" is the calculated water surface elevation

D. "Energy Line" and "Velocity head" are self explanatory

E. "Alpha" is the horizontal velocity distribution factor

F. "Top width" is total water surface width

G. "Avg bed" is the water surface elevation minus the hydraulic depth

H. "Avg velocity in subsection 1 2 3 ... 7" are the average velocity values in each subsection (i.e., left overbank, channel, right overbank)

I. "Accumulated days" is the number of days since time zero

J. "Inflow" and "Outflow" are the accumulated volume of sediment

K. "Bed change" is the accumulated amount since time zero

L. "W. S. Elev" is the water surface elevation for the stream bed profile at the beginning of the event being analyzed

M. "Thalweg el" is the lowest elevation in cross section at the end of the event being analyzed

N. "Water discharge" self explanatory

O. "Sediment load" is the amount of clay, silt, or sand that is passing the cross section, identified in column 1, expressed in tons/day

OUTPUT SPECIFICATION

FIELD 1		FIELDS 2-10	
COLUMN 1 2 3 4 5 6 7 8 * HY SED		TITLE	
$PRT	N-off A-on		
CP			
PN	(COMMENT)	XSECTION#	XSECTION#
END			

H-889

Workshop 1

Using HEC-6 on the PC (Fixed Bed Mode)

DEVELOPMENT OF HYDROLOGIC DATA FOR HEC-6

References: [1] HEC-6 User's Manual

Objective: The student demonstrates skill in coding Hydrologic Data, executing the program and reading the output.

1. END PRODUCT

The end product is an example execution.

2. PROCEDURE

2.1 **Summary of Tasks.** Locate the basic HEC-2 data file provided for this workshop. (A copy is shown below.) Modify the HEC-2 file to incorporate the additional data required to execute HEC-6. Execute the job and provide the interpretations requested below.

2.2 **HEC-2 Input Data File.**

```
T1 WORKSHOP PROBLEM 1  MONDAY
T2 COED YOUR TEAM NO, NAMES, DATE, AND DESCRIPTIVE INFO FOR THIS WORKSHOP HERE
T3 WORKSHOP TO DEMONSTRATE THE APPLICATION OF HEC-6 IN A FIXED BED MODE.
NC  .080    .080     .03      .3      .5
X1  0.67      20             653
GR 743.1       0     710      68     710     120   710.2     150   709.1     178
GR 711.6     214   711.9     264   710.5     320     709     360     707     390
GR   706     415   703.3     450   703.1     492     702     530   703.9     570
GR 703.1     610     705     635     711     647     715     649   743.1     653
X1   .78      19             696     590     590     590
GR 743.1       0   711.5      62   710.3      78   711.7     102   710.9     137
GR   711     173   712.5     208   714.6     270   713.3     320   711.3     340
GR 708.8     402   707.3     458   706.3     475     706     493   705.3     513
GR   706     558   707.8     611     709     625   743.1     696
X1   .92      13     710    1122    1690    1690    1690
GR 743.1       0     717      53     717     550     715     673     735     710
GR 707.5     740   707.9     780   706.7     840   706.8     878   708.2     910
GR 708.8     990   707.4    1046   743.1    1122
X1  1.16      17    1040    1593    2290    2290    2290
GR 743.3       0     717      52     717     964     715    1008     730    1040
GR   710    1074     708    1080   708.1    1140   707.9    1190   708.2    1230
GR   710    1304   711.7    1324   713.5    1360     715    1395     717    1450
GR   717    1540   743.3    1593
EJ
```

A. **Geometric Data Set:**

H-record Add an H-record after each cross section data set.
X3-record An ineffective area record is always recommended even though it is not required for the program to execute.

B. **Sediment Data Set:**

Omit for a fixed bed execution.

C. **Hydrologic Data Set:**

Run the 2 events shown below.

Discharge CFS	Starting Water Surface Elevation
25,000	710
50,000	715

D. **Fluid Properties:**

T-record Water temperature, Degrees F, is not needed for a fixed-bed execution.

3. READING THE OUTPUT

Use your output to answer the following questions.

3.1 Geometric Data.

Were any "error or diagnostic" messages indicated as the program read and processed the Geometric Data Set?

Why is "NO OF CROSS SECTIONS READ IN" important?

What is the maximum number of cross sections that can be used in a single run?

3.2 Hydraulic Computations.

Locate the message "FIXED BED MODEL" in the output. This only appears if there is no sediment data. It indicates the beginning of hydraulic calculations.

3.2.1 A-Level Output.

How does one request output from hydraulic computations?

What output is produced if none is requested?

What does the reference to "Boundary Condition Data" mean?

In the column headings following the boundary conditions table, in the output, there is a reference to "AVG VELOCITY IN SUBSECTION".

What subsection is the Channel? _____

What subsection is the Left Overbank? _____

What subsection is the Right Overbank? _____

What percent of the total discharge flows in the channel at section 1.16?

What is the HYDRAULIC DEPTH at section 1.16?

3.2.2 B-Level Output.

In addition to the calculated results indicated by the **** column headings, this level of output shows values for 3 other "sets" of variables. One of these other sets is entitled "Reach Properties by Strip" and contains the values used in the solution of the Manning equation at this cross section. Locate and describe what the other two sets show.

Velocity and flow distribution are critical in sediment movement calculations. Complete the following table.

Table 1. Channel Velocity and Flow Distribution

Section ID River Mile	Q cfs	V fps	Q_{ch} 4	Q	V fps	Q_{ch} 4
0.67	25000	_____	_____	50000	_____	_____
0.78	25000	_____	_____	50000	_____	_____
0.92	25000	_____	_____	50000	_____	_____
1.16	25000	_____	_____	50000	_____	_____

If this were an accurate model of velocity and flow in the river, describe what you expect the channel bed deposits to look like as one moves from section 1.16 toward section 0.67?

What is the maximum number of EVENTS that can be coded for a single run?

HYDROLOGIC INPUT

$HYD

$RATING

RC	Defines Downstream Boundary as f(Q)
*	Title card for each event
Q	Discharges (cfs)
R	Downstream WSEL (ft)
S	Shift in rating curve (ft)
T	Water temperature (°F)
W or X	Duration (Days)

PROCEDURE FOR RUNNING HEC-6 IN A FIXED BED MODE

1. With reference to HEC-6 User's Manual, Appendix A, Input Description.

   a. Required records: T1 through T3, NC, X1, GR, H, EJ, $HYD, *, Q, T, W, and $$END. Also, the user needs to include a downstream boundary condition by using R records.

   b. Optional records: NV, X3, X5, $RATING and RC.

   c. Do not include records T4 through LQS and the command records $DREDGE and $NO DREDGE.

   d. Use 1-day on the W record (for this example).

2. Calculation of Multiple Water Surface Profiles

   a. If only one stream segment is being modeled, up to ten multiple profiles may be calculated by using the parallel computation option on the Q record, if MNQ (I1 record, Field 4) is set to 10.

   b. If tributaries are present, a series of profiles may be calculated by stacking *, Q, R, W sets of records in the data stream. There is no program limit on the total number of sets. The R record may be omitted if a $RATING table is being used.

3. Output

   The default output from water surface profile calculations is "NO OUTPUT". Therefore, put an "A" in column 5 of each * record in the data set to trigger an A-level output.

Workshop 1

Solutions

HEC-6 – Development of Hydrologic Data

DEVELOPMENT OF HYDROLOGIC DATA FOR HEC-6

References: [1] HEC-6 User's Manual

Objective: The student demonstrates skill in coding Hydrologic Data, executing the program and reading the output.

1. END PRODUCT

The end product is an example execution.

2. PROCEDURE

2.1 Summary of Tasks. Locate the basic HEC-2 data file provided for this workshop. (A copy is shown below.) Modify the HEC-2 file to incorporate the additional data required to execute HEC-6. Execute the job and provide the interpretations requested below.

2.2 Final HEC-6 Input Data File.

```
T1 WORKSHOP PROBLEM 1
T2   R. Copeland, R. MacArthur, J. Tinios
T3 WORKSHOP TO DEMONSTRATE THE APPLICATION OF HEC6 IN A FIXED BED MODE
NC  .080    .080     .03      .3      .5
X1  0.67      20             653
GR 743.1       0     710      68     710     120   710.2     150   709.1     178
GR 711.6     214   711.9     264   710.5     320     709     360     707     390
GR   706     415   703.3     450   703.1     492     702     530   703.9     570
GR 703.1     610     705     635     711     647     715     649   743.1     653
H
X1   .78      19             696     590     590     590
GR 743.1       0   711.5      62   710.3      78   711.7     102   710.9     137
GR   711     173   712.5     208   714.6     270   713.3     320   711.3     340
GR 708.8     402   707.3     458   706.3     475     706     493   705.3     513
GR   706     558   707.8     611     709     625   743.1     696
H
X1   .92      13     710    1122    1690    1690    1690
GR 743.1       0     717      53     717     550     715     673     735     710
GR 707.5     740   707.9     780   706.7     840   706.8     878   708.2     910
GR 708.8     990   707.4    1046   743.1    1122
H
X1  1.16      17    1040    1593    2290    2290    2290
GR 743.3       0     717      52     717     964     715    1008     730    1040
GR   710    1074     708    1080   708.1    1140   707.9    1190   708.2    1230
GR   710    1304   711.7    1324   713.5    1360     715    1395     717    1450
GR   717    1540   743.3    1593
H
EJ
```

```
$HYD
*   A   RUN 1.   ILLUSTRATE THE HYDROLOGIC DATA SET
Q  25000
R    710
W      1
*   B   RUN 2.   ILLUSTRATE A MORE DETAILED PRINTOUT
Q  50000
R    715
W      1
$$END
```

A. **Geometric Data Set:**

H-record — Add an H-record after each cross section data set.
X3-record — An ineffective area record can be used, though it is not required for the program to execute.

B. **Sediment Data Set:**

Omit for a fixed bed execution.

C. **Hydrologic Data Set:**

Run the 2 events shown below.

Discharge CFS	Starting Water Surface Elevation
25,000	710
50,000	715

D. **Fluid Properties:**

T-record — Water temperature, Degrees F, is not needed for a fixed-bed execution.

3. READING THE OUTPUT

Use your output to answer the following questions.

3.1 Geometric Data.

Were any "error or diagnostic" messages indicated as the program read and processed the Geometric Data Set?

NO

Why is "NO OF CROSS SECTIONS READ IN" important?

The model can only handle a limited number of cross sections. This limit can be found in the banner on page 1 of the output.

What is the maximum number of cross sections that can be used in a single run?

150

3.2 Hydraulic Computations.

Locate the message "FIXED BED MODEL" in the output. This only appears if there is no sediment data. It indicates the beginning of hydraulic calculations.

3.2.1 A-Level Output.

How does one request output from hydraulic computations?

Enter A, B, C, D, or E in column 5 of the * records in the Hydrologic Data set.

What output is produced if none is requested? NONE!

What does the reference to "Boundary Condition Data" mean?

The water discharge, water surface elevation and water temperature at the "outflow" boundary of the model. Control Point #1 is always the downstream boundary of the model.

In the column headings following the boundary conditions table, in the output, there is a reference to "AVG VELOCITY IN SUBSECTION".

What subsection is the Channel? 2

What subsection is the Left Overbank? 1

What subsection is the Right Overbank? 3

What percent of the total discharge flows in the channel at section 1.16?

84.7% at 25,000 cfs and 75.0% at 50,000 cfs

What is the HYDRAULIC DEPTH at section 1.16?

8.56 at 25,000 cfs and 12.38 at 50,000 cfs

3.2.2 B-Level Output.

In addition to the calculated results indicated by the **** column headings, this level of output shows values for 3 other "sets" of variables. One of these other sets is entitled "Reach Properties by Strip" and contains the values used in the solution of the Manning equation at this cross section. Locate and describe what the other two sets show.

1) X-Section coordinates immediately following the X-Section identification and

2) N-VALUE,SLOPE,EFW,EFD,VAG hydraulic parameters for the sediment computations later.

Velocity and flow distribution are critical in sediment movement calculations. Complete the following table.

Table 1. Channel Velocity and Flow Distribution

Section ID River Mile	Q cfs	V fps	Q_{ch} 4	Q	V fps	Q_{ch} 4
0.67	25000	11.89	100	50000	11.38	100
0.78	25000	8.06	100	50000	11.86	100
0.92	25000	7.10	97.1	50000	9.23	87.4
1.16	25000	5.03	84.7	50000	5.98	75.0

If this were an accurate model of velocity and flow in the river, describe what you expect the channel bed deposits to look like as one moves from section 1.16 toward section 0.67?

I would expect scour.

What is the maximum number of EVENTS that can be coded for a single run?

The program does not limit the number of events that one can code.

```
1*************************************************
 *  SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS     *
 *        BETA TEST VERSION - FEBRUARY 1990           *
 *                                                    *
 *                                                    *
 *  RUN DATE 03/06/90   TIME 16:14:34                 *
 *****************************************************
```

```
*************************************
 *  U.S. ARMY CORPS OF ENGINEERS     *
 *  THE HYDROLOGIC ENGINEERING CENTER *
 *  609 SECOND STREET                 *
 *  DAVIS, CALIFORNIA 95616-4687      *
 *  (916) 756-1104                    *
 *************************************
```

```
X     X  XXXXXXX   XXXXX          XXXXX
X     X  X        X    X         X    X
X     X  X        X              X
XXXXXXX  XXXX     X       XXXXX  XXXXXX
X     X  X        X              X    X
X     X  X        X    X         X    X
X     X  XXXXXXX   XXXXX          XXXXX
```

```
*****************************************************************************
 *  MAXIMUM LIMITS FOR THIS VERSION ARE:                                     *
 *                                                                           *
 *  Stream Segments (Main Stem + Tributaries) =   10      Control Points =   10  *
 *  Cross Sections =  150                                 Grain Sizes =   15     *
 *                                                                           *
*****************************************************************************
```

```
              **** NOTE ****
      This version of HEC-6 is based on:
       SEDIMENTATION IN STREAM NETWORKS
            HYDRAULICS LABORATORY
         WATERWAYS EXPERIMENT STATION
            VERSION 1.11, DEC 1988

            PC implementation by:
      THE HYDROLOGIC ENGINEERING CENTER
       HEC Beta Test Version - FEB 1990

              **** WARNING ****
 This is a PRELIMINARY release for Corps offices.
 Please notify HEC of any problems or suggestions.
```

```
1

*****************************************************************************
 *            INPUT FILE: WS4SOLN.DAT                                        *
 *            OUTPUT FILE: WS4SOLN.OUT                                       *
*****************************************************************************
```

```
T1 WORKSHOP PROBLEM 4, MONDAY, MARCH 12, 1990 (Copeland/MacArthur)
T2   R. Copeland, R. MacArthur, J. Tinios
T3 WORKSHOP TO DEMONSTRATE THE APPLICATION OF HEC6 IN A FIXED BED MODE
```

```
      ALER      ASEL        CE        CC        LFA       NR       TAN       CRL
P   .050000   .000000  1.000000  1.000000        1

NC .0800   .0800   .0300   .3000   .5000

SECTION NO.  1 RIVER MILE=       .670

SECTION NO.  2 RIVER MILE=       .780

SECTION NO.  3 RIVER MILE=       .920

SECTION NO.  4 RIVER MILE=      1.160

NO. OF CROSS SECTIONS READ IN FOR THIS STREAM SEGMENT=  4
NO. OF INPUT DATA MESSAGES =   0

TOTAL NO. OF CROSS SECTIONS IN THE NETWORK =   4
END OF GEOMETRIC DATA
```

==========

```
1
 FIXED BED MODEL
```

==========

```
*   A   RUN 1.   ILLUSTRATE THE HYDROLOGIC DATA SET

BOUNDARY CONDITION DATA, CONTROL POINT NO.  1
  TIME STEP NO.      1
WATER    DISCHARGE=   25000.00
         ELEVATION=    710.000
       TEMPERATURE=       .000
FLOW DURATION(DAYS)  1.000

**** N  DISCHARGE   WATER     ENERGY   VELOCITY    ALPHA      TOP     AVG          AVG VELOCITY IN SUBSECTION
          CFS      SURFACE    LINE      HEAD                WIDTH    BED      1     2     3     4     5     6

SEC NO.      .670

**SUBROUTINE ELOEQ** CRITICAL W.S. USED AT SEC NO.    .670 AT TIME =       1.00 DAYS.
****  1   25000.0   711.042   713.238     2.196     1.000    486.29    706.72   .00 11.89   .00   .00   .00
                                                     FLOW DISTRIBUTION (%) =    .0 100.0    .0    .0    .0

SEC NO.      .780
****  1   25000.0   715.326   716.335     1.009     1.000    583.62    710.01   .00  8.06   .00
                                                     FLOW DISTRIBUTION (%) =    .0 100.0    .0

SEC NO.      .920
****  1   25000.0   718.315   719.076      .761     1.495    969.83    708.29   .76  7.10   .00
                                                     FLOW DISTRIBUTION (%) =   2.9  97.1    .0

SEC NO.     1.160
****  1   25000.0   720.613   720.949      .336     2.088   1466.53    712.05  1.07  5.03   .00
                                                     FLOW DISTRIBUTION (%) =  15.3  84.7    .0
```

==========

```
*   B   RUN 2.   ILLUSTRATE A MORE DETAILED PRINTOUT

BOUNDARY CONDITION DATA, CONTROL POINT NO.  1
  TIME STEP NO.      2
WATER    DISCHARGE=   50000.00
         ELEVATION=    715.000
       TEMPERATURE=       .000
FLOW DURATION(DAYS)  1.000

**** N  DISCHARGE   WATER     ENERGY   VELOCITY    ALPHA      TOP     AVG        AVG VELOCITY IN SUBSECTION
          CFS      SURFACE    LINE      HEAD                WIDTH    BED      1     2     3     4     5     6     7

SEC NO.      .670
 X-SECTION COORDINATES (STA,ELEV)
            .000   743.100      .000   743.100      .001   743.100   68.000   710.000   120.000   710.000
         150.000   710.200   178.000   709.100   214.000   711.600  264.000   711.900   320.000   710.500
         360.000   709.000   390.000   707.000   415.000   706.000  450.000   703.300   492.000   703.100
         530.000   702.000   570.000   703.900   610.000   703.100  635.000   705.000   647.000   711.000
         649.000   715.000   652.999   743.093   653.000   743.100

****  1   50000.0   715.000   717.014     2.014     1.000    591.27   707.57  .00 11.38   .00   .00   .00   .00   .00
                                                          FLOW DISTRIBUTION (%) =   .0 100.0    .0    .0    .0    .0    .0

       REACH PROPERTIES BY STRIP          1          2          3          4          5          6          7
                 INEFF FLOW  EL   -99999.00  -99999.00  -99999.00  -99999.00  -99999.00  -99999.00  -99999.00
    U/S SECTION...    CONVEYANCE         0.    823211.         0.         0.         0.         0.         0.
                           AREA         0.      4392.         0.         0.         0.         0.         0.
                      HYD RADIUS        .00       7.36        .00        .00        .00        .00        .00
    REACH...                  N      .0800      .0300      .0800      .0000      .0000      .0000      .0000
                         SQRT(L)     1.0000      .0000     1.0000      .0000      .0000      .0000      .0000
    D/S SECTION...         AREA         0.         0.         0.         0.         0.         0.         0.
                      HYD RADIUS        .00        .00        .00        .00        .00        .00        .00

   N-VALUE,SLOPE,EFW,EFD,VAG=    .030000    .003689     445.77       9.85      11.38

SEC NO.      .780
 X-SECTION COORDINATES (STA,ELEV)
            .000   743.100      .000   743.100      .001   743.099   62.000   711.500    78.000   710.300
         102.000   711.700   137.000   710.900   173.000   711.000  208.000   712.500   270.000   714.600
         320.000   713.300   340.000   711.300   402.000   708.800  458.000   707.300   475.000   706.300
         493.000   706.000   513.000   705.300   558.000   706.000  611.000   707.800   625.000   709.000
         695.999   743.100   696.000   743.100

****  1   50000.0   717.238   719.424     2.186     1.000    591.28   710.11  .00 11.86   .00
                                                          FLOW DISTRIBUTION (%) =   .0 100.0    .0

       REACH PROPERTIES BY STRIP          1          2          3
                 INEFF FLOW  EL   -99999.00  -99999.00  -99999.00
    U/S SECTION...    CONVEYANCE         0.    770360.         0.
                           AREA         0.      4216.         0.
                      HYD RADIUS        .00       7.09        .00
    REACH...                  N      .0800      .0300      .0800
                         SQRT(L)    24.2899    24.2899    24.2899
    D/S SECTION...         AREA         0.      4392.         0.
                      HYD RADIUS        .00       7.36        .00

   N-VALUE,SLOPE,EFW,EFD,VAG=    .030000    .004085     475.75       8.86      11.86

SEC NO.      .920
 X-SECTION COORDINATES (STA,ELEV)
            .000   743.100      .000   743.100    53.000   717.000  550.000   717.000   673.000   715.000
         710.000   735.000   740.000   707.500   780.000   707.900  840.000   706.700   878.000   706.800
         910.000   708.200   990.000   708.800  1046.000   707.400 1121.999   743.100  1122.000   743.100

****  1   50000.0   722.102   723.267     1.165     1.964    996.72   708.70  1.87  9.23   .00
                                                          FLOW DISTRIBUTION (%) =  12.6  87.4    .0
```

```
        REACH PROPERTIES BY STRIP          1          2          3
                   INEFF FLOW  EL   -99999.00  -99999.00  -99999.00
     U/S SECTION...     CONVEYANCE    187179.   1300690.         0.
                           AREA       3359.      4733.         0.
                      HYD RADIUS       5.20      13.07        .00
     REACH...                  N      .0800      .0300      .0800
                         SQRT(L)    41.1096    41.1096    41.1096
     D/S SECTION...        AREA         0.      4216.         0.
                      HYD RADIUS        .00       7.09        .00

    N-VALUE,SLOPE,EFW,EFD,VAG=    .030000    .002274     337.18      14.04       9.23

 SEC NO.     1.160
  X-SECTION COORDINATES (STA,ELEV)
            .000   743.300      .000   743.300    52.000   717.000   964.000   717.000  1008.000   715.000
        1040.000   730.000  1074.000   710.000  1080.000   708.000  1140.000   708.100  1190.000   707.900
        1230.000   708.200  1304.000   710.000  1324.000   711.700  1360.000   713.500  1395.000   715.000
        1450.000   717.000  1540.000   717.000  1592.999   743.300  1593.000   743.300

**** 1   50000.0   724.767   725.194      .426     2.122   1498.93    712.39  1.64  5.98   .00
                                                   FLOW DISTRIBUTION (%) =  25.0  75.0    .0

        REACH PROPERTIES BY STRIP          1          2          3
                   INEFF FLOW  EL   -99999.00  -99999.00  -99999.00
     U/S SECTION...     CONVEYANCE    550395.   1649541.         0.
                           AREA       7628.      6274.         0.
                      HYD RADIUS       7.66      12.23        .00
     REACH...                  N      .0800      .0300      .0800
                         SQRT(L)    47.8539    47.8539    47.8539
     D/S SECTION...        AREA       3359.      4733.         0.
                      HYD RADIUS       5.20      13.07        .00

    N-VALUE,SLOPE,EFW,EFD,VAG=    .030000    .000841     436.41      14.38       5.98


==================================================================================================


SSEND

       0   DATA ERRORS DETECTED.

TOTAL NO. OF EVENTS READ=        2
TOTAL NO. OF WS PROFILES=        2
ITERATIONS IN EXNER EQ  =        0
END OF JOB

JOB COMPLETED
RUN TIME =  0 HOURS,  0 MINUTES &  1.38 SECONDS
```

REVIEW OF

SEDIMENT TRANSPORT FUNCTIONS

By

David T. Williams

WEST Consultants, Inc.

ACKNOWLEDGEMENTS

Portions of the following document have been extracted from a number of sources including the following:

1. Sediment Transport, lectures presented at HEC, December 1982, Ranjan Ariathurai

2. Prediction of Flow Depth & Sediment Transport in Open Channels, 1981, William R. Brownlie

3. ASCE Sedimentation Manual, 1975, Vito A. Vanoni, ed.

4. Bed-load Formulas, 1968, Sam Shulits and Ralph Hill

5. Sediment Transport Technology, 1976, Daryl Simons and Fuat Senturk

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I. SEDIMENT TRANSPORT MECHANICS

1. DETACHMENT AND THRESHOLD OF TRANSPORT

1.1 Cohesive and Non-cohesive Sediments

It is important to be aware of the presence of cohesive sediments in a problem area. Cohesive sediments are very fine particles of clay, organic material, fine silts, and certain industrial and mining wastes that exhibit colloidal properties. The surface charge present on these particles can cause them under certain physical and chemical conditions in the suspending water, to form flocs that settle out much faster than the individual particles. Higher salt content and pH promote flocculation. Cohesive sediments resist erosion due to the interparticle bond which is a force usually much larger than the weight of the particle. A soil with only 5% clay may exhibit properties similar to that of the pure clay rather than the 95% non-cohesive material it is composed of.

1.2 Incipient Motion

1.2.1 Instantaneous Forces on a Particle

The condition of incipient movement for an assembly of cohesionless, loose, and solid particles is described in terms of the forces acting on the particle by:

$$\tan \phi = \frac{F_t}{F_n} \qquad (1)$$

where F_t and F_n are the forces parallel and normal to the angle of repose ϕ. In our study F_t and F_n are resultants of the hydrodynamic drag F_D, the lift force F_L, and the submerged weight W. The condition of incipient movement under the action of these forces becomes, according to Eq. (1):

$$\tan \phi = \frac{W\sin\sigma + F_D}{W\cos\sigma - F_L} \qquad (2)$$

where angle σ is the inclination of the bed from the horizontal at which incipient sediment movement takes place. This situation is illustrated in Fig 1.

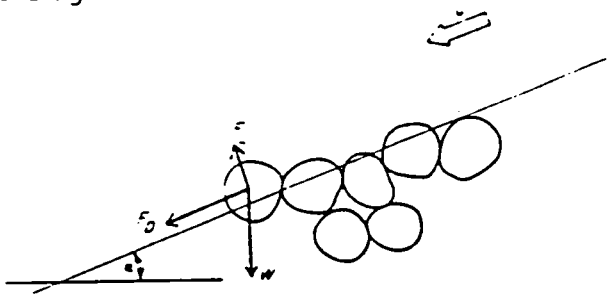

FIGURE 1

FORCE DIAGRAM ON PARTICLES IN A COHESIONLESS LOOSE BED

In the usual way, drag and lift forces are expressed by:

$$F_D = C_D k_1 d^2 \frac{p u_b^2}{2} \tag{3}$$

and

$$F_L = C_L k_2 d^2 \frac{p u_b^2}{2} \tag{4}$$

where u_b = fluid velocity at the bottom of the channel

C_D, C_L = drag and lift coefficient, respectively

d = particle diameter

k_1, k_2 = particle shape factors

p = liquid density

The submerged weight of the particle is expressed as:

$$W = k_3 (p_s - p) g d^3 \tag{5}$$

with k^3 being another shape factor and p_s being the solid-particle density.

Introducing Eqs. (3), (4) and (5) into Eq. (2) yields:

$$\frac{(u_b^2)_{cr}}{(\rho_s/\rho - 1)gd} = \frac{2k_3(\tan\phi\cos\sigma - \sin\sigma)}{C_D k_1 + C_L k_2 \tan\phi} \qquad (6)$$

with $(u_b)_{cr}$ as the critical bottom velocity at which, according to Eq. (1), incipient sediment motion takes place.

However, the lift coefficient C_L is dependent on the velocity gradient (which is related to the shear stress at the bottom) and not on the velocity itself. For example, there is no lift on a sphere in a uniform free stream.

1.2.2 Critical Shear Stress for Scour

It is not possible to define a particular shear stress at the bottom at which motion is incipient. Both the hydraulic shear stress produced by the flow, and the resistance of bed particles to scour, are not single valued functions. Turbulent velocity fluctuations produce a distribution of shear stress at the bed. Similarly, inhomogeneity of particle size and shape results in a distribution of critical shear stresses at the bed.

Critical shear stress is measured in the field or in laboratory flumes and other devices that are able to apply variable hydraulic shear stress to a bed or soil sample. Typically, a plot of erosion rate vs. mean hydraulic shear stress is made.

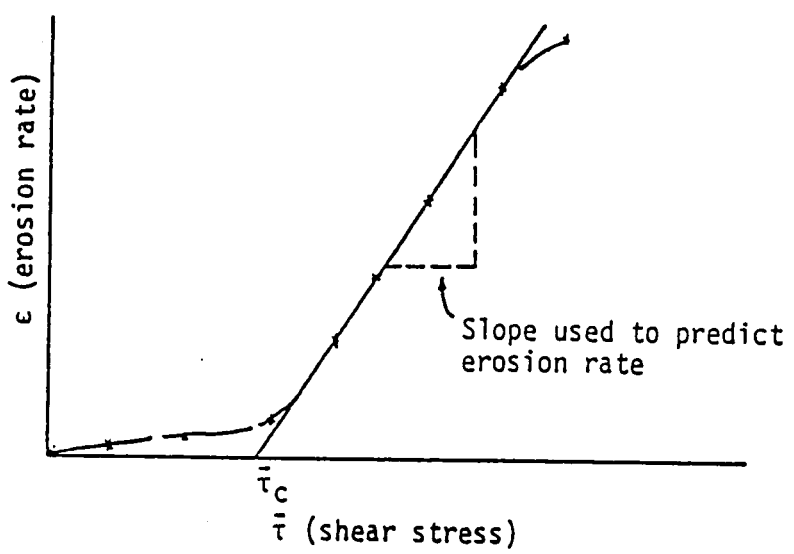

FIGURE 2

Measurement of Critical Shear Stress

The idealization shown above is usually adequate for practical problems where the sediment is of uniform size or cohesive in nature. It is not valid for a mixture of different particle sizes.

1.3 Shields Diagram

Shield's Diagram (Figure 3) for the critical shear stress for scour is based on experimental data. Shields used the dimensionless shear or boundary Reynolds number $u_* d_s/v$ and the dimensionless shear stress $\tau_0/(\gamma_s-\gamma)d_s$ to develop a curve of critical values for scour.

Here,

u_* = friction or shear velocity

d = mean sediment diameter

γ_s = specific gravity of sediment

γ = specific gravity of suspending water

τ_0 = shear stress at the bed

and v = kinematic viscosity

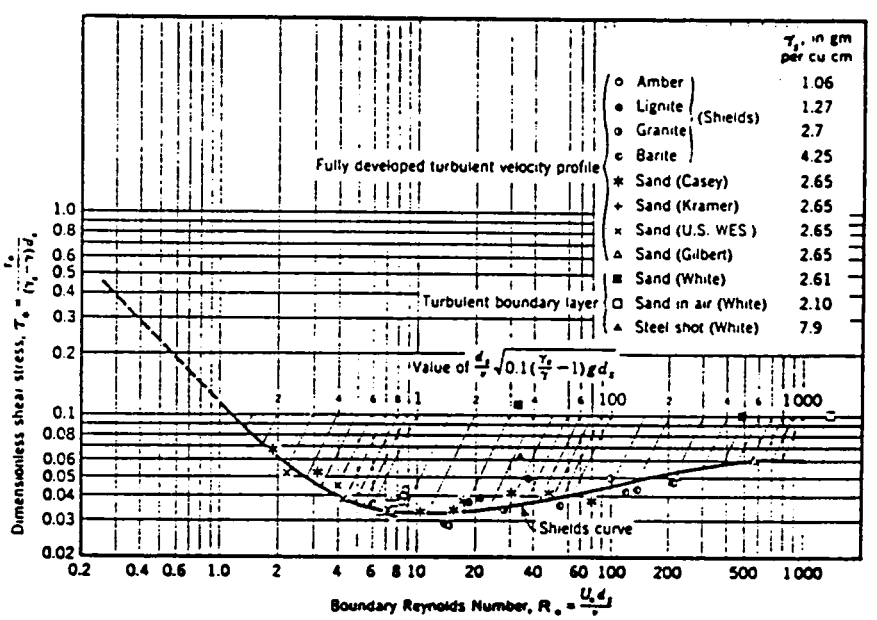

FIGURE 3

Shields Diagram

If it is assumed that the initiation of motion is determined by the critical shear stress τ_c, $(\gamma_s-\gamma)$ d_s and the kinematic viscosity ν, dimensionless analysis yields,

$$\frac{\tau_c}{(\gamma_s-\gamma)d_s} = f\left(\frac{u_{*c}\, d_s}{\nu}\right) \tag{7}$$

where f denotes function of. The left hand portion of the equation will be called the dimensionless critical shear stress and denoted by τ_*, and the variable on the right is called the critical boundary Reynolds number, R_*

1.4 Critical Velocity

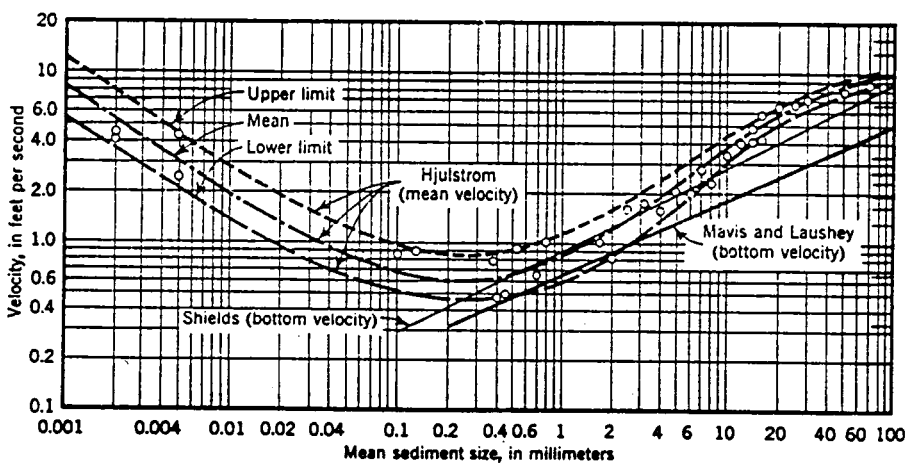

FIGURE 4

Critical Water Velocities for Quartz Sediment
as Function of Mean Grain Size

Figure 4 shows data on critical velocity plotted against mean sediment size for quartz sediment in water (p_s = 2.65 g/cm³) obtained from three sources. The data points and the curves of the upper limit, mean, and lower limit of the critical mean velocity are taken from the work of Hjulstrom (1935) who prepared the curves based on the data of several workers. The curves are

for flows with depths of at least 1m. The data for mean sediment size less than 0.01 mm were taken from Fortier and Scobey (1926). In such fine sediments, cohesion is an important factor in determining critical conditions. The relationship of Mavis and Laushey (1949) was developed by fitting a curve to observed data most of which were obtained under Mavis's supervision. In these cases, the bottom velocity was obtained by extrapolating velocity profile measurements to the plane of the bed. The curve in Fig. 4 labeled Shields, was calculated from Shields' diagram for quartz sand in water at 65° F. In the calculations, the roughness size k_s, of the sediment was taken equal to the mean size and the bottom velocity was assumed to occur at $y = d_s$ or $y = 11.6v/u^*$, whichever was larger. The curve marked "Shields" in Fig. 4 has a slope of 0.5 indicating that the bottom velocity, u_o, is proportional to $d_s^{1/2}$ which agrees with the sixth power law (Sutherland, 1966).

The curve for Shields' data gives substantially higher critical bottom velocities than that of Mavis and Laushey. However, Mavis and Laushey (1966) have called attention to the fact that their curve represents a lower envelope of the data on which it was based. Because of this, the data of Mavis and Laushey are in better agreement with the Shields results than is indicated on Fig. 4. Bottom velocities were calculated from the Hjulstrom data by the same relationship used in calculating u_o from Shields' data assuming a flow depth of 1 m. These results did not agree with either of the values given by the other two curves of Fig. 4. Thus, the data for critical velocity are considerably less consistent than those for critical shear stress. Therefore, it is recommended that data on critical shear stress be used wherever possible.

2. DEFINITIONS OF VARIOUS SEDIMENT LOADS

Einstein in developing his bed-load function made the following definitions:

<u>Bed load:</u> Bed particles moving in the bed layer. This motion occurs by rolling, sliding, and, sometimes, by jumping.

<u>Suspended load:</u> Particles moving outside the bed layer. The weight of suspended particles is continuously supported by the fluid.

<u>Bed layer:</u> A flow layer, 2 grain diameters thick, immediately above the bed. The thickness of the bed layer varies with the particle size.

<u>Bed material</u>: The sediment mixture of which the moving bed is composed.

Wash load: That part of the sediment load which consists of grain sizes finer than those of the bed.

Bed-material load: That part of the sediment load which consists of grain sizes represented in the bed.

Bed-load function: The rates at which various discharges will transport the different grain sizes of the bed material in a given channel.

Bed-load equation: The general relationship between bed-load rate, flow condition, and composition of the bed material.

Vanoni describes the various loads as:

Contact load: Rolling and sliding bed particles:

Saltation load: Bed particles that jump for short times and then return to the bed to come to rest, continue to move on the bed, or execute further jumps.

Suspended load: Bed particles that make frequent jumps and may remain in suspension for appreciable lengths of time.

We can simplify all this and remove ambiguities by making the following definitions.

1. BED LOAD - Particles derived from the bed that roll, slide and saltate.
Their motion is in a layer near the bed and their transport rate is lower than that of the surrounding water due to periods of rest and acceleration. The composition of the bed load will usually differ from that of the material that composes the bed.

2. SUSPENDED LOAD- Particles that move at a horizontal velocity that can be approximated by that of the local suspension velocity.
These particles may be derived from the bed materials or have remained in the water column from upstream sources (i.e., wash load). We can estimate their transport rate from the local suspension velocity.
Note that in unsteady flows at different times and locations different sediments can compose each type of load.

3. SUSPENDED SEDIMENT TRANSPORT

The suspended sediment discharge in lbs per second per unit width of channel, q_s, for steady uniform two-dimensional flow is

$$q_s = \gamma \int_a^{y_o} v\, c\, dy \qquad (8)$$

where v and c vary with y and are the time averaged flow velocity and volumetric concentrations, respectively. The integration is taken over the depth between the distance "a" above the bed and the surface of the flow "y_o". The level "a" is assumed to be 2 grain diameters above the bed layer. Sediment movement below this level is considered as bed load rather than suspended load.

The discharge of suspended sediment for the entire stream cross-section, Q_s, is obtained by integrating Equation (8) over the cross-section to give,

$$Q_s = \gamma_s Q C \tag{9}$$

where C is the average suspended sediment concentration by volume.

The vertical distribution of both the velocity and the concentration vary with the mean velocity of the flow, bed roughness, and the size of bed material. The distributions are illustrated in Figure 5. Also v and c are inter-related. That is, the velocity and turbulence at a point is affected by the sediment at the point, and the sediment concentration at the point is affected by the point velocity. Normally this inter-relation is neglected or a coefficient is applied to compensate for it.

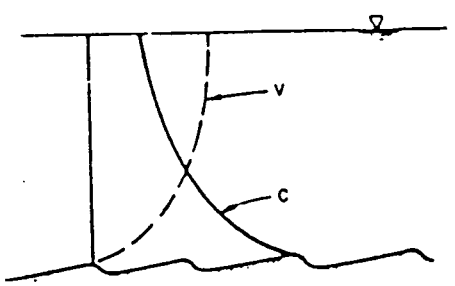

Figure 5
Schematic sediment and velocity profiles

To integrate Equation (9) v and c must be expressed as functions of y. The one-dimensional gradient type diffusion equation is employed to obtain the vertical distribution for c and the logarithmic velocity distribution is assumed for v in turbulent flows.

The one-dimensional diffusion equation describes the equilibrium condition when the quantity of sediment settling across a ~~unit~~ area due to the force of gravity is equal to the quantity of sediment transported upwards resulting from the vertical component of turbulence and the concentration gradient.

After extensive manipulation of these previous equations, the vertical sediment distribution for turbulent flow can be derived and is shown below,

$$\frac{c}{c_a} = \left(\frac{y_o - y}{y} \frac{a}{y_o - a} \right)^Z \qquad (10)$$

where

c = the concentration at a distance y from the bed:

c_a= the concentration at a point a above the bed; and

Z = w/Bku_* the Rouse number, named after the engineer who developed the equation in 1937.

W = fall velocity of the sediment particle at a point

k = Von Karman's constant

B = a coefficient relating the kinematic eddy viscosity and mass transfer coefficient, normally taken as 1.

u_* = Shear velocity

Figure 6 shows a family of curves obtained by plotting Equation 10 for different values of the Rouse number Z. It is seen that for small values of Z, the sediment distribution is nearly uniform. For large Z values, little sediment is found at the water surface. The value of Z is small for large shear velocities u_* or small fall velocities.

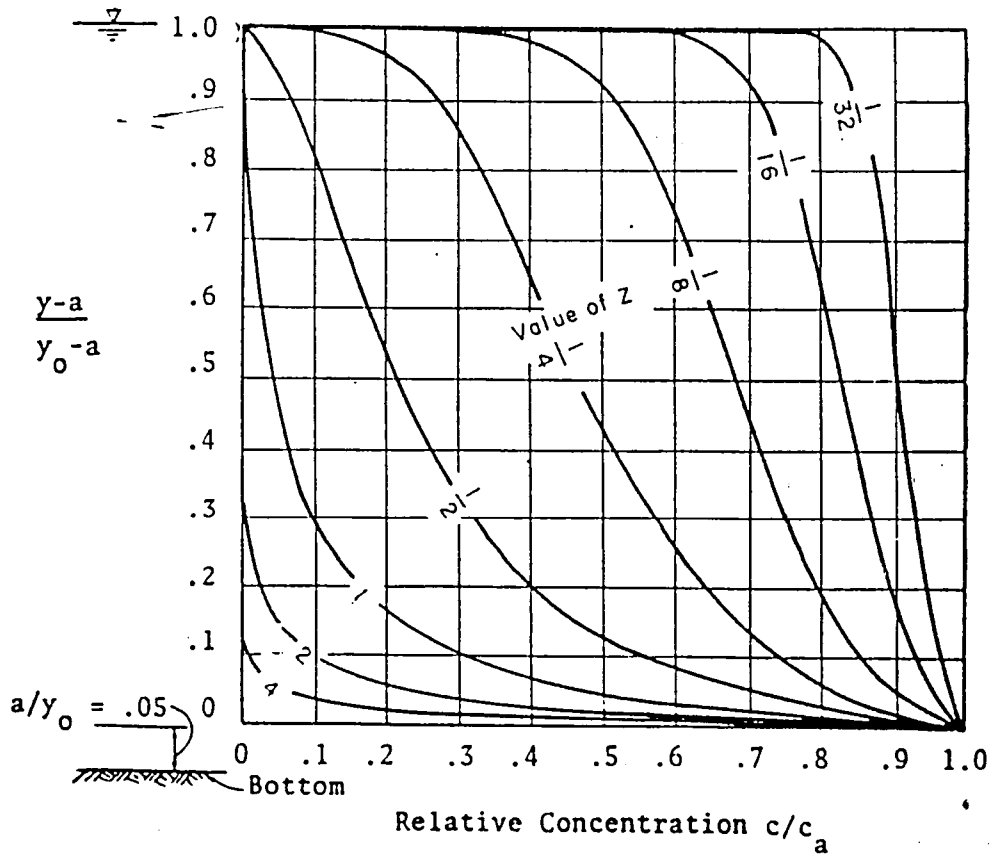

Figure 6
Graph of suspended sediment distribution

Thus for small particles or for extremely turbulent flows, the concentration profiles are uniform.

The values of B and k have been investigated. For fine particles B~1.0. Also, it is well known that in clear water k = .4 but apparently decreases with increasing sediment concentration.

4. BED FORMS

In open channel flow the Froude number F is often used as the criterion for bed form development.

F < 1	normal depth > critical depth, tranquil flow
F > 1	normal depth < critical depth, rapid flow
F = 1	critical flow

Idealized sketches of the various bed-forms are shown below. At extremely low velocities the critical shear stress of the bed is not exceeded and sediment motion does not occur. An increase in the velocity may result in sediment movement and formation of bed-forms. The common bed-forms occurring in a lower regime have dune pattern and are triangular-shaped elements with a steep downstream and a gentle upstream slope. The downstream slope is inducive to flow separation and migrates in the downstream direction. The spacing and the geometry of the elements are random for an individual one, but uniform in the statistical sense. Individual dune patterns are referred to as ripples or dunes. Ripples are understood to be small bed-forms, whereas dunes are larger ones and are out of phase with the water surface. Ripples may be superposed upon the upstream side of dunes.

As the flow velocity is increased further the upper regime is reached. The first bed-form to be observed is a plane bed, a bed surface devoid of any "bed-form". A further increase in the velocity causes the water surface to become unstable. The plane bed changes into a bed-form similar to and in phase with the surface wave--called antidunes, which may remain stationary or move upstream or downstream. At lower Froude numbers, anti -

Flow regime	*Bedform*	*Bed material concentrations, ppm*	*Mode of sediment transport*	*Type of roughness*	*Roughness, $C/\sqrt{g}$*
Lower regime	Ripples Ripples on dunes Dunes	10–200 100–1,200 200–2,000	Discrete steps	Form roughness predominates	7.8–12.4 — 7.0–13.2
Transition	Washed-out dunes	1,000–3,000		Variable	7.0–20.0
Upper regime	Plane beds Antidunes Chutes and pools	2,000–6,000 2,000 — 2,000 —	Continuous	Grain roughness predominates	16.3–20 10.8–20 9.4–10.7

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[1] Note that antidunes as defined here do not necessarily move upstream.

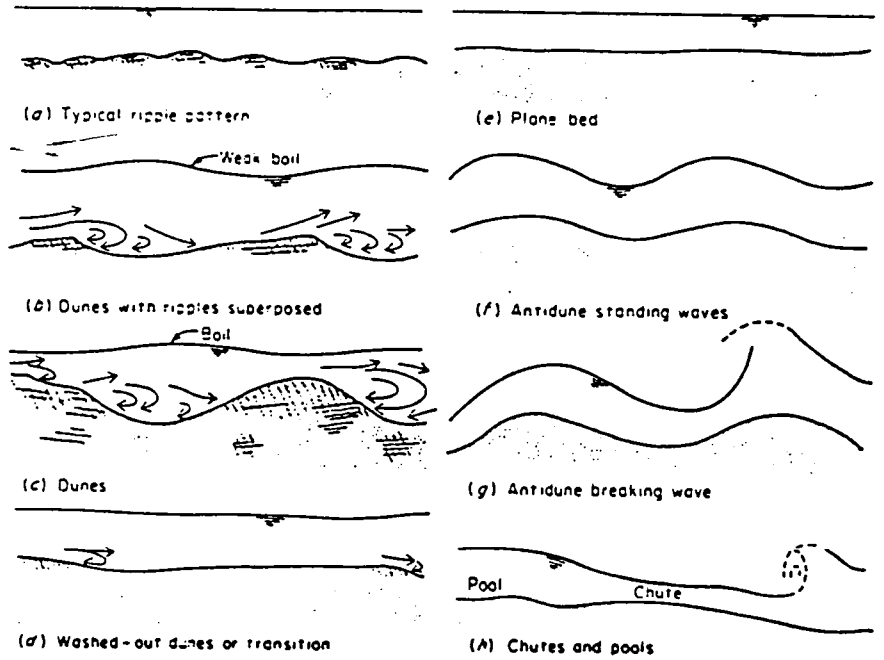

Figure 7
Idealized bed-forms in Alluvial Channels
After Simons et. al. (1961)

dunes appear as standing sand and water waves. However, at higher Froude numbers, the surface waves may grow, become unstable, and break in the upstream direction, If the latter occurs, the antidunes are destroyed, the bed becomes flat, and formation of antidunes starts all over again. Extremely strong antidune activity leads to chutes and pools flow.

Between the lower and the upper regime there is a transition zone. For a given flow condition, the bed configuration is erratic; it may range from developed dunes to a flat bed, or it may consist of a heterogeneous array of bed-forms.

One bed-form not necessarily linked with a flow regime, and probably reflecting more than any other bed-form the three-dimensionality of natural streams, is the bar. Bars are large depositional features and have a length of the same order as the channel width or longer. Several different types of bars have been observed. In general it may be said that they have the geometry of a dune, but are much larger. Bars are created at high flow and may appear as little islands or peninsulas during low flow.

II. SEDIMENT TRANSPORT EQUATIONS

Sediment transport equations are broken down in the section as to the type of transport, being either bed load or total bed material load. They are further subdivided according to the

basic concepts behind the various equations including tractive force, discharge formulae, lift force, dimensional analysis, and other regression analyses. In the following discussion the wash load or fine material load is not considered. Therefore, the bed material load is taken to be equivalent to the total load which can be divided into a bed load and a suspended load.

Sediment transport equations are often subdivided into tractive force formulas of a DuBoys form such that transport is a function of $(\tau-\tau_{critical})$, and discharge formulas such as that of schoklitsch written as a function of $(q-q_{critical})$. Other investigators (Einstein, Toffaleti) use very complex formulae based on the balance of lift forces and gravitational forces coupled with stochastic methods. The Yang, and Ackers-White methods utilize dimensional analyses. Yet other procedures, including Colby, and Shen and Hung are based on regression analyses of fairly extensive data bases.

1. BED LOAD FORMULAE

1.1 Tractive Force Equations

1.1.1 Duboys Formula (1879, Brown 1950)

$$g_s = \Psi_D \tau_o(\tau_o - \tau_c) \tag{11}$$

in which g_s = sediment discharge, in pounds per second per foot of width; Ψ_D = coefficient with dimensions of cubic feet per pound per second; $\tau_o = \gamma r_b S$ bed shear stress, in pounds per square foot; γ = specific weight of water, in pounds per cubic foot; τ_c = critical bed shear stress at which sediment movement begins; r_b = bed hydraulic radius, in feet (determined by the Side-wall Correction method); and S = slope of stream, in feet per foot. Values of Ψ_D and τ_c obtained by Straub and reported in Brown, 1950 are given as functions of median size of the bed sediment, d_{50}, in Fig. 8. These quantities were based mainly on data from experiments by Gilbert (1914; Johnson, 1943) in small flumes. Eq. 11 as presented herein is valid only for the foot-pound-second system of units.

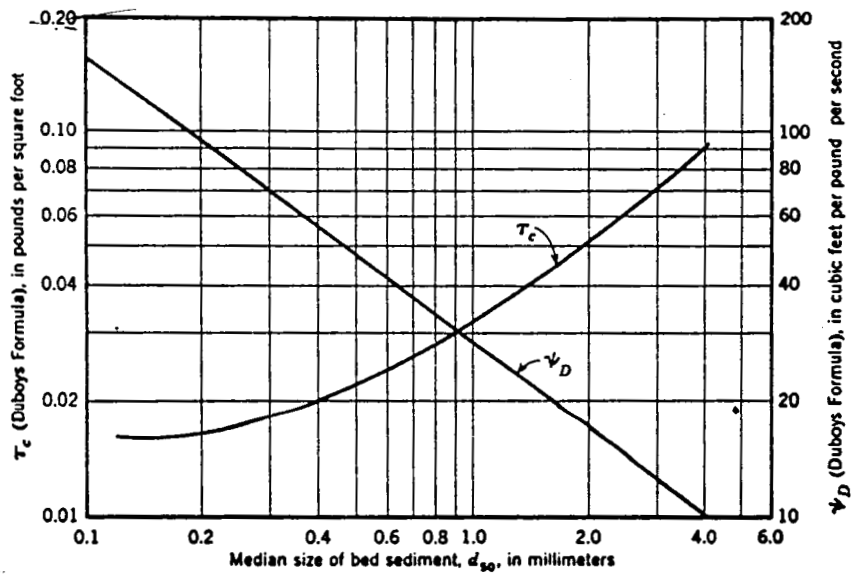

Figure 8
Coefficient Ψ_D and Critical Shear Stress τ_c for BuBoy's Eq 2.227 as Functions of Median Size of Bed Sediment.

1.1.2 Shields Formula (Shields, 1936)

$$g_s = 10q\,S\frac{(\tau_o - \tau_c)}{\left(\frac{\gamma_s}{\gamma} - 1\right)^2 d_{50}} \tag{12}$$

in which γ_s = specific weight of the sediment grains; τ_c = critical bed shear stress for sediment of size d_{50} given by Shields graph, Fig. 3, and all other quantities in Eq. (12) are already defined except that since the equation is dimensionally homogeneous, the quantities can be expressed in any consistent set of units.

The Shields formula is based mainly on data from two flumes with widths of 40 cm and 80 cm, respectively, with five sediments of specific gravities ranging from 1.06-4.2. The lightest sediment was made of amber particles with a median size of 1.56 mm. The other sediments were well sorted with median sizes ranging from 1.7 mm-2.5 mm. Ripples were produced on the bed but none of them were very high or steep. Because the sediments in the experiments were coarse and the shear stresses low, essentially all of the sediment moved was bed load.

1.2 Discharge Formulas

1.2.1 Schoklitsch Formula (Shulits, 1935)

$$g_s = \sum_i p_i \frac{25.3}{\sqrt{d_{si}}} S^{3/2} (q - q_{ci}) \tag{13}$$

$$q_{ci} = 0.638 \frac{d_{si}}{S^{4/3}} \tag{14}$$

in which q_{ci} = critical value of q for initiating motion of sediment of mean size, d_{si} as given by Eq. 14, p_i = fraction by weight of that fraction of the bed sediment with mean size, d_{si}; the symbol, $\sum_i$, denotes summation for all sets of values of p_i, d_{si}, and q_{ci}, and other symbols are as defined previously. All quantities in Eq. (14) are expressed in the foot-pound-second system of units.

To determine sets of values of p_i and d_{si} a mechanical analysis of a representative sample of the bed sediment is made and a size distribution curve prepared. A set of size grades is then selected and the corresponding p_i values can be determined from the size distribution curve. The mean size, d_{si}, of a fraction is often taken as the geometric mean of the extreme sizes in the fraction.

The Schoklitsch formula was based mainly on data from experiments by Gilbert (1914) in small flumes with well-sorted and also graded sediments with median sizes ranging from 0.3 mm-5 mm. Sediment discharges calculated with the formula also agreed well (Shulits, 1935) with bed load discharges calculated with the samplers in two European rivers that have gravel beds. This suggests that it is a bed load formula that should not be applied to sand bed steams that carry considerable bed sediment in suspension.

1.3 Similitude and Dimensional Analysis

1.3.1 Meyer-Peter and Muller Formula (1948)

The Meyer-Peter and Muller formula is based on data from experiments in flumes ranging in width from 15 cm-2 m with slopes varying from 0.0004-0.02 and water depths ranging from 1

cm-120 cm. The sediments used in the experiments ranged from coal with a small specific gravity, γ_s/γ, = 1.25, to river sediment to barite with a specific gravity in excess of four. Some of the sediments were graded and others were sorted. The mean sizes and effective diameters, d_m, of the sediments ranged from 0.4 mm-30 mm. The advantage of this formula over the older Meyer-Peter formula, is that it can be used for graded sediments under flow conditions that give rise to dunes and other bed forms. Most of the data upon which the formula is based were obtained in flows with little or no suspended load which suggests that the formula is not valid for flows with appreciable suspended loads.

2. BED MATERIAL LOAD EQUATIONS

2.1 Tractive Force Equations

2.1.1 Laursen (1958)

For the Laursen (1958) method, the particle size distribution is divided into n size fractions, p_i, which have mean size D_{si} and fall velocity w_i. The concentration is calculated from

$$c = 0.01 \sum_{i=1}^{n} p_i \left(\frac{D_{si}}{r}\right)^{7/6} \left[\frac{v^2}{58\, Y_c\, D_{si}\, g\left(\frac{\rho_s - \rho}{\rho}\right)} \left(\frac{D_{50}}{r}\right)^{1/3} - 1 \right] \cdot f\left(\frac{u_*}{w_i}\right) \qquad (15)$$

The value of Y_c is obtained from

$$Y_c = \begin{cases} 0.04 \;\ldots\ldots\; D_{si}/\delta > 0.1 \\ 0.08 \;\ldots\ldots\; 0.1 \geq D_{si}/\delta > 0.03 \\ 0.03 \;\ldots\ldots\; D_{si}/\delta \leq 0.03 \end{cases} \qquad (16)$$

where $S = 11.6v/u_*$ is the thickness of the laminar sublayer.

The function $f(u_*/w_i)$ is given in Figure 9.

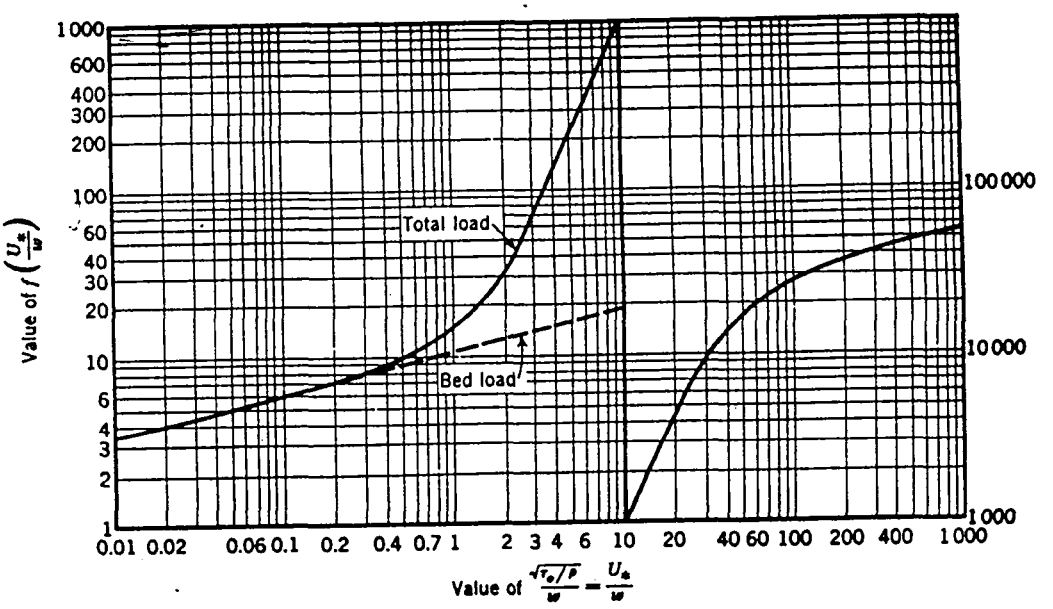

Figure 9
Function $f(u_*/w)$ for Laursen Formula, Eq. 2.231a

The Laursen formula is intended to apply only to natural sediments with specific gravity of 2.65.

Laursen determined the function in Fig. 9 by correlating values of the function obtained from flume data of several investigators with u_*/w from the data. The flumes used by the investigators ranged in size from one 10.5 in. wide and 40 ft long to the one used by Laursen that was 3 ft wide and 90 ft long. The sediments all hade specific gravities of close to 2.65 and varied in median sizes from 0.011 mm-4.08 mm with grain size distributions from well-sorted to well graded.

Laursen also compared values of sediment discharge calculated by his relation with values observed on three small streams: the Niobrara River near Cody, Neb. (Colby and Hembree, 1955); Mountain Creek in South Carolina (Einstein, 1944), and West Goose Creek in Mississippi (Einstein, 1944). The streams had flow depths in the range from 0.12 ft-1.3 ft and bed sediment with median sizes 0.277 mm, 0.86 mm, and 0.287 mm, respectively. The agreement between observed and calculated sediment discharge was good for the Niobrara River, but only fair for the other two streams.

2.2 Lift Force - Stochastic Approaches

2.2.1 Einstein (1950)

Probably the most complex computational procedure is that of Einstein. To begin the procedure bed material is divided into size fractions. Suspended load is computed by size fraction using the Rouse equation (equation 19).

Calculation of the sediment discharge of a stream by the Einstein bed load function can be carried out in three parts. The first part involves collecting field data that include measurements of: (1) Slope; (2) data on cross section from which one can determine the bed width and the cross-sectional area and wetted perimeter of the banks as functions of depth; (3) a representative sample of the bed sediment; (4) a mechanical analysis of the bed sample from which the weight fraction, p_i, can be determined for each size, d_{si}, and values of d_{35} and d_{65} can be read; and (5) an estimate of the friction factor of the channel banks.

In the second part, calculations are made to determine values of the bed hydraulic radius, r'_b, due to sand grain roughness for a range of values of water discharge Q.

The third part of the calculation uses the results of the first two to finally determine the total bed sediment discharge, G_3, for several values of Q.

The steps in the calculation of bed load transport are:

1. Field data required for calculation are: (a) S=channel slope; (b) data on bed width and cross-sectional area and wetted perimeter of banks as a function of water depth; (c) friction factor of banks of channel (estimated); (d) sample of bed sediment from which values of weight fractions p_i can be determined foe several mean sizes d_{si} along with the specific weight; γ_s, d_{35}, and d_{65}; and (e) water temperature.
2. Hydraulic calculations (see Vanoni 1975 ASCE Sedimentation Manual)
3. Sediment discharge calculation (see Vanoni 1975)

The coefficients in Einstein's bed load function, were determined by fitting the function to flume data. The data were obtained in flume experiments with two well-sorted sediments of mean size 28.65mm and 0.785 mm, respectively. These are shown to demonstrate the fact that the theory agrees with data from experiments with sorted sediments. The data used to determine the coefficients were from experiments in a flume 10.5 in. wide and 40 ft long with high transport rates of graded fine sands.

2.2.2 Toffaleti (1968)

Toffaleti (1968) used the Einstein (1950) method as an inspiration for the development of this technique. Since the

technique is quite complex, a full description is not given here. Full descriptions of the method can be found in Vanoni (1975, pp. 209-213) and White, Milli, and Crabbe (1973, pp. 35-41).

The principal similarity between the Einstein and Toffaleti techniques is the use of an empirical equation to determine a bed load concentration from which the suspended load concentration can be determined. For the Toffaleti technique, the suspended zone is divided into an upper, middle, and lower zone. For each zone the integral of the product of the concentration equation and the velocity equation has been replaced by an explicit function. These functions were developed for the English system of measurement, and are not dimensionally homogeneous.

The Toffaleti formula is based on extensive data from seven rivers and flume data from four investigators. The rivers are the Mississippi at St. Louis (Jordan 1966), Rio Grande at Bernalillo (Nordin 1964), Middle Loup (Hubbell and Matejka 1959), Niobrara (Colby and Hembree 1955), and three rivers in the lower Mississippi Basin, the data for which are not published. These seven rivers had depths ranging from less than 1 ft to over 50 ft and bed sediments in the fine and medium sand ranges. The flume data were by Kennedy (1961), Vanoni and Brooks (1957), Einstein and Chien (1953), Guy, et all (1966), and Waterways Experiment Station of the United States Corps of Engineers. The flumes ranged in width from 10.5 in - 8 ft, the flow depths ranged from as little as 2 in - 2 ft and the bed sediment had median grain sizes ranging from 0.3 mm - 0.93 mm.

2.3 Similitude and Dimensional Analysis

2.3.1 Ackers and White (1973)

The Ackers and White (1973) method is based on a combination of grain shear stress and shear stress. The basic concentration equation is

$$C = c \frac{\rho_s}{\rho} \frac{D_{50}}{r} \left(\frac{v}{u_*}\right)^n \left[\frac{F_{gr}}{A} - 1\right]^m \tag{17}$$

where F_{gr} is the mobility number defined by

$$F_{gr} = \frac{u_*^n \, u_*'^{\,1-n}}{\sqrt{gD_{50}\left(\frac{\rho_s - \rho}{\rho}\right)}} \tag{18}$$

and u_*' is given by

$$u_*' = \frac{v}{\sqrt{32} \log \frac{10r}{D_{50}}} \tag{19}$$

The quantities n, A, m, and c are functions of D_{gr} which is defined by

$$D_{gr} = \left[\sqrt{\frac{\rho_s - \rho}{\rho}}\, R_g\right]^{2/3} \tag{20}$$

where $R_g = \sqrt{gD_{50}^3}/\nu$ is the grain Reynolds number.

When $D_{gr} > 60$ the four coefficients are:

$n = 0.0$

$A = 0.17$

$m = 1.5$

$c = 0.025$

and for $60 \geq D_{gr} \geq 1$:

$$n = 1 - 0.56 \log D_{gr}$$

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14$$

$$m = \frac{9.66}{D_{gr}} + 1.34$$

$$\log c = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53$$

The Ackers and White equation was developed from a combination of laboratory flume and river data. It is most applicable in the sand size range from approximately 1 to 3 mm.

2.3.2 Yang (1973)

This technique is based primarily on dimensional analysis. The principal variable is the dimensionless unit stream power, vS/w. Concentration is obtained from

$$\log C = a_1 + a_2 \log\left(\frac{vS}{w} - \frac{v_{cr}S}{w}\right) \tag{21}$$

where

and w is fall velocity.

The critical velocity is determined from

$$v_{cr} = \begin{cases} 2.05 \ldots\ldots\ldots\ldots\ldots\ldots\ldots & \dfrac{u_* D_{50}}{\nu} \geq 70 \\ \dfrac{2.5}{\log\left(\dfrac{u_* D_{50}}{\nu}\right) - 0.06} \ldots\ldots\ldots & 1.2 < \dfrac{u_* D_{50}}{\nu} < 70 \end{cases} \qquad (22)$$

As written here, the concentration is given in mass per unit mass. To convert to ppm, 6 should be added to the right side of Eq. (21).

Yang based his equation on sets of flume and field data including the Niobrara River near Cody, Middle Loup at Dunning, Nebraska, Mississippi River at St. Louis, Mountain Creek at Greenville, S.C. and the Rio Grande near Bernalillo, N.M. Flume studies included were those of Guy, Simons and Richardson (1966) Schneider, Nomicos (1956), Vanoni and Brooks (1957), Stein (1965), and Williams (1967). Particle sizes varied from 0.152-1.35 mm.

2.4 Regression approaches or others not easily classified

2.4.1 Colby (1964)

After investigating the effect of mean flow velocity, shear, shear velocity computed from mean velocity, stream power of flow, flow depth, viscosity, water temperature, and concentration of fine sediment on the bed-material discharge per foot of channel width, Colby (1964) developed the four graphical relations shown in Figures 10 and 11 for determining the bed-material discharge. In developing his computational curves Colby was guided by Einstein's bed-load function (Einstein 1950) and an immense amount of data from streams and flumes (Simons and Richardson 1966). Data were used from at least a score of streams including those from the Middle Loup River, Niobrara River, Colorado River at Taylor's Ferry and the Mississippi at St. Louis. However, it should be understood that all curves for the 100 ft depth, most curves of 1.0 ft and 0.1 ft are not based entirely on data but are developed from limited data and theory.

In utilizing Figures 10 and 11 to compute the bed-material discharge the following procedure is utilized: (1) the required data are mean velocity U, depth d, median size of bed material D_{50}' water temperature T and fine sediment concentration C_f; (2) uncorrected sediment discharge q_{Ti} for the given U, d, and D_{50} can be found from Figure 11 by first reading q_{Ti} knowing U and

D_{50} for the two depths that bracket the desired depth. Then a logarithmic scale of depth versus q_{Ti} is used to interpolate in order to determine the bed-material discharge per unit width for the actual d, U and D_{50}; (3) two correction factors k_1 and k_2 shown in Figure 11a and 11b respectively, account for the effect of water temperature and fine suspended sediment on the bed-material discharge. If the bed-material size falls outside the 0.2 to 0.3 mm range, factor k_3 from Figure 11c is applied to correct for sediment size effect. True sediment discharge q_T corrected for water temperature effect, presence of fine suspended sediment, and sediment size is given by

$$q_T = [1 + (k_1 k_2 - 1)\ 0.01\ k_3]\ q_{Ti} \tag{23}$$

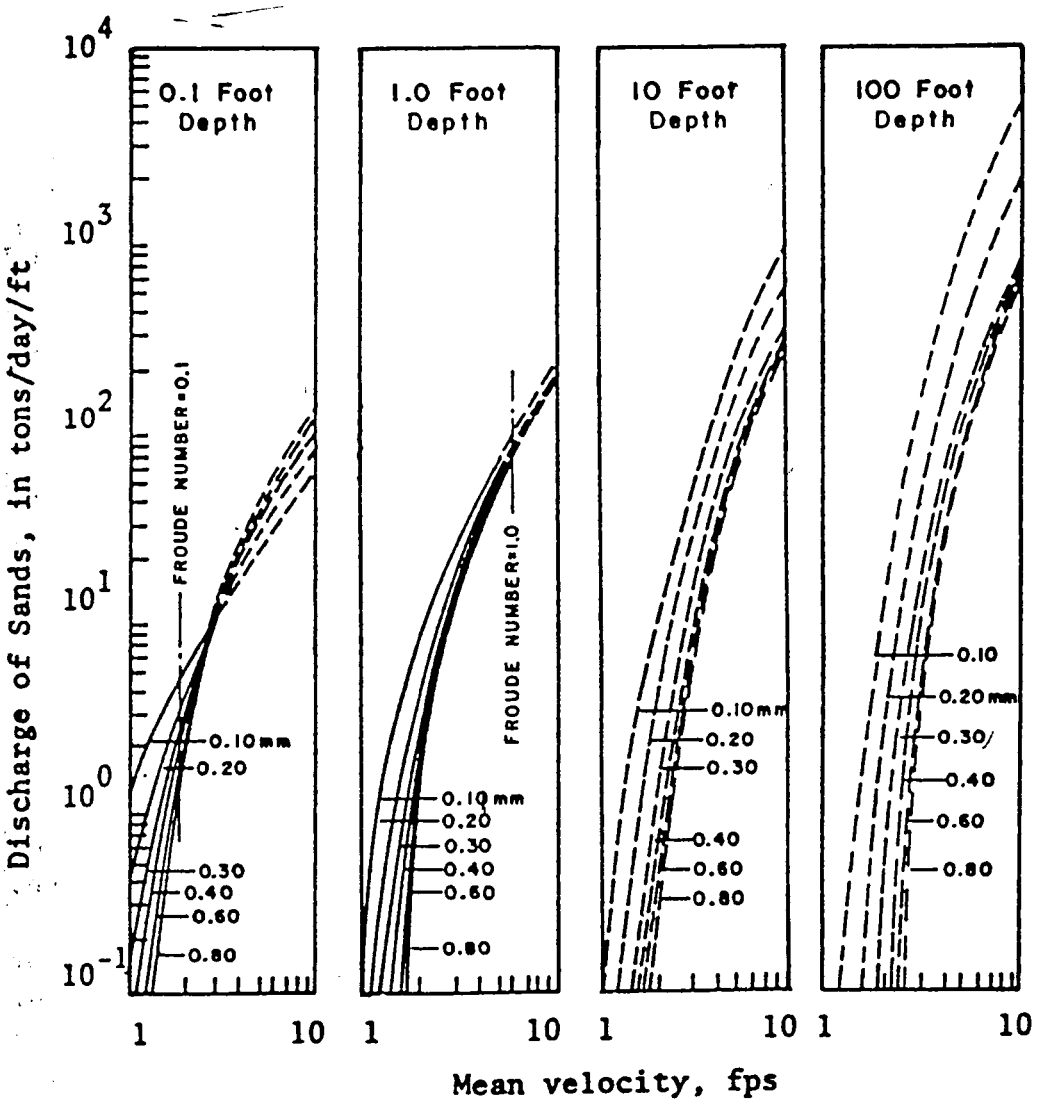

Figure 10. Relation of discharge of sands to mean velocity for six median sizes of bed sands, four depths of flow, and a water temperature of 60 degrees F (Colby 1964).

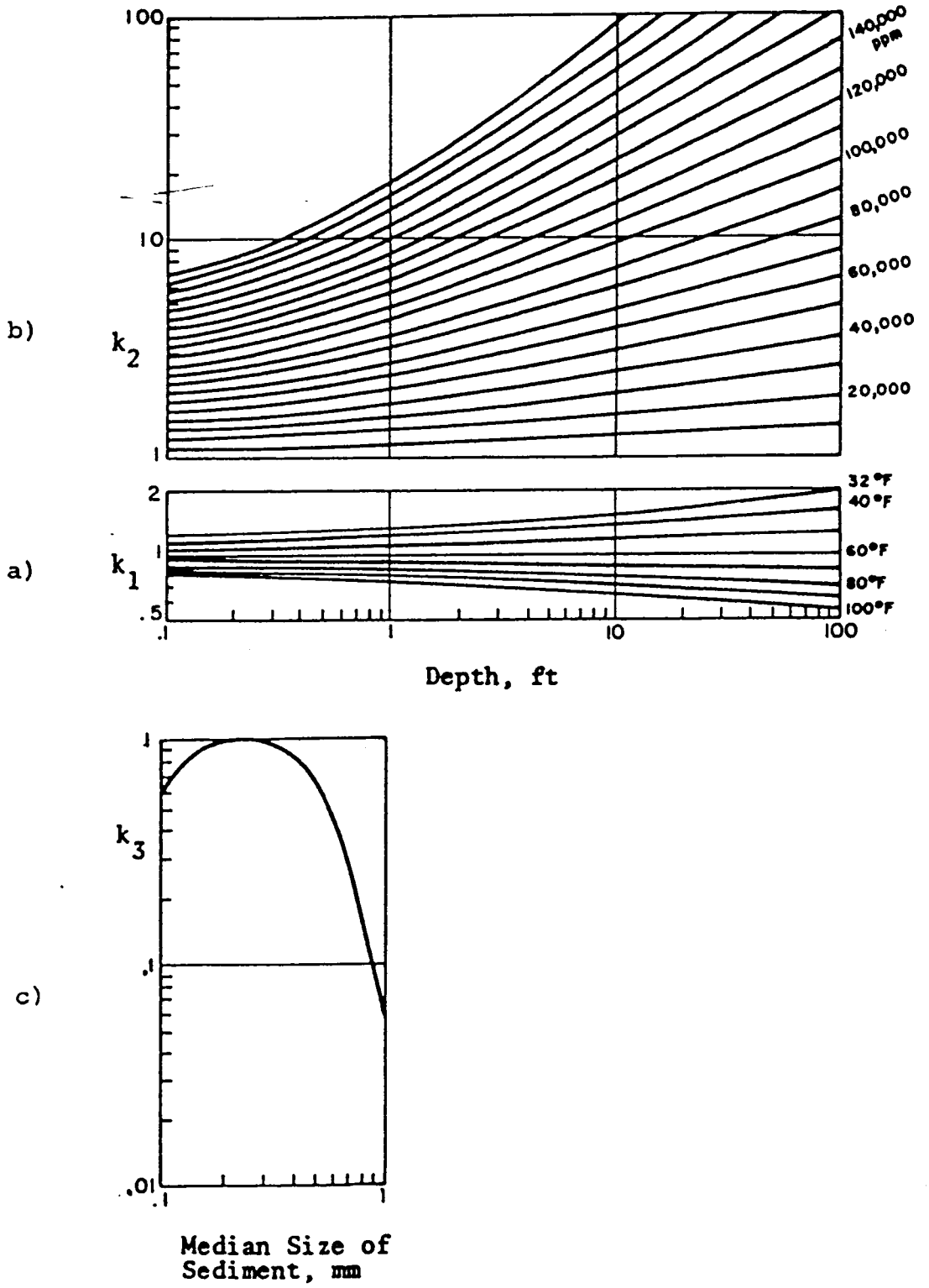

Figure 11. Colby's correction curves for temperature and fine sediment (Colby 1964).

2.4.2 Shen and Hung (1971)

Shen and Hung (1971) developed a single equation using advanced curve fitting techniques. The equation does not use dimensionless parameters and the units are in the English system. The equation for C in ppm by mass is:

$$\log C = a_o + a_1X + a_2X^2 + a_3X^3 \tag{24}$$

where

$$X = v^{a_4} S^{a_5} w^{a_6} \tag{25}$$

The quantities v and w are the flow velocity and fall velocity of the median sediment particle, respectively, in ft/s. The coefficients are:

a_o = -107404.46

a_1 = 324214.75

a_2 = -326309.59

a_3 = 109503.87

a_4 = 0.00750189

a_5 = 0.00428802

a_6 = -0.00239974

which have been rounded to 8 significant figures.

This equation is based on 587 data points mainly for flume data. An evaluation (Simons and Senturk 1966) indicated that prediction of sediment transport for flumes to be quite good. However, the equation underpredicted measured transport for the Rio Grande, Mississippi, Atchafalaya, Red Rivers and Pakistani canals. Its major limitation is its dependance on flow depths for a limited range.

2.5 Equations Based on Partial Measured Data

2.5.1 Modified Einstein (1955)

Colby and Hembree (1955) and subsequently others proposed a modified Einstein procedure to obtain the total sediment transport rate in a river. The term "modified Einstein procedure" usually gives the impression that it serves the same purpose as Einstein's (1950) procedure. Actually these two procedures, although based on similar principles, serve entirely

different purposes. Einstein's procedure used mainly for design purposes (as well as other equations that predict the bed-material discharge), estimates bed-material discharges for different river discharges based on channel cross section and sediment bed samples on selected uniform-flow river reaches. The modified Einstein procedure, on the other hand, estimates total sediment discharge (including wash load) for a given water discharge from measured depth-integrated suspended sediment samples, stream flow measurements, bed-material samples, and water temperature for specific discharge at the cross section.

Major differences between the modified Einstein procedure (1955) and original Einstein procedure (1950) include:

1. The modified calculation is based on a measured mean velocity rather than on a calculated velocity from the given slope, and depth is observed in each vertical in which velocity is measured.

2. The suspended-load exponent Z in equation (19) is determined from the observed Z value for a dominant grain size. Values of Z for other grain sizes are derived from that of dominant size and are assumed to vary with the 0.7 power of their fall velocity.

3. A slight change in the hiding factor is introduced.

4. The depth d is used to replace the hydraulic radius.

5. The value of Einstein's intensity of bed-load transport is arbitrarily divided by a factor of two to fit the observed transport data more closely. There is some criticism on this point.

Data needed are stream discharge Q, mean velocity U, cross sectional area A, stream width B, mean value d_v of the depths at verticals where suspended sediment samples were taken, measured sediment discharge concentration C_s', size distribution of the measured load i_s, size distribution of bed material at the cross section i_b, and water temperature T.

The modified Einstein procedure rendered good predictions for the Niobrara and Loup Rivers as demonstrated by Schroeder and Hembree (1956). Also, the theory should be generally more applicable to streams of different character because much of the sediment discharge is actually measured. This is particularly true for deeper streams.

3. Develop Your Own Transport Equation - Power Relations

The following paragraphs describe an accurate and efficient method of evaluating sediment discharge. The method is based on easy to apply power relationships that estimate the sediment transport rate based on the velocity and depth of flow. The

power relationships were developed from computer generated data obtained from solution of the Meyer-Peter, Muller bed-load transport equation and EInstein's integration of the suspended bed-material discharge. A publication by Simons, Li and Fullerton (1981) details the development procedure.

The results of the sediment transport equation determination are presented in Table 1. These results show the high level of dependence that sediment transport rates have with respect to velocity. The dependence on depth is less important. Note that some sizes have a proportional dependence and others are inversely proportional. Some exhibited almost no dependence. The smaller sizes have the proportional dependence since the smaller material is more easily suspended and the resulting sediment concentration profiles are more uniform. Thus, the larger the depth, the more sediment which will be suspended for a given velocity. For the larger sizes of sediment, the sediment is more difficult to suspend and keep in suspension. As the depth increases for a given velocity, the intensity of the turbulent transfer properties decreases for these sizes. The increase in area available for suspended sediment with the increased depth does not totally counterbalance the reduced turbulent transfer characteristics. The result is an inverse dependence of transport rate on depth for these larger sizes. The sizes with almost no dependence on depth in their transport rate fall between these two extremes.

TABLE 1

$$q_s = a_1 Y^{a_2} V^{a_3}$$

	d_{50}=0.1 mm	d_{50}=0.25 mm	d_{50}=0.5 mm	d_{50}=1.0 mm	d_{50}=2.0 mm	d_{50}=3.0 mm	d_{50}=4.0 mm	d_{50}=5.0 mm
				G = 1.0				
a_1	3.30×10^{-5}	1.42×10^{-5}	7.6×10^{-6}	5.62×10^{-6}	5.64×10^{-6}	6.32×10^{-6}	7.10×10^{-6}	7.78x10
a_2	0.715	0.495	0.28	0.06	-0.14	-0.24	-0.30	-0.34
a_3	3.3	3.61	3.82	3.93	3.95	3.92	3.89	3.87
				G = 2.0				
a_1		1.59×10^{-5}	9.8×10^{-6}	6.94×10^{-6}	6.32×10^{-6}	6.62×10^{-6}	6.94×10^{-6}	
a_2		0.51	0.33	0.12	-0.09	-0.196	-0.27	
a_3		3.55	3.73	3.86	3.91	3.91	3.9	
				G = 3.0				
a_1			1.21×10^{-5}	9.14×10^{-6}	7.44×10^{-6}			
a_2			0.36	0.18	-0.02			
a_3			3.66	3.76	3.86			
				G = 4.0				
a_1				1.05×10^{-5}				
a_2				0.21				
a_3				3.71				

q_s = sediment transport rate in ft^3/sec (unbulked)
Y = depth in feet
V = velocity in ft/sec
G = gradation coefficient

When applying the equations given in Table 1, care should be taken so that the range of parameters being used is not out of the range used to develop the equations. Table 2 lists the range of parameters used in the equation development. When using the equations to determine sediment transport rates, the conditions should be checked against Table 2. If conditions are within the ranges outlined in Table 2, the regression equations should provide results within ten percent of the theoretically computed values.

Table 2
Range of Parameters Examined

Parameter	Value Range
Froude No.	1-4
Velocity	6.5-26 (ft/sec)
Manning's n	0.015 - 0.025
Bed Slope	0.005 - 0.040
Unit Discharge	10-200 (cfs/ft)
Particle Size	$d_5 \geq 0.062$ mm $d_{90} \leq 15$ mm

4. Summary

A number of bed load and bed material transport equations have been presented in previous sections. They are not the only equations in use, in fact many more are available. They are, however, available in the "CORPS" system of programs from WES or in HEC - 6. As we have developed so many equations for application to specific circumstances it is to be expected that one might become confused over which method to use. The key is to utilize an equation within the range of variables for which it was developed. The rest of this section will attempt to provide some hard and fast rules of applications. Should you ever question the most applicable formula for your problem, please consult someone with more background in sedimentation engineering.

Table 3 lists the transport equations described herein and indicates whether they are bed load on total bed material transport equations, are for a single grain size or a full size distribution, gives the size range and hydraulic conditions for which the equations were developed, and lists the data bases used in their development.

TABLE 3

Sediment Transport Equation	Type	Uniform Grain Size	Size Range (mm)	Slope	Basis of Equation
Duboys	Bed-load	Yes	0.1-4.0	------	Gilbert and Johnson small flume data.
Shields	Bed-load	Yes	1.7-2.5	------	Two flumes widths 40-80 cm., 5 sediments s.g. = 1.06-4.2. All moved as bed-load, well sorted.
Schoklitsch	Bed-load	Yes	0.3-5.0	.006 - .03	Gilbert flume data, well graded and sorted. Compared well with 2 European gravel bed rivers.
Meyer-Peter & Muller	Bed-load	Yes	0.4-30	.0004 - .02	Flume experiments, widths 15cm - 2m, depths 1cm - 120cm. Sediments ranged from coal to river sediment
Laursen	Bed Material Transport	No	.011-4.08 flumes .277-.86 rivers	------	Flumes from 10.5 in. wide and 40 ft. long to 3 ft. wide and 90 ft. long. s.g. =2.65 Well sorted to well graded. Niobrara River, Mountain Creek, and West Goose Creek. Depth ranged from .12-1.3 ft. with D50=.277, .86 and 2.87 mm.
Einstein	Bed Material Transport	No	.785mm 28.65mm	------	Flume experiments 10.5 in. wide 40 ft. long with sorted sediment and graded fine sand.
Toffaleti	Bed Material Transport	No	Fine to Medium Sand Rivers, .3-9.3 flumes	------	7 rivers, depths .1 - 50 ft., flumes 10.5 in.- 8 ft., depths 2 in. - 2 ft.. Mississippi, Rio Grande, Middle Loup, Niobrara, Lower Mississippi-3 rivers.
Ackers - White	Bed Material Transport	Yes	1-3	------	Flume and lowland rivers.
Yang	Bed Material Transport	Yes	.152-1.35	.0000428-.0075	Six sets of flume data, Niobrara, Middle Loup, Mississippi, Mountain Creek, Rio Grande. Depths vary from .1 - 5ft. with exception of Mississippi, D=16-50ft.
Colby	Bed Material Transport	Yes	.1-.8	------	Extensive flume and river data. Probably most complete in this regard. Depth 1 - 100 ft.
Shen and Hung	Bed Material Transport	Yes	Sands	------	Flumes and rivers of small depth.
Modified Einstein	Total Load	No	.28 Niobrara	.0013 Niobrara	Niobrara and Middle Loup Rivers.

Direct comparison of available methods for calculation of sediment transport has been done in the fairly recent past by the following authors:

1) Shulits and Hill (1968)

2) White, Milli and Crabbe (1973)

3) Brownlie (1981)

Additional references that the reader might wish to investigate include,

1) ASCE Sedimentation Manual (1975)

2) Simons and Senturk (1976)

3) Other Sedimentation engineering texts.

Please see the complete list of references appended to this section for further information. The most complete work is Brownlie's (1981). Figure 12 shows Brownlie's comparison of the accuracy of fourteen sediment transport equations including his own. Brownlie based his statistical analyses on 20 sets of flume data and 11 sets of field data. In other words he applied each transport equation using these individual data for comparison. As he had not developed his own equation prior to the analysis it is not surprising that his function shows the best fit to the data. If each equation had been applied only within the constraints for which they were developed agreement would have been much better. It is instructive, however, to note the range of variability.

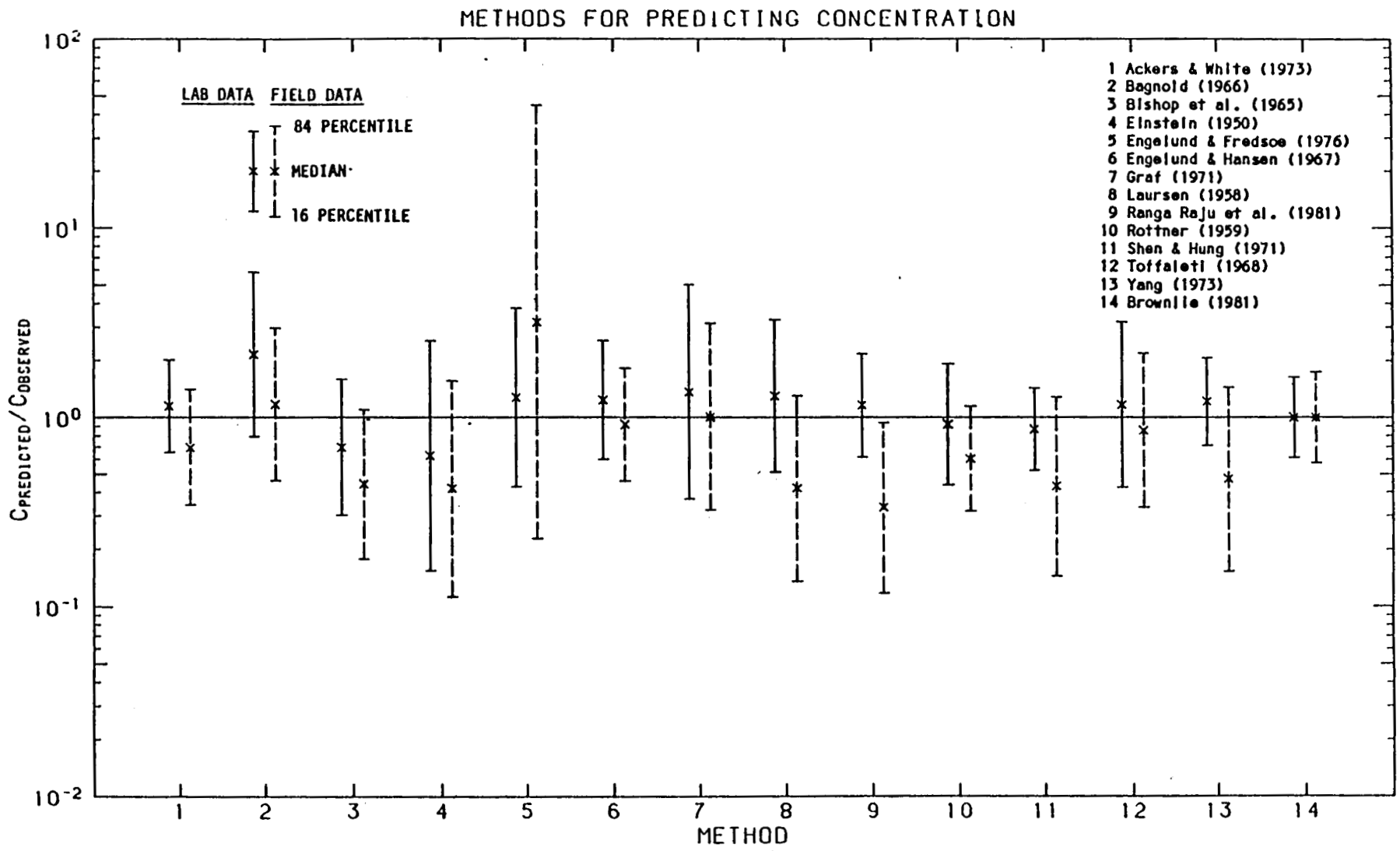

Figure 12 Comparison of methods for predicting sediment concentration. Median and 16 and 84 percentile values are based on the approximation of a log-normal distribution of errors.

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SELECTION OF SEDIMENT TRANSPORT RELATIONS

by

David T. Williams

WEST Consultants, Inc.

INTRODUCTION

Need

Presently, there are numerous sediment transport relations developed under various river and flume conditions. In fact, Alonso (1980) identified 14 bedload formulas and 17 total bed material load formulas that have been used to some extent. There are many more that have not attained prominence and more formulas will continue to be developed. The sediment modeler is then confronted with which of these sediment transport relations is the best for the river under investigation.

Selection of an appropriate sediment transport relation is very important in modeling of a river's response to existing and project conditions. Ideally, one would measure the sediment transport of a river for a wide range of flow conditions and compare the results with computed values using various sediment transport relations. The relation that best fits the data for the full range is then selected. Two problems come into mind, however. Often there is not sufficient data, either in time and/or in space, to fully evaluate the effectiveness of a transport relation. Another problem is that we are often required to simulate future conditions involving significant changes in the flow and sediment conditions. For instance, a future upstream impoundment may completely change the flow range and the amount of sediment entering the reach of concern. A channel shortening could completely change the bed material, slope, and channel geometry. Calibration of a sediment relation for existing conditions may not be valid if the described future conditions are anticipated.

In order to properly determine the appropriate sediment transport relation for any given river condition, a physically and process based selection method is required. This presentation shows some commonly used qualitative selection procedures and references a paper by this writer regarding an attempt at a quantitative procedure.

SEDIMENT TRANSPORT RELATION SELECTION PROCESS

Selection Process

Sediment transport rates depend on such variables as particle size and gradation, stream dimensions and configuration, amount of washload, bedforms, turbulent intensity, and bed armoring. The macroscale variables such as differing hydrology, geology, and climate also affect the transport rate. Because of the large range and number of influencing variables, it is not possible to select a sediment transport relation that satisfactorily encompasses all the stream conditions that the sediment engineer would encounter. However, a stream may be analyzed using certain transport functions if the selection of these functions is performed under a systematic selection procedure and their limitations are fully understood.

Qualitative Selection Procedure

The following selection procedure is suggested by Shen (1971).

If field data is available:

1. Use the Modified Einstein Method (Colby and Hembree, 1955) to estimate the measured suspended load and bedload based on measured data. There is a question of whether Einstein's intensity of bedload transport should be arbitrarily divided by a factor of two.

2. Separate bed material load from the washload and analyze them separately.

3. Decide which available sediment transport equation best agrees with the measured data and use it to estimate the sediment transport rate for the design flow, where actual measurement is not available.

If no measured data are available:

1. Use Einstein's (1950) procedure if bedload is a significant portion of the total bed material load. Otherwise see 4 below.

2. Use Colby's (1964) method for rivers with flow depths less than or about 10 feet: also see 4 below.

3. Use Toffaleti's (1968) method for large rivers.

4. Use Shen and Hung (1971) method for flume data and small rivers.

Yang (1986) makes these further suggestions for no measured data:

1. Use Meyer-Peter and Müller's (1948) formula when the bed material is coarser than 5mm.

2. Use Yang's (1973) sand formula for sand bed laboratory flumes and natural rivers with washload excluded. Use Yang's (1984) gravel formula for gravel transportation when the bed material is between 2 and 10mm.

3. Use Ackers and White (1973) or Engelund and Hansen's (1967) equation for subcritical flow in the lower flow regime.

4. Use Laursen's (1958) formula for laboratory flumes and shallow rivers with fine sand or coarse silt.

5. A regime or regression equation can be applied to a river only if the flow and sediment conditions are similar to that from which the equation was derived.

The above procedures and recommendations are useful but no guidance is given on what criteria must be satisfied to decide which transport equation best agrees with the data. Also, the range of conditions to be analyzed is often larger than the range of data used to develop the transport equation. This does not necessarily preclude the use of the relation but no guidance is given to evaluate the confidence one should have in these transport functions if applied beyond their data range and there is no field data for verification.

Quantitative Selection Procedure

Because of the lack of a systematic procedure to quantify the applicability of a sediment transport relation's ability to emulate a river situation, Williams (1986) proposed a procedure to give relative weightings to sediment transport relations as they apply to a given river system. An abbreviated version of the paper is enclosed.

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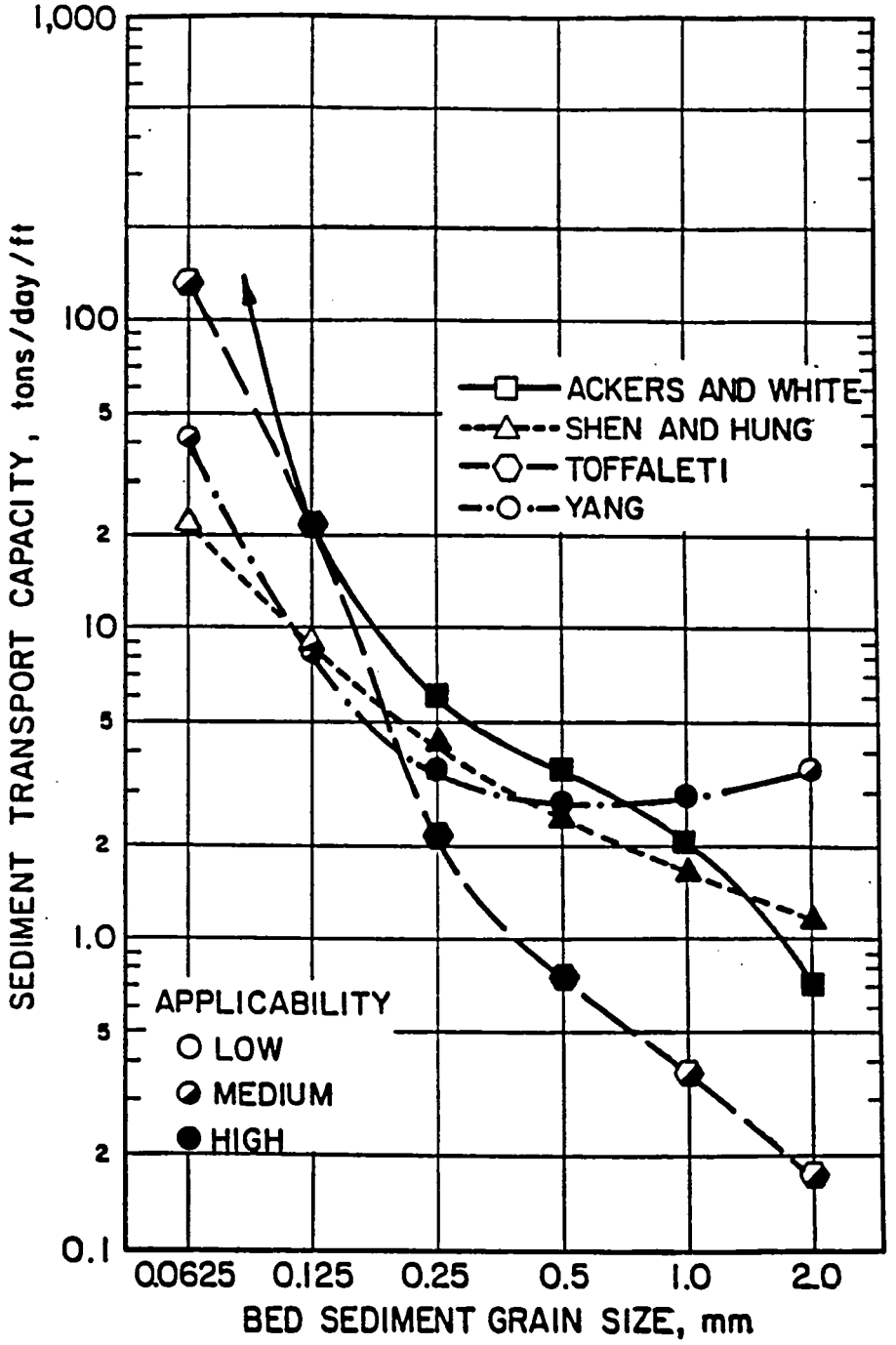

FIGURE 1. DEPTH of 2 FEET

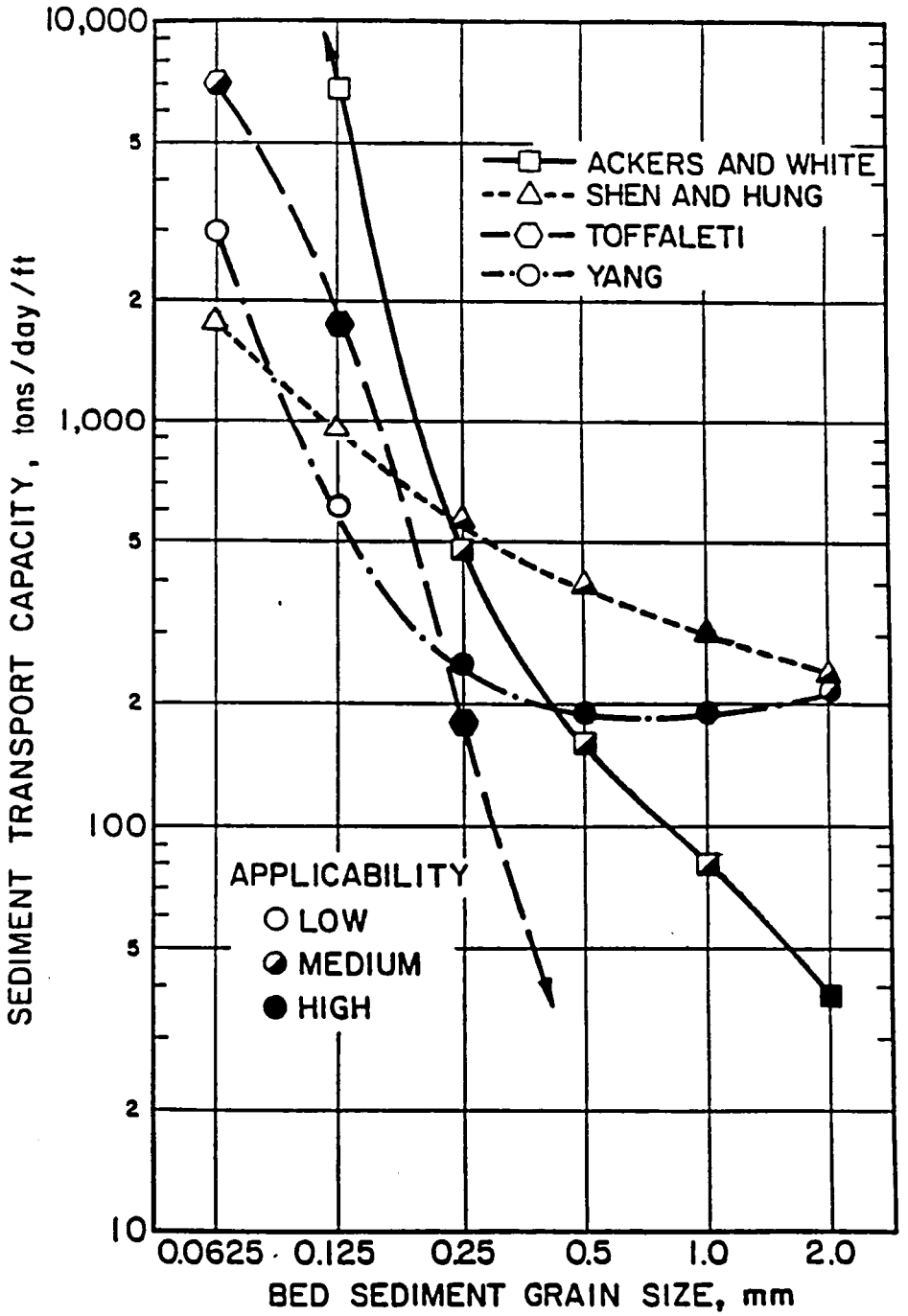

FIGURE 2. DEPTH OF 10 FEET

ON THE SELECTION OF SEDIMENT TRANSPORT EQUATIONS

David T. Williams[1], M.ASCE, and Pierre Y. Julien[2], M.ASCE

ABSTRACT

Existing sediment transport relationships have been calibrated under a certain range of experimental conditions which can be described by the dimensionless grain size, the mobility number, and the dimensionless flow depth. For given stream flow conditions an index describing the number of parameters within the range of experimental values is defined. The applicability of four sediment transport equations for sand-bed channels under limited flow conditions (Slope = 0.0005 ft/ft and n= 0.02)can be assessed from the value of this index. Higher applicability is found at flow depths less than 2 ft. Low applicability is observed either at flow depths larger than 10 ft or for sediment sizes smaller than 0.125 mm.

METHODOLOGY

In the analysis of the alluvial river response to natural and man-induced changes, engineers and modelers are often confronted with the selection of an appropriate sediment transport equation. The complexity of the selection process has been recognized by most investigators and existing guidelines include those of Shen (1971) and Yang (1986).

Existing sediment transport relationships are based upon calibration against flume and river data. It is believed that an analysis highlighting the range of applicability and the inherent limitations of sediment transport relationships should be conducive to an implementation of existing guidelines. The interesting results of a preliminary investigation limited in scope to four sediment transport equations applied to hypothetical flow conditions are presented.

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1 Research Hydraulics Engineer, Hydraulics Laboratory, USAE Waterways Experiment Station, Vicksburg, MS.

2 Asst. Prof., Department of Civil Engineering, Colorado State University, Fort Collins, Colorado 80523.

In spite of the complexity of sediment transport due to the large number of variables involved, the dominant processes can be described with fewer dimensionless parameters. Among the key dimensionless parameters selected in this analysis, the relative roughness (or submergence) Z, the mobility number F_{gr} and the dimensionless grain sizes d_{gr} defined below are common to several transport equations.

$$d_{gr} = d \left[\frac{g(G-1)}{\nu^2}\right]^{1/3} \tag{1}$$

$$F_{gr} = \frac{U_*^2}{gd(G-1)} \tag{2}$$

$$Z = \frac{D}{d} \tag{3}$$

The parameter d_{gr} indicates the ratio of gravity to viscous forces applied on sediment particles and involves the following variables: the sediment size d, the gravitational acceleration g, the specific gravity of sediments G and the kinematic viscosity ν. The parameter F_{gr} is equivalent to the Shields number; and depends on the shear velocity U_*. The relative submergence Z, describes resistance to flow and varies with flow depth D.

The four sediment transport equations selected are those of Ackers and White (1973), Shen and Hung (1971), Toffaleti (1968) and Yang (1973). The range of applicability for each of the three dimensionless parameters for these equations is shown in Table 1. Note that these values were obtained using the combinations of variables that maximized or minimized the parameters.

Table 1 - Range of the Parameters d_{gr}, F_{gr} and Z

Equation	d_{gr}	F_{gr}	Z
Ackers-White	4 - 60	< 5.7	20-2500
Shen-Hung	3.3-33.3	< 7.2	23-3400
Toffaleti	2.2-24	< 9.5	41-92500
Yang	2.6-43.8	< 5.8	20-19500

Under given field conditions, the three parameters, d_{gr}, F_{gr} and Z can be calculated from Eqs. 1, 2 and 3 and compared with the ranges presented in Table 1. An applicability index is defined as the sum of the number of parameters within the range of values in Table 1 (High = 3 parameters; Medium = 2 or 1 parameter; Low = 0 parameter). Of course, best results are expected for high values of the index because the field conditions are within the flow conditions used for calibration of the sediment transport equation. Low values of the index indicate that the sediment transport calculations involve extrapolation beyond the range of applicability of the sediment transport equation, which may yield either accurate or incorrect results.

Hypothetical flow conditions have been selected to test the usefulness of the applicability index to sand bed channels. Steady uniform flow in wide channels was considered with keeping the slope constant at 0.0005 ft/ft, Manning's n = 0.02, water temperature at 70°F, and specific gravity of the sediments G = 2.65. Sediment transport capacity was calculated for flow depth ranging from 0.5 to 20 feet assuming uniform sand bed with sediment size ranging from 0.0625 to 2mm. In spite of these flow limitations, the variabilities of the three parameters are:

(1) $1.6 < d_{gr} < 51.3$; (2) $0.045 < F_{gr} < 57.3$; (3) $76 < Z < 100000$.

RESULTS

The results of this analysis are shown in terms of applicability tables showing the values of the applicability index in a matrix of sediment size and flow depth. As an example, the applicability table for each of the four sediment transport equations are shown in Table 2. The results obtained from this analysis of limited flow conditions are rather instructive: (1) Most equations have a relatively high applicability at flow depth less than 2 ft; (2) None of these equations shows high applicability for sediment sizes less than 0.125 mm; and (3) the applicability index for these equations at flow depths larger than 10 ft are in general relatively low.

Additional information on the comparison of sediment transport capacity of these four equations has been compiled by Williams (1986). Extension of this investigation to a wide range of slope and roughness values has been undertaken.

ACKNOWLEDGMENT

This study has been carried out as part of the first writer's studies at Colorado State University. The findings and opinions of the writers do not necessarily reflect those of the Corps of Engineers. Permission to publish this paper was granted by the Chief of Engineers.

Table 2.
Applicability tables of four sediment transport equations
(at slope = 0.0005 ft/ft, n = 0.02)

Method	Sediment Size (mm)	Depth, Feet				
		0.5	2.0	5.0	10.0	20.0
Ackers and White	0.0625	L	L	L	L	L
	0.125	M	M	L	L	L
	0.25	H	H	H	M	L
	0.5	L	H	M	L	L
	1.0	L	H	M	L	L
	2.0	L	M	M	M	L
Shen and Hung	0.0625	M	M	M	M	M
	0.125	M	M	M	M	M
	0.25	H	H	M	M	L
	0.5	H	H	H	M	L
	1.0	H	H	M	L	L
	2.0	H	H	M	L	L
Toffaleti	0.0625	M	M	M	M	M
	0.125	H	H	H	H	H
	0.25	H	H	H	H	M
	0.5	H	H	M	M	L
	1.0	M	M	M	L	L
	2.0	M	M	L	L	L
Yang	0.0625	L	L	L	L	L
	0.125	H	M	M	M	M
	0.25	H	M	M	M	L
	0.5	H	H	M	L	L
	1.0	H	H	M	L	L
	2.0	H	M	M	M	L

APPENDIX - REFERENCES

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

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Shen, H. W., and Hung, C. S., "An Engineering Approach to Total Bed Material Load by Regression Analysis," Proceedings of the Sedimentation Symposium, Chapter 14, Berkeley, CA, 1971.

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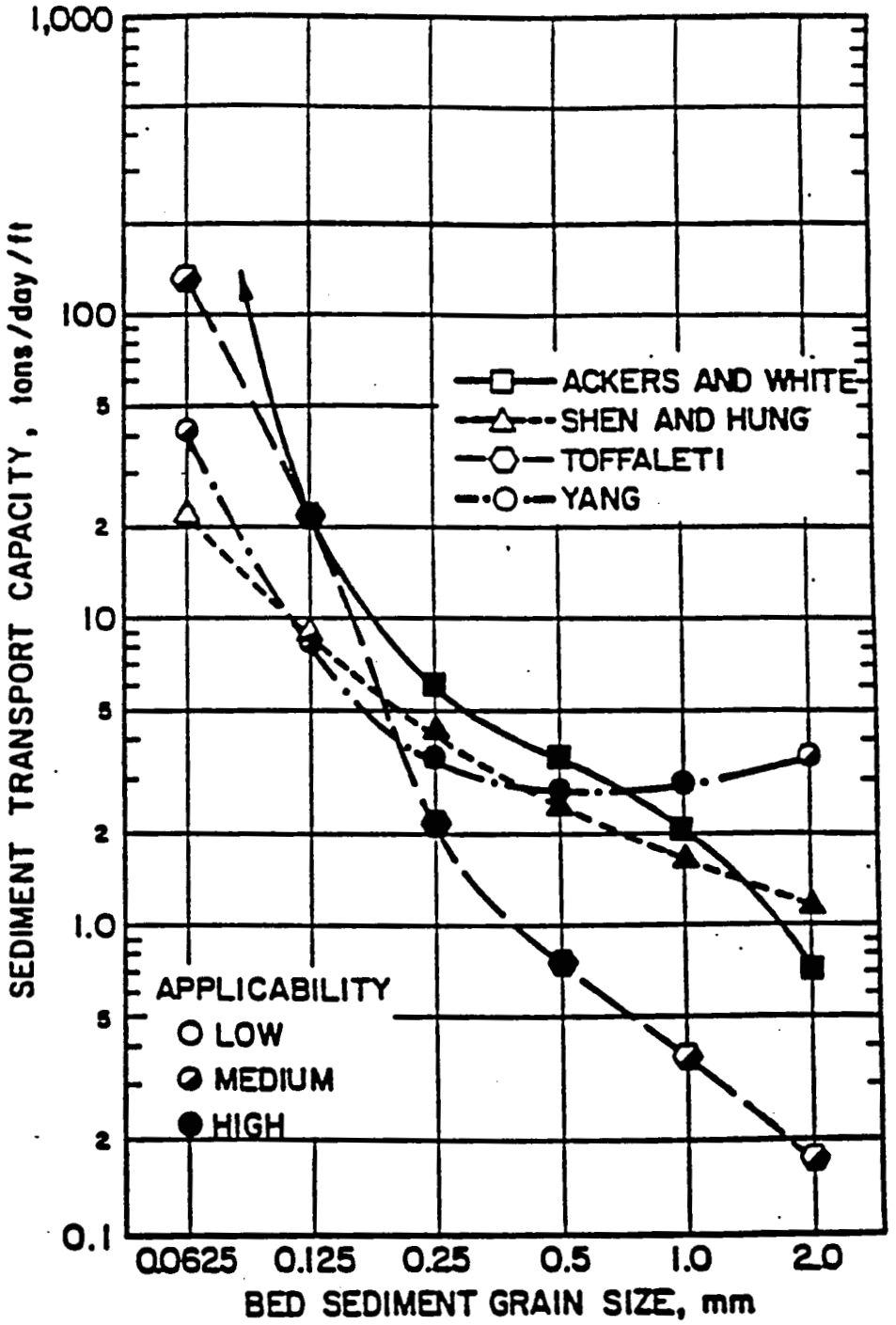


FIGURE 1. DEPTH of 2 FEET

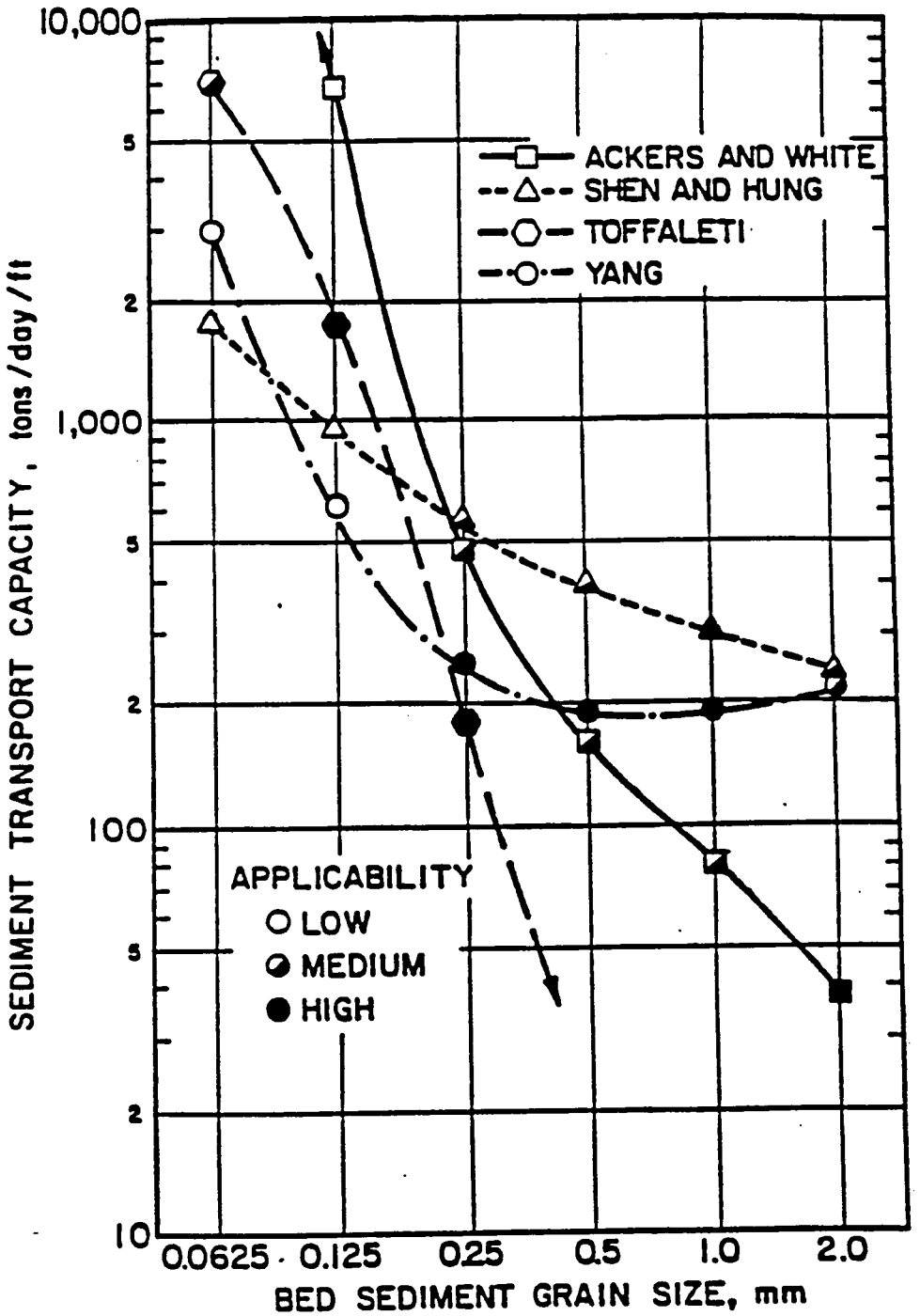


FIGURE 2. DEPTH OF 10 FEET

DEVELOPMENT OF BED MATERIAL AND INFLOWING LOAD DATA

BED MATERIAL DATA

A. Classification of Rivers by Bed Material

1. Cohesive

   a. Particle diameter
   b. Specific Weight of material
   c. Threshold of particle deposition
   d. Shear stress threshold for particle erosion
   e. Shear stress threshold for mass erosion
   f. erosion rate for particle erosion
   g. erosion rate for mass erosion
   h. unit weight of initial deposit
   i. compaction rate
   j. unit weight of compacted deposit

2. Non-cohesive

   a. Particle diameter and distribution
   b. Specific weight

B. Characteristics of Non-cohesive Streambeds

1. Sand-bed streams are characterized by bedforms
   a. dunes
   b. antidunes
   c. plain bed

2. Gravel-bed streams
   a. riffles and pools
   b. gravel bars

3. Boulder-bed streams
   a. pools
   b. steps

C. Bed Material Distributions

1. Cumulative frequency curves

   a. Uniform distributions are characteristic of many large sand-bed streams
   b. Heterogeneous distributions are characteristic of coarser bed
   c. Bimodal distributions occur in sand and gravel streams

2. Standard Deviation applies to uniform distributions

D. Bed Material Variation

1. Longitudinally : Expect a steady decrease in grain size in the downstream direction. This is generally attributed to decrease in slope. Longitudinal oscillations are due to variations in river cross-sections and meandering.

2. Laterally : Due to meandering and variation in depth.

3. Vertically : Due to variations in hydraulic conditions with hydrograph.

4. Temporally : Due to change in supply from watershed or change in hydraulic conditions upstream.

E. Input to HEC-6

1. Identify study objective and focus bed material data collection on appropriate size material.

   a. Maintenance is usually concerned with sediment accumulation - focus on deposits

   b. Degradation and scour studies are dependant on armoring process - be sure armoring sizes are included in sampling program.

2. N Card

   Field 1: Comment

   Field 2: SAE - The fraction of the bed surface are exposed. Used as a means of providing artificial armor.
   1.0 = total area exposed
   blank = 1.0
   .000001 = armored

   Field 3: DMAX - Maximum grain size in feet Usually larger than maximum grain size class in model.

   Field 4: DXPI - Grain size of upper break point in gradation curve in feet

   Field 5: XPI - Percent finer for DXPI

   Field 6: Total grain size fraction in bed
   0 = Sums fractions on subsequent fields
   1.0 = Normalizes subsequent fractions to 100 percent

Field 7: Fraction in smallest model size class

Fields 8-10: Fractions for subsequent size classes

Fields 2-10: Continuation card for additional size class fractions

3. PF Card

Field 1: Comment

Field 2: Cross Section Location (from X1 card)

Field 3: SAE

Field 4: DMAX in mm

Field 5: Grain Size on gradation curve in mm

Field 6: Corresponding Percent finer

Continuation on PFC card starting in Field 1

SEDIMENT INFLOW DATA

A. <u>Definition of Sediment Load</u>

1. By sampling technique

   a. Measured Load
   b. Unmeasured Load

2. By primary transport driving force

   a. Turbulence: Suspended Load
   b. Shear Stress: Bed Load

3. By primary sediment source

   a. Watershed: Wash Load
   b. Streambed: Bed Material Load

4. By source and force

   a. Suspended Bed Material Load
   b. Bed Load

B. <u>Sampled Suspended Load as input data for HEC-6</u>

1. Requires data for a full range of discharges: beware of simple power regression fits!

2. Expect data scatter

   a. Long-term changes occur due to watershed development

   b. Short-term changes occur due to construction or flood-drought cycles

   c. Changes during the rise and fall of the hydrograph occur due to changes in bed form or bed material gradation

3. Conduct sensitivity analysis using envelope of sampled data

4. Determine size class distribution

   a. Separate wash load and bed-material load

   b. Percentage in each size-class varies with discharge

   c. Estimate size-class percentage

      1) Calculations

      2) Use limited sample data and sediment transport weighted average

$$Pi = \frac{\sum_{j=1}^{n} Pij\ Qsj}{\sum_{j=1}^{n} Qsj}$$

where: Pi = Weighted average percent in size class i
n = Number of samples
Qsj = Sediment discharge of sample j
Pij = Percentage of sediment sample j in size class i

C. <u>Sampled Bed Load</u>

1. In sand-bed streams can usually be estimated or ignored

2. Requires extensive sampling program over a wide range of discharges to obtain reliable results

D. <u>Transferring Data from Adjacent Basin</u>

$$Se = Sm\ (\ Ae\ /\ Am\ )^{0.8}$$

where: Se = Sediment Yield from project basin
Sm = Sediment Yield from gaged basin
Ae = Drainage area from Project basin
Am = Drainage area from gaged basin

E. Calculating Sediment Inflow Assuming Equilibrium Transport

1. Identify a stable upstream reach with a definable average bed material gradation representative of the study reach

2. Apply several transport functions

3. Calculate by size class

F. Use as an Adjustment parameter

1. Need surveys with aggradation or degradation trends

2. Hydrology in between surveys

3. Assume stable channel

G. Tributary Inflow

1. Sampled data

2. Assume same concentrations as main stem

3. Calculate equilibrium potential

H. Bank Erosion

1. Compare upstream and downstream sampled data

2. Historical data

   a. aerial photos

   b. surveys

Development of Sediment Data

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

Objective: The student will know a method for developing the sedimentary data set for HEC-6.

References: US Army Corps of Engineers, "Channel Stability Assessment for Flood Control Projects," Engineering Manual 1110-2-1418, October 31, 1994.

1. Instructions for coding the sedimentary data are found in Appendix A, Section 2 in the HEC-6 User's Manual. **Record names are also listed in Appendix A, pgs. v and vi.** Tasks in this workshop are presented in the order that follow.

The following records will be required:

```
T4                          A-23(Page in HEC-6 Manual)
T5                          "
T6                          "
T7                          "
T8                          "
I1                          A-24
I4                          A-31 - 33
LQ    CFS    80000          A-37
LT    T/D    ?????          A-38
LF    VFS                   A-39
LF     FS                   "
LF     MS                   "
LF     CS                   "
LF    VCS                   "
LF    VFG                   "
LF     FG                   "
LF     MG                   "
LF     CG                   "
LF    VCG                   "
PF   cmt                    A-40
PFC                         "
```

2. <u>Classify the Stream.</u> A stream can be classified as a bed load, a suspended load or a wash load stream depending on the properties of the sediment in the boundary material. If the boundaries are primarily clay, the stream is a wash load stream. If

the boundaries are sand, the stream can be simulated as a suspended, bed-material load stream. If the bed is primarily sand with a thin gravel surface layer, it is probably a sand bed stream with armoring. If the bed is gravel, the stream is a gravel bed stream. When the bed is predominately gravel with a secondary (relatively small) mode of sand deposits in the samples, it is a gravel bed stream with a sand through put.

The Bed Material Gradation curve for the stream in this example is shown in figure 2. 1.

Dmax is _____ mm

Dmin is _____ mm

D50 is _____ mm

How much cohesive sediment was found in the bed samples? _____

How much sand? _____

2.2 Therefore, the stream channel in this example can be classified as [wash load, sand bed, sand and gravel bed] channel.

2.3 Non-cohesive Sediment Transport theory [can, can not] be used to calculate the inflowing sediment load at this study area.

2.4 <u>Is HEC6 applicable?</u> _____

(HEC6 can be applied to all of the above streams, but it <u>**can not**</u> calculate its inflowing sediment load if the stream is a clay boundary-wash load type stream. In wash load type of streams the only way to determine the transport rate for the sediment entering the study area is to measure it.)

3. Selection of a Transport Function. Use the Corps of Engineers Table attached to this workshop (Figure 6.2) and select the transport function . _____

_____

4. **Code the PF-Record.**

Type Menu6 and select the basic data file: **H6WRKSH1.DAT.**

4.1 Geometric Data and Hydraulic Data have been coded. Locate where Sedimentary Data should be placed in the file.

4.2 Following the instructions for the PF record, code the SECID of the first X1 record.

SAE	leave blank
Dmax -	Start with Dmax and code enough points along the Gradation Curve (Fig. 2.1) to approximate it with a series of straight lines.

Only 1 PF record will be required. The data will be applied to every cross section in the model.

5. **Code the I4-Record.** Code the number of the transport function that you selected in I4-2(MTC). (i.e. the notation I4-2 means the I4 record, field 2)

5.1 Number of grain sizes. Choose the number of grain sizes to code using the table on p A-31 of the HEC-6 User's Manual and Figure 2.1. Code the ID NUMBER (Column 1, Table A2-2, page A-32) for the smallest grain size in I4-3, and the ID NUMBER for the largest grain size in I4-4.

5.2 Let the other variables on this record default. (This is the usual case.)

6. **Code the I1-Record.** The only pertinent field on the I1-Record is the I1-2(SPI). Type in 10 for this example to decrease computer running time, but in the actual case use 20.

7. <u>Calculate the Inflowing Load.</u>

7.1 <u>Code the LQ-LT-LF Records, TRIAL 1.</u> The LQ - LT Records form a table which defines the inflowing sediment discharge for any water discharge in the Hydrologic Data Set. The water discharge is read in and the sediment discharge is found by log-log interpolation from this table. The sediment load is found by multiplying the sediment discharge by the fractions on the LF-Records which follow.

This work shop will calculate the inflowing sediment load for only 1 water discharge:

Q = 80,000 cfs.

(Note: This discharge, 80,000 cfs, was selected because it is about the bank full flow. In the general case at least 2 discharges - one low and one high, are needed, and usually more than 2 discharges should be calculated to define the shape of the inflowing load curve. However, the procedure is the same for each.)

7.1.1 **First Trial.** Code the 80,000 cfs in LQ-2. Code only the record types on the LT and LF records which follow. **Note: There must be one LT-Record, and there must be one LF-Record for each grain size class which was selected on the I-Records.**

7.1.2 Execute

7.1.3 View the output on Console. Search for the string $VOL

Locate the first **TABLE SB-2** above this print out (i.e. Page Up) and record the Time

TIME = _____ days

Locate the table below the $VOL print out entitled:

SUMMARY TABLE: MASS AND VOLUME OF SEDIMENT

and record the Total Sediment Inflow _____ tons

Total Sediment passing Section 0.78 _____ tons

Calculate the discharge rate passing
Section 0.78 by dividing mass by time _____ tons/day

Code the sediment discharge rate passing Section 0.78 on the LT record for Trial 2.

Locate the next table: (titled)

TOTAL SEDIMENT - per grain size - THROUGH EACH CROSS SECTION (tons)

and record the sediment load for each grain size class, for cross sections 0.92 and 0.78, in the following table. Calculate the fraction of each size class in this table. (Col E.)

Trial 1. Calculate Inflowing Bed Material Load

SIZE CLASS A	CROSS SECTION 0.92 B	CROSS SECTION 0.78 C	TOTAL BY SIZE CLASS TONS = COL B+C D	FRACTION COL(D) = ---------- COL D(TOTAL) E
	TONS	TONS	TONS	
VFS				
FS				
MS				
CS				
VCS				
VFG				
FG				
MG				
CG				
VCG				
TOTAL				

7.2 **Code LQ-LT-LF Records, TRIAL 2.** Code the fractions from column E on the LF records in the field below the 80,000 cfs water discharge. Rerun HEC6 with this new data set.

7.2.1 View the output on Console. Search this new output for the string $VOL and repeat 7.1

Record the Time TIME = _____ Days

Record the Total Sediment Inflow _____ tons

Total Sediment passing Section 0.78 _____ tons

Calculate the discharge rate passing
Section 0.78 by dividing mass by time _____ tons/day

Locate the "TOTAL SEDIMENT - per grain size ..." table and calculate the new fractions for each size class.

Trial 2. Calculate Inflowing Bed Material Load

SIZE CLASS A	CROSS SECTION 0.92 B	CROSS SECTION 0.78 C	TOTAL BY SIZE CLASS TONS = COL B+C D	FRACTION COL(D) = ---------- COL D(TOTAL) E
	TONS	TONS	TONS	
VFS				
FS				
MS				
CS				
VCS				
VFG				
FG				
MG				
CG				
VCG				
TOTAL				

8.0 Check Long Term Behavior. Replace the TRIAL 1 LF values with the fractions from table 2. Create a long period hydrology by adding the following records to the workshp2.dat input file just above the $VOL record.

```
*     B   RUN 6.
Q   80000
X      30      .25
*     B   RUN 7.
Q   80000
X              .25       30
*     B   RUN 8.
Q   80000
X              .25       30
*     B   RUN 9.
Q   80000
X              .25       30
```

Execute this data set and fill in the following table using the SB-2 results at TIME = 120 days.

Table 6.3 Status of the Bed Profile and Sand Transport

SECTION NUMBER	BED CHANGE ft	Q cfs	TRANSPORT RATE tons/day
1.160		80,000	
0.920		80,000	
0.780		80,000	
0.670		80,000	

There is no physical reason why the bed elevation should change in this study reach. (i.e. Why the BED CHANGE column should show such large plus/minus values.) Reduce the inflowing sediment discharge (LT-Record) until the BED CHANGE at Section 0.67 is approximately 0. Record your final Inflowing Sediment Discharge, Q_s, in the space below:

Inflowing Sediment Discharge for Q_w = 80,000 cfs _____ tons/day.

Convert the Sediment Discharge to Concentration _____ mg/l
(i.e. $Q_s = 0.0027*C*Q_w$)

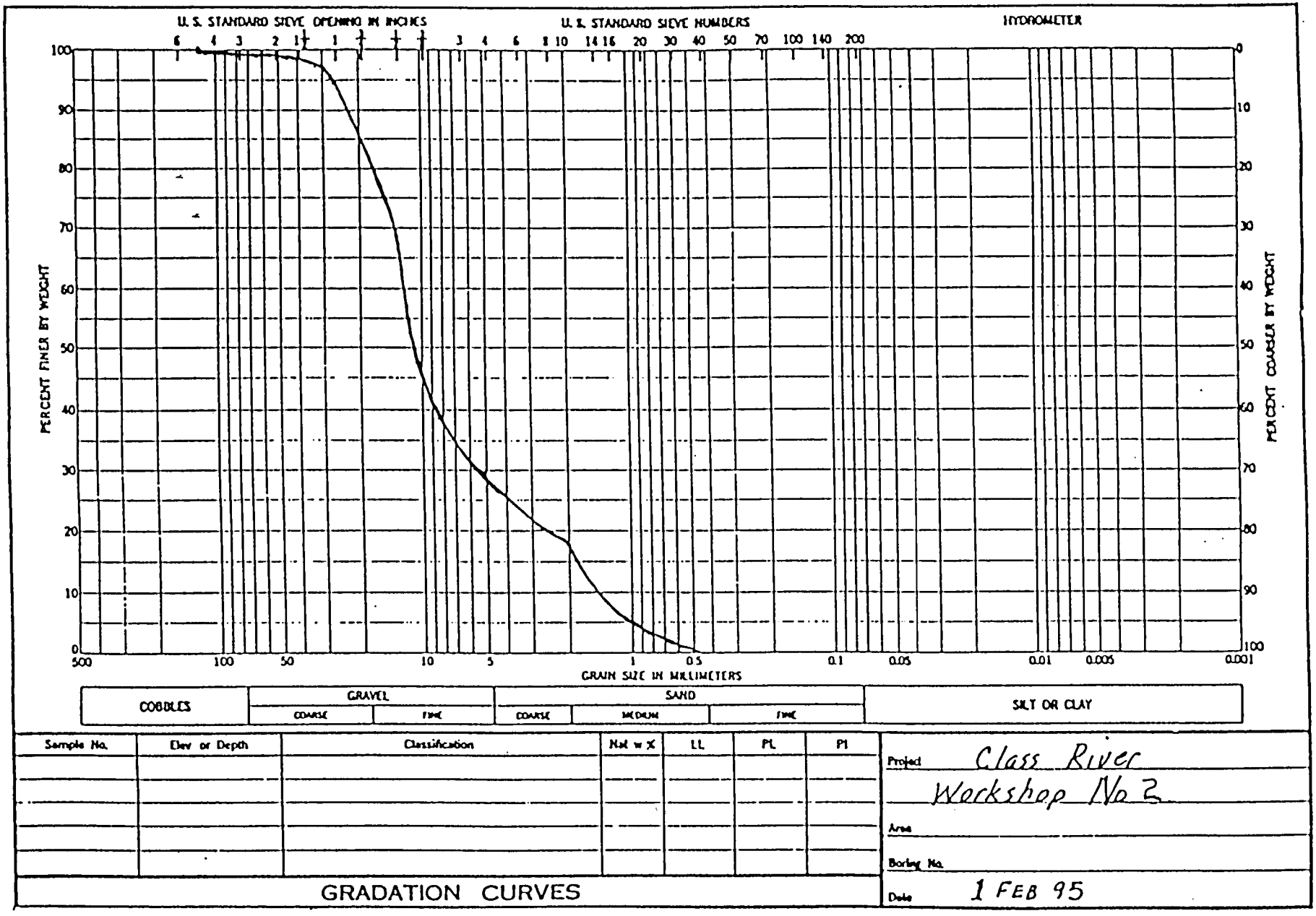


Figure 2.1 Gradation Curves for Workshop 2

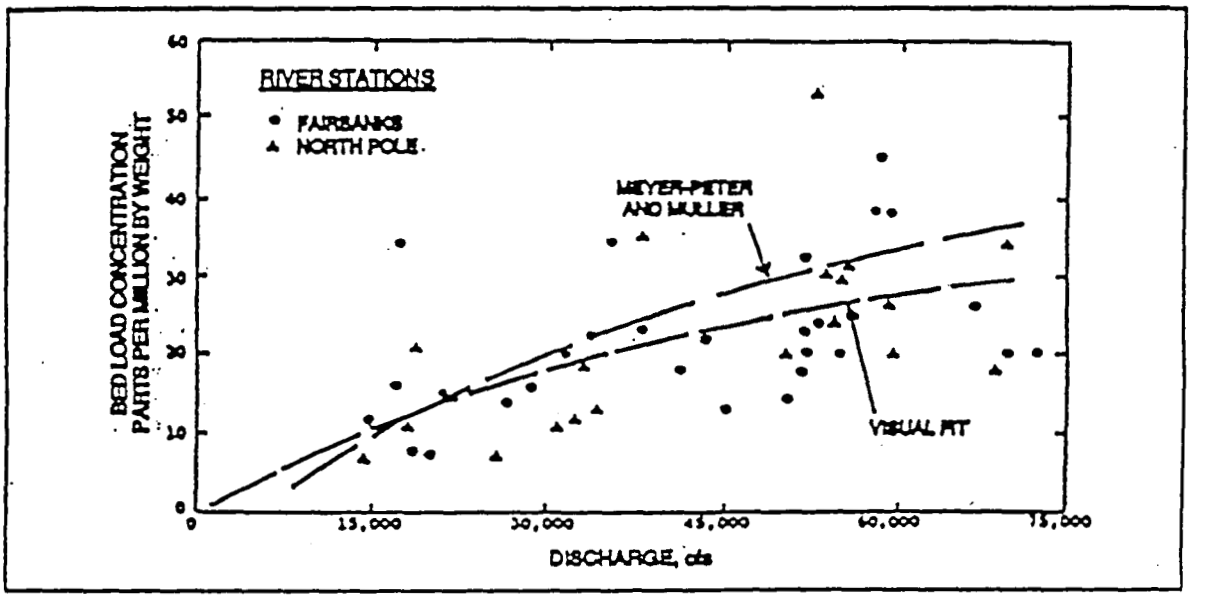


Figure 5-13. Comparison of computed and measured bed load in Tanana River near Fairbanks, Alaska (Busick et al. 1984)

Table 5-2
Sediment Transport Functions

Class of Channel	Suggested Functions	Reference
Large sand-bed rivers	Laursen-Madden Toffaleti	U.S. Hydrologic Engineering Center (1993) Toffaleti (1968)
Intermediate-size sand-bed rivers	Laursen-Madden Yang unit stream power	U.S. Hydrologic Engineering Center (1993) Yang (1973, 1984)
Small sand-bed rivers	Yang unit stream power Colby for streams with high sediment concentration	Yang (1973, 1984) Colby (1964a, 1964b)
Sand- and gravel-bed rivers	Yang unit stream power Toffaleti combined with Meyer-Peter and Müller	Yang (1973, 1984) See above and below
Gravel-bed rivers	Meyer-Peter and Müller	Meyer-Peter and Müller (1948)

Note: Tentative guidance is provided below for functions most appropriate to various classes of channels. This guidance is based on experience at the U.S. Army Engineer Waterways Experiment Station and various districts, primarily with simulations involving the HEC-6 computer program. In the HEC-6 program, the functions as originally published have been modified in most cases to compute transport by size classes and to allow for high wash load concentrations where necessary. Additional guidance for selection of sediment transport functions is available in the SAM computer program package (Thomas et al., in preparation). The distinctive hydraulic variables from the user's river are compared to a large data set developed by Brownlie (1981), and a river data set is selected from a river with the most similar characteristics. The guidance program then selects a sediment transport function that best reproduces the selected data set.

Figure 2.2 Guidance on Selection of Transport Function

Development of Sediment Data Solutions

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

Objective: The student will know a method for developing the sedimentary data set for HEC-6.

References: US Army Corps of Engineers, "Channel Stability Assessment for Flood Control Projects," Engineering Manual 1110-2-1418, October 31, 1994.

Solution file is H6WRK2S.DAT

1. Instructions for coding the sedimentary data are found in Appendix A, Section 2 in the HEC-6 User's Manual. **Record names are also listed in Appendix A, pgs. v and vi.** Tasks in this workshop are presented in the order that follow.

The following records will be required:

```
T4                          A-23(Page in HEC-6 Manual)
T5                          "
T6                          "
T7                          "
T8                          "
I1                          A-24
I4                          A-31 - 33
LQ    CFS    80000          A-37
LT    T/D    ?????          A-38
LF    VFS                   A-39
LF     FS                   "
LF     MS                   "
LF     CS                   "
LF    VCS                   "
LF    VFG                   "
LF     FG                   "
LF     MG                   "
LF     CG                   "
LF    VCG                   "
PF   cmt                    A-40
PFC                         "
```

2. <u>Classify the Stream.</u> A stream can be classified as a bed load, a suspended load or a

wash load stream depending on the properties of the sediment in the boundary material. If the boundaries are primarily clay, the stream is a wash load stream. If the boundaries are sand, the stream can be simulated as a suspended, bed-material load stream. If the bed is primarily sand with a thin gravel surface layer, it is probably a sand bed stream with armoring. If the bed is gravel, the stream is a gravel bed stream. When the bed is predominately gravel with a secondary (relatively small) mode of sand deposits in the samples, it is a gravel bed stream with a sand through put.

The Bed Material Gradation curve for the stream in this example is shown in figure 2. 1.

Dmax is _____128_____ mm

Dmin is _____0.0625_____ mm

D50 is _____11_____ mm

How much cohesive sediment was found in the bed samples? ___0___

How much sand? _____18%_____

2.2 Therefore, the stream channel in this example can be classified as [wash load, sand bed, sand and gravel bed] channel.

2.3 Non-cohesive Sediment Transport theory [can, can not] be used to calculate the inflowing sediment load at this study area.

2.4 Is HEC6 applicable? _____YES_____

(HEC6 can be applied to all of the above streams, but it **can not** calculate its inflowing sediment load if the stream is a clay boundary-wash load type stream. In wash load type of streams the only way to determine the transport rate for the sediment entering the study area is to measure it.)

3. Selection of a Transport Function. Use the Corps of Engineers Table attached to this workshop (Figure 2.2) and select the transport function . _____

_____Toffaleti plus Meyer-Peter and Mueller Combination_____

4. **Code the PF-Record.**

Type Menu6 and select the basic data file: **H6WRKSH1.DAT**

4.1 Geometric Data and Hydraulic Data have been coded. Locate where Sedimentary Data should be placed in the file.

4.2 Following the instructions for the PF record, code the SECID of the first X1 record.

SAE leave blank
Dmax - Start with Dmax and code enough points along the Gradation Curve (Fig. 2.1) to approximate it with a series of straight lines.

```
PF          .67   1.0   128    64    99    32    98    16    78
PFC    8     38     4    25     2    17     1     4    .5    .1
PFC.0625      0
```

Only 1 PF record will be required. The data will be applied to every cross section in the model.

5. **Code the I4-Record.** Code the number of the transport function that you selected in I4-2(MTC). (i.e. the notation I4-2 means the I4 record, field 2)

5.1 Number of grain sizes. Choose the number of grain sizes to code using the table on p A-31 of the HEC-6 User's Manual and Figure 2.1. Code the ID NUMBER (Column 1, Table A2-2, page A-32) for the smallest grain size in I4-3, and the ID NUMBER for the largest grain size in I4-4.

5.2 Let the other variables on this record default. (This is the usual case.)

6. **<u>Code the I1-Record.</u>** The only pertinent field on the I1-Record is the I1-2(SPI). Type in 10 for this example to decrease computer running time, but in the actual case use 20.

```
I4        12    1    10
```

7. **Calculate the Inflowing Load.**

7.1 **Code the LQ-LT-LF Records, TRIAL 1.** The LQ - LT Records form a table which defines the inflowing sediment discharge for any water discharge in the Hydrologic Data Set. The water discharge is read in and the sediment discharge is found by log-log interpolation from this table. The sediment load is found by multiplying the sediment discharge by the fractions on the LF-Records which follow.

This work shop will calculate the inflowing sediment load for only 1 water discharge:

Q = 80,000 cfs.

(Note: This discharge, 80,000 cfs, was selected because it is about the bank full flow. In the general case at least 2 discharges - one low and one high, are needed, and usually more than 2 discharges should be calculated to define the shape of the inflowing load curve. However, the procedure is the same for each.)

7.1.1 First Trial. Code the 80,000 cfs in LQ-2. Code only the record types on the LT and LF records which follow. **Note: There must be one LT-Record, and there must be one LF-Record for each grain size class which was selected on the I-Records.**

		TRIAL			
		1	2	3	4
LQ	CFS	70001	70002	80000	80004
LT	T/D		118357	120645	100000
LF	VFS		.0008	.0017	.0017
LF	FS		.0008	.0016	.0016
LF	MS		.0008	.0015	.0015
LF	CS		.0751	.0828	.0828
LF	VCS		.1841	.1862	.1862
LF	VFG		.1023	.1017	.1017
LF	FG		.1504	.1483	.1483
LF	MG		.3763	.3686	.3686
LF	CG		.1090	.1073	.1073
LF	VCG		.0004	.0004	.0004

7.1.2 Execute

7.1.3 View the output on Console. Search for the string $VOL

Locate the first **TABLE SB-2** above this print out (i.e. Page Up) and record the Time

TIME = 1.25 days

Locate the table below the $VOL print out entitled:

SUMMARY TABLE: MASS AND VOLUME OF SEDIMENT

and record the Total Sediment Inflow	0	tons
Total Sediment passing Section 0.78	147,947	tons
Calculate the discharge rate passing Section 0.78 by dividing mass by time	118,357	tons/day

Code this new sediment discharge rate on the LT record for Trial 2.

Locate the next table: (titled as follows)

TOTAL SEDIMENT - per grain size - THROUGH EACH CROSS SECTION (tons)

and record the sediment load for each grain size class, for cross sections 0.92 and 0.78, in the following table. Calculate the fraction of each size class in this table. (Col E.)

Trial 1. Calculate Inflowing Bed Material Load

SIZE CLASS A	CROSS SECTION 0.92 B	CROSS SECTION 0.78 C	TOTAL BY SIZE CLASS TONS = COL B+C D	FRACTION COL(D_i) = ------ COL D(TOTAL) E
	TONS	TONS	TONS	
VFS	73	126	199	0.0008
FS	73	126	199	0.0008
MS	73	126	199	0.0008
CS	7534	10879	18,413	0.0751
VCS	18541	26592	45,133	0.1841
VFG	10279	14813	25,092	0.1023
FG	14966	21911	36,877	0.1504
MG	36354	55912	92,266	0.3763
CG	9364	17366	26,730	0.1090
VCG	1	93	94	0.0004
TOTAL	97,258	147,944	245,202	1.0000

```
TABLE SB-2:  STATUS OF THE BED PROFILE AT TIME =     1.250 DAYS
-----------------------------------------------------------------------------
  SECTION    BED CHANGE    WS ELEV    THALWEG          Q       TRANSPORT RATE (tons/day)
  NUMBER        (ft)         (ft)       (ft)         (cfs)        SAND
     1.160      -3.04      725.69     704.86       80000.       43860.
     0.920      -0.33      722.66     706.37       80000.       81867.
     0.780      -1.61      720.03     703.69       80000.      101409.
     0.670       0.05      719.00     701.05       80000.       97954.
```

7.2 **Code LQ-LT-LF Records, TRIAL 2.** Code the fractions from column E on the LF records in the field below the 80,000 cfs water discharge. Rerun HEC6 with this new data set.

7.2.1 View the output on Console. Search this new output for the string $VOL and repeat 7.1

Record the Time TIME = 1.25 Days

Record the Total Sediment Inflow 147,946 tons

Total Sediment passing Section 0.78 150,806 tons

Calculate the discharge rate passing Section 0.78 by dividing mass by time 120,645 tons/day

Locate the "TOTAL SEDIMENT - per grain size ..." table and calculate the new fractions for each size class.

Trial 2. Calculate Inflowing Bed Material Load

SIZE CLASS A	CROSS SECTION 0.92 B	CROSS SECTION 0.78 C	TOTAL BY SIZE CLASS TONS = COL B+C D	FRACTION COL(D_i) = ------ COL D(TOTAL) E
	TONS	TONS	TONS	
VFS	187	238	425	0.0017
FS	187	235	422	0.0016
MS	174	208	382	0.0015
CS	9514	11763	21,277	0.0828
VCS	20643	27228	47,871	0.1862
VFG	11121	15025	26,146	0.1017
FG	15968	22139	38,107	0.1483
MG	38397	56340	94,737	0.3686
CG	10040	17533	27,573	0.1073
VCG	2	97	99	0.0004
TOTAL	106,233	150,806	257,039	1.0001

```
TABLE SB-2:  STATUS OF THE BED PROFILE AT TIME =     1.250 DAYS
-----------------------------------------------------------------------------
 SECTION    BED CHANGE   WS ELEV   THALWEG        Q      TRANSPORT RATE (tons/day)
 NUMBER        (ft)        (ft)      (ft)        (cfs)       SAND
     1.160       0.83    726.33    708.73      80000.      112522.
     0.920       0.41    722.76    707.11      80000.       95977.
     0.780      -1.41    720.03    703.89      80000.      107627.
     0.670       0.20    719.00    701.20      80000.      100912.
```

8.0 Check Long Term Behavior. Replace the TRIAL 1 LF values with the fractions from table 2. Create a long period hydrology by adding the following records to the workshp2.dat input file just above the $VOL record.

```
*     B  RUN 6.
Q  80000
X      30      .25
*     B  RUN 7.
Q  80000
X              .25       30
*     B  RUN 8.
Q  80000
X              .25       30
*     B  RUN 9.
Q  80000
X              .25       30
```

Execute this data set and fill in the following table using the SB-2 results at TIME = 120 days.

Table 6.3 Status of the Bed Profile and Sand Transport, TIME = 120 Days

SECTION NUMBER	BED CHANGE ft	Q cfs	TRANSPORT RATE tons/day
1.160	2.03	80,000	120,656
0.920	2.17	80,000	120,653
0.780	-0.92	80,000	120,653
0.670	0.51	80,000	120,653

The channel in this study is in equilibrium, and there is no physical reason why the bed elevation should change over time. Therefore, the BED CHANGE column should not show such large plus/minus values. Reduce the inflowing sediment discharge (LT-Record) until the BED CHANGE at Section 0.67 is approximately 0. Record your final Inflowing Sediment Discharge, Q_s, in the space below.

Inflowing Sediment Discharge for Q_w = 80,000 cfs _____100,010_____ tons/day.

Convert the Sediment Discharge to Concentration _____463_____ mg/l
(i.e. $Q_s = 0.0027*C*Q_w$)

CALIBRATION AND VERIFICATION TECHNIQUES

OBJECTIVE: Establishment of steps for calibrating and verifying HEC-6

Definition of calibration: The development of representative data and model parameters based on known or deduced prototype behavior.

Definition of verification: The demonstration of the calibrated model's ability to simulate prototype behavior for a time record different from that used in calibration. A calibrated model is not necessarily a verified model.

I. Understanding the historic behavior of the system.

A. Assemble all pertinent records

B. Determine data deficiencies

1. Assess effect of deficiencies on ability to model

2. Establish program of data acquisition

C. Gain knowledge on system response to extreme events in terms of channel changes and sediment transported.

D. Establish the impacts of impoundments, land use, etc., outside the study area, present and future.

E. Locate anomalies in geometric, hydrologic, hydraulic, and sediment characteristics.

F. View the study area with a person familiar with the historic behavior of the area.

1. Note scour and deposition locations

2. Locate and identify

a. encroachment areas

b. man-made and natural levees

c. cutoffs

d. ineffective flow areas

e. rock outcrops or areas resistant to scour

f. sand bars

g. changes in bed gradation

h. bed roughness

i. bed forms

3. Locate and interview people who have observed the system during extreme events.

II. Hydraulics - Fixed Bed Mode

A. Geometry

1. Check data "busts" by computer plots of the cross sections and comparing them to hand plotted or previously plotted (e.g., HEC-2 plots) cross sections.

2. Be willing to modify surveyed geometry if the modification is representative of the reach.

3. Obtain detailed printout of geometry and look for any unusual behavior of the hydraulic parameters.

B. Test with a range of discharges using fixed bed mode.

1. Low flow

a. Use an extremely low flow that is in the records.

b. Check for extreme changes in velocity, depth, or width of flow.

2. Bankfull flow

a. Plot bank elevations versus calculated water surface elevation.

b. Adjust geometry to "smooth out" irregularities.

3. Flood flow

a. Use highest flow of record or highest flow in study if larger than maximum historical flood.

b. Plot water surface and velocity profiles and verify that all drastic changes, either increases or decreases, are valid.

c. Compare changes in valley width with water surface slope and adjust geometry if needed.

C. Calibration of n-values

1. Compare calculated water surface profiles with rating curves and observed profiles.

2. If necessary, change n-values by discharge if bed for. s predominate.

3. Change n-values with distance, if needed.

4. Establish performance criteria - suggested

   a. ±5 percent of the water depth

   b. Lesser of (a) and ± 0.5 ft

D. HEC-6 limitations and capabilities on n-values

1. May vary with elevation or discharge

2. May change at each section

3. Must be specified for each subsection

4. Not related to water temperatures

5. Not related to bed gradation

6. Cannot change with time during a run

E. Other adjustments

1. Expansion and contraction losses

2. Channel and overbank limits

3. Expansion, contraction, raising, or lowering of cross sections

4. Ineffective flow areas when water surface is below levee height

5. Placement of weirs and head loss of weirs

F. Flow distribution

1. Verify that the model conveys the correct percentage of total flow in the channel for all flood discharges.

2. When adjusting this distribution, check ineffective flow area first.

3. Make final adjustment for percentage of flow in channel by using n-values.

4. The A-level printout (column 5 on *-Cards in Hydrology) prints flow distribution.

III. Hydrology

A. Determine computational intervals (w-card)

1. Dependent on:

a. water discharge

b. sediment load

c. cross section spacing

2. Test for each low, bank full, and peak flood flow

a. Check for oscillating bed change

b. Adjust time intervals to the largest but still stable intervals

c. Repeat for several cross sections

4. Check model performance against expected prototype behavior

5. Extend hydrograph at the established interval and check for equilibrium conditions

B. Establish discharge histogram

1. Insure that peaks are represented

2. Check for annual mass continuity

a. water

b. sediment

3. Time interval should be long enough to allow the water to pass through the longest reach.

4. Utility program "Sediment Weighted Historgam Generator," HYHIS

IV. Sediment data calibration - movable bed mode

A. Inflowing sediment load

1. Develop inflowing sediment load curve

a. Measured (suspended) load - 90 to 95% of total

b. Unmeasured load

c. Total load

d. Check for proper annual sediment volume by integrating with the annual water hydrograph

(1) measured for project

(2) water quality papers

(3) regional analysis of sediment yield

(4) sediment yield models such as USLE, MUSLE, and other erosion type models

2. Develop gradation curve of inflowing load

a. Plot fraction of total load for clay, silt, and sand versus discharge using suspended measurement.

b. Using both suspended measurements and bed material gradation, subdivide sands into class intervals.

c. If bed gradations are accurate and the assumption of equilibrium conditions is valid, have the program calculate inflowing gradation by iteration of outflow gradation as inflow gradation until both are identical.

B. Bed gradation

1. Plot profiles of bed gradation along river mile

a. Compare gradation changes with hydraulic changes

b. Use for interpolation of bed gradation of unmeasured cross section

2. If the gradation of the inflowing sediment load is accurate, have the program calculate the bed gradation required to transport the sediment load.

3. In cross sections with continual deposition (such s in reservoirs) detailed bed gradations are not necessary.

V. Full calibration run

A. Minor adjustments for simulation of calibration time period and compare results to prototype behavior.

B. If major adjustments are required, repeat calibration procedures previously described.

VI. Verification

A. Compare calibrated model performance with observed prototype behavior for verification time period.

1. Evaluate changes over time

a. Water surface profile

b. Average bed elevation

c. Sediment yield

2. Check discrepancies by comparison with any prototype anomalies that the program cannot simulate.

a. Make adjustments, if necessary

b. If the anomalies are severe (e.g., multi-dimensional), develop approximation techniques.

B. Recalibrate if required changes for verification are severe

SEDIMENT WEIGHTED HISTOGRAM GENERATOR (SWHG)

Introduction

SWHG is a utility program that processes mean daily data and, using various criteria, develops a histogram that lumps mean daily events into representative discharges and time periods. How the representative discharge is determined is discussed in the theory section. The program also sums water and sediment discharge volumes by month and time interval as specified by the H card. If gage or temperature records are input immediately after the first H card, minimums, maximums and averages are displayed by month.

Discharge/Stage Input

Mean daily data for the main stem can be in the form of discharges in cfs or stages. If stages are used, a rating curve must be provided. Up to 9 tributaries may be input after the main stem input; however, they must be in cfs. If there are no mean daily discharges available for a tributary, they can be generated by insertion of F cards. The F cards generate tributary flow by using a relationship (specified by the user) of main stem flow to tributary flow. Tributary data is not displayed on the printout, only the data input immediately after the first H card and before the first ER card is displayed. When calculation of a histogram is requested (IDH on H card), the histogram time intervals are determined by main stem input only and the representative tributary discharges are the average of discharges in the time interval.

Gage Record Input

Sometimes sediment transpect is significantly affected by sudden or rapid change in water surface elevation which may not be related to discharge (e.g.,

backwater effects, weir operation, etc.). Mean daily gage records may be input and a criterion of maximum change in water surface elevation within a time interval can be specified. When this criterion is exceeded, the time is cut off and, if histogram calculation is specified, the average gage elevation is computed and output as R cards for HEC-6 hydrologic input. If the study area is between two gage stations, two gage records may be input and a weighting of each gage record specified to represent the actual mean daily water surface elevation in the study area.

Temperature Record Input

Temperature changes can change sediment transport rates. If the changes are significant, temperature records may be input and a criterion of maximum change in temperature can be specified. The data may be entered as average monthly temperatures, one year of mean daily temperatures to be used for the entire record period, or actual mean daily temperatures for the entire record period. When the temperature criterion is exceeded, the time is cut off and, if histogram calculation is specified, the average temperature is computed and output as T cards for HEC-6 hydrologic input.

Allowable Data Size and Time Intervals

The total number of mean daily data for main stem, tributaries, and gages must not exceed 22,000. The total number of mean daily temperatures input must not exceed 9200. If only a main stem analysis is to be made, 60 years of record can be input. If a main stem and two tributaries are to be analyzed, the record length can be up to 20 years. If one of the tributary discharges was generated by the F card option, 30 years of record can be input. The maximum time interval for each H card is 366 days. Analysis by water year can be done by inputting 10 in field 5 and 9 on field 6 on the H cards and starting with October input. No gaps are allowable between H card time intervals.

Suggested Sequence of Analysis

Each data set of main stem, tributaries, gages, and temperatures should be

analyzed separately before merging together and calculating the histogram.

a. Main stem check (exclude F, T, and B cards).

1. On H cards, leave fields 2, 3, 4, 7, 9, and 10 blank and run program with main stem discharges or stages and a sediment load curve (G card).

2. Check daily, monthly, and time interval totals against published records and make any corrections.

3. Run program again and, if satisfied with the data, change field 10 (NGSF) on the H card.

4. If an average annual sediment yield is being calibrated, adjust the sediment load curve (G card) until the right yield is obtained.

5. After the data are corrected and a satisfactory sediment load curve obtained, change field 10 on the H cards to 0 and make a production run. Plotting the data is recommended.

b. Tributary check.

Do the same as for the main stem analysis but using tributary data. Analyze each tributary separately. Leave field 2 on H card blank.

c. Gage check (exclude F, T, G, and B cards).

1. If more than one gage is to be used, analyze separately. Place the gage data after the first H card and end with an ER card followed by additional H cards.

2. On H cards, leave fields 2, 3, 4, 7, 9, and 10 blank and run program.

3. Check maximums, minimums and averages by month and time interval against published records and make any corrections. Plotting of the data is recommended.

4. Repeat Steps 1 through 3 for second gage if applicable.

d. Temperature check (exclude F, T, G, and B cards).

If mean daily temperatures are used, go through the same steps as in the gage check.

e. Combined check.

1. After all components have been corrected, include F cards if tributaries are to be generated, G cards for sediment load curve, T cards if temperatures are input, B cards if gage records are input. On the H cards, input the number of tributaries (exclude the number of tributaries generated by F cards) in field 2 (ITRB), input 0 in field 9 (IDH) and input 1 in field 10 (NGSF).

2. Place main stem, tributary, gage(s) and temperature data separated by ER cards immediately after the first H card. After the last ER card, place the remaining H cards. Run the program.

3. Check for any error messages and make appropriate corrections and rerun.

4. Select appropriate tolerances for temperature and gage changes on the B card and sediment accumulation (see theory section) on the H cards. Input 1 in field 9 (IDH) on the H cards and run program.

5. Check output and adjust histogram criteria as needed and rerun until satisfied with the histogram being generated.

6. Input 1 in field 7 (PUN) to generate HEC-6 hydrology on I/O unit 7 (tape 7). Rename and save the I/O unit. Plot the HEC-6 hydrology and overplot with the mean daily data to assure that significant events are properly represented but a histogram is generated with as few events as possible. Programs have been made to easily do this plotting. If there are too many histogram events or significant events are being "smoothed over," repeat steps 4 through 6.

7. Run HEC-6 with the generated histogram and do the analysis as described in the theory section.

Theory

The generalized computer program HEC-6, "Scour and Deposition in Rivers and Reservoirs," uses a sequence of discrete discharges (a histogram) to calculate sediment transport for the time period to be modeled. Simulation runs of 50 years or more are sometimes needed for evaluation of prototype behavior. A 50 year simulation would require 18,250 backwater profiles if mean daily flow records were used. This number of computations could be reduced if the actual mean daily flows could be grouped into periods of longer duration and still maintain the important properties of the water discharge vs. sediment transport process. Such is the purpose of the "Sediment Weighted Histogram Generator" (SWHG).

It has been found from many sediment studies that sediment discharge is generally related to water discharge in the form:

$$G = KQ^c \qquad \text{Eq. 1}$$

where

G = sediment discharge (usually in tons/day)

Q = water discharge (usually in cfs)

K = a factor which can be taken as an index of relative erodibility

c = slope of the curve on logarithmic paper measured in units of logarithmic cycles.

Histograms are usually generated by time incrementing a continuous hydrograph and obtaining average discharges for the time increments such that the areas under the hydrograph and histogram are equal. If this procedure is used, water volume is conserved. If a sediment hydrograph and a sediment histogram generated by the water histogram and Equation 1 were compared, the area under actual sediment hydrograph and the generated

sediment histogram would not be equal because of the nonlinearity of Equation 1.

Example 1:

$K = 1$

$c = 2$

$\therefore \; G = Q^2$

Day	Q	G tons/day	Q x G
1	1	1	1
2	4	16	64
3	8	64	512
4	10	100	1000
Σ	23	181	1577
ave.	5.75	45.25	394.25

If the average discharge is used as the governing parameter,

$G = (5.75)^2 = 33.06$ tons/day

Total G for 4 days = 33.06 x 4 = 132.24 tons

The actual G for 4 days is 181 tons (27% error)

If the average sediment discharge is used as the governing parameter,

$$Q_{ave} = \sqrt{G_{ave}} = \sqrt{45.25} = 6.73 \text{ cfs}$$

Total Q for 4 days = 6.73 x 4 = 26.92 cfs-days

The actual Q for 4 days is 23 cfs-days (17% error)

It can be seen that if a time period is to be represented by one discharge

and actual duration, both water volume and sediment volume cannot be conserved. In sediment studies, conservation of input sediment volume is essential because it is the only source of sediment other than the bed. However, conservation of water volume is also important because of the influence it has on hydraulic conditions; which, in turn, affect the sediment transport capacities. Because of the importance of both water and sediment conservation (with sediment conservation being the most important), it is proposed that the product of the water and sediment discharge (sediment weighted discharge) best describes the influence of both. For each discharge this product (Q x G) is calculated and averaged over the time period. A Q vs. Q x G table can be generated and a Q can be obtained for the averaged Q x G.

Example 2:

$$G = KQ^c$$

$$G \times Q = KQ^{c+1}$$

$$\frac{G \times Q}{K} = Q^{c+1}$$

$$Q = \sqrt[c+1]{\frac{G \times Q}{K}} \quad \text{for this case,} \quad Q = \sqrt[3]{G \times Q}$$

$$(Q \times G)_{ave} = 394.25$$

$$Q_{ave} = \sqrt[3]{394.25} = 7.33 \text{ cfs/day}$$

$$G_{ave} = (7.33)^2 = 53.77 \text{ tons/day}$$

Since total sediment is to be conserved, the time duration is changed so that for the interpolated G, total sediment volume is conserved. This is the computational duration but represents the real time duration.

$$\text{Computational duration} = \frac{181 \text{ tons}}{53.77 \text{ tons/day}} = 3.37 \text{ days}$$

Total G = 3.37 days x 53.77/day = 181 (0% error)

Total Q = 7.33 x 3.37 days = 24.7

Actual average Q is 23 (7.4% error)

However, 7.4% error is much less than 17% error in Example 1 The 4 days of water and sediment flow is now represented by a Q of 7.3? for a duration of 3.37 days with 0% error in sediment volume and 7.4% error in water volume (compared to 17%).

The "Sediment Weighted Histogram Generator" program will produce representative events of discharge and the associated duration in days with a maximum event duration of 30 days. In some cases, however, averaging the flow hydrograph for a month filters out important hydraulic events or produces time periods which are too long for the HEC-6 model. A second constraint is introduced to accommodate these considerations. This constraint sets a limit, AMAGIC in tons, on the maximum amount of inflowing sediment discharge accumulated during a single histogram event. Daily sediment weights (tons) are accumulated until the quantity exceeds AMACIC. At that point, the representative water discharge for the time period is calculated as described above. An approach for assigning AMAGIC is to calculate the weight of sediment that would be required to fill the bed of the shortest reach 1 foot deep. Another way to establish AMAGIC is estimate the sediment discharge, tons/day, at which the stream bed begins to significantly change from the G vs. Q curve. The final test for AMAGIC is whether or not the HEC-6 code will execute properly with the calculated Histogram.

The test in HEC-6 can be conducted by selecting a relatively short but highly variable Q time period (e.g. 2 mo.) in which one model is run with the actual mean daily flows and an other with a generated histogram. Significant differences in model performance (i.e. magnitude and temporal trend of computed bed profiles) suggests AMAGIC is too large. A couple of trials and checks will usually be sufficient.

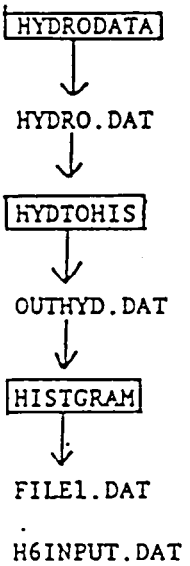
I. Get data from "HYDRODATA".

II. Run "HYDTOHIS": Converts hydrodata to a file that will go into "HISTGRAM".

Edit "HYDTOHIS" output file following HYHIS documentation. Must add following card: G, T, B, H. First H card will appear in top of file after B card. Others will appear at bottom of file. Remember to also add input on H cards at bottom of file.

III. Run "HISTGRAM"

IN: OUTFILE FROM "HYDTOHIS"
OUT: FILE1.DAT
OUT: H6INPUT.DAT



T Card - Title Cards - 3 Required

Field	Variable	Value	Description
0	ID	T	Card identification.
1-10		AN	Alphanumeric title or description.

R Card - Rating Curve - Required if mean daily stages (S cards) are input instead of mean daily discharge (Q cards) for the main stem.

Field	Variable	Value	Description
0	ID	R	Card identification in column 1.
1	NPTS	+	The number of water surface values that will be read.
2	SZERO	+	If the rating table is a stage-discharge curve rather than elevation-discharge, enter gage zero here.
3	QT(1)	+	Lowest flow in cfs, subsequent flows must be increasing.
4	ST(1)	+	Lowest water surface elevation, or stage, corresponding to lowest flow.
5	QT(2)...		Enter up to 20 points using field 1-10 on subsequent cards. Put R in column 1 on all cards.
6	ST(2)...		Continue entering up to NPTS pairs of numbers.
.	.		
.	.		
.	.		
10	etc.		

F CARD Tributary flow generation card. Optional. Used for calculating tributary flow as a ratio of main stem flow for HEC-6 hydrologic input in the absence of tributary flow data. Up to 3 tributaries can be generated by placing sets of F cards in sequence. If, for instance, there is data on Q or S cards for the first and third tributary upstream from the downstream boundary and the second tributary is to be generated, then NTRB(NFT) is 2 and Q or S cards for tributary one and three would be right after each other.

Field	Variable	Value	Description
0	ID	F	Card identification in column 1.
1	NTRB(NFT)	+	Tributary number that this tributary generation corresponds to, counting from downstream to upstream.
2	NFPT(NFT)	+	Number of points (up to 20) defining the relationship of main stem flow to tributary flow.
3	LOGFQ(NFT)	Ø	Main stem flow interpolation is arithmetic.
		1	Main stem flow interpolation is logarithmic, $\log_{10}$.
4	LOGFQT(NFT)	Ø	Tributary flow interpolation is arithmetic.
		1	Tributary flow interpolation is logarithmic, $\log_{10}$.
5	QFM(NFT,1)	+	Lowest discharge of main stem, subsequent discharges must be increasing.
6	QFT(NFT,1)	+	Tributary discharge corresponding to main stem discharge.
7	QFM(NFT,2)	+	Enter up to 20 points using fields 1-10 on subsequent cards. Put F in column 1 on all cards.
8	QFT(NFT,2)	+	Continue entering up to NFPT(NFT) pairs of points.
.	.		
.	.		
.	.		
10	etc.		

G Card - Sediment Load Curve - Required

Field	Variable	Value	Description
0	ID	G	Card identification in column 1.
1	INPTS	+	Number of sediment load values that will be read (up to 20).
2	LOGQ	Ø	Flow interpolation is arithmetic
		1	Flow interpolation is logarithmic, $\log_{10}$, (recommended)
3	LOGQS	Ø	Sediment load interpolation is arithmetic.
		1	Sediment load interpolation is logarithmic, $\log_{10}$, (recommended).
4	XMULT	Blank	Default to 1.0.
		+	Multiplying factor of sediment load (e.g., to increase sediment load by 7%, input 1.07).
5	FLT(1)	+	First discharge (in cfs) of the table, subsequent discharges must be increasing.
6	QS(I)	+	Sediment load (in tons/day) corresponding to first discharge.
7	FLT(2)	+	Enter up to 20 points using fields 1-10 on subsequent cards. Put G in column 1 on all cards.
8	QS(2)	+	Continue entering up to INPTS pairs of points.
.	.		
.	.		
.	.		
10	etc.		

T CARD - Water Temperature - Required if temperature cards are input and T-cards are to be output with the histogram for use in HEC-6 hydrologic input.

Field	Variable	Value	Description
Ø	ID	T	Card identification in column 1.
1	JTT	Ø	Water temperature is input in units of Farenheit degrees.
		1	Water temperature is input in units of Celsius degrees.
2	NT	Ø	Average monthly water temperature will be input.
		1	366 days of average daily water temperature. (Include February 29) will be input. See note below for encoding details. This data will be reused as many times as necessary to provide a daily water temperature for each mean daily water discharge on Q or S cards.
		2	Input a continuous record of mean daily water temperatures equal in length to Q or S cards of the main stem.
3	TB(I)	+	Input average monthly temperature for January if NT = 0. Follow with monthly temperatures for February, March, etc. using fields 4-10 and continuing on another T card starting in Field 1.

Note: If NT = 1 or 2, the following form should be used for all additional T-cards, and the last T-card should be followed by an ER card. This set of T cards is to be placed after the Q, S or Y cards (after the corresponding ER card), whichever is input last.

Field	Variable	Value	Description
Ø	ID	T	Card identification in column 1.
1	---	AN	Time identification (e.g., February 1972 is 1972-02).
2-1Ø	DWT(I)	+	Mean daily water temperature. Subsequent cards use fields 2-1Ø for values of DWT. Must have four cards for each month.

B-CARD - Parameter Definition Card - Required if R-cards or X-cards are to be output with the histogram for use in HEC-6 hydrologic input. Required if gage records are input.

Field	Variable	Value	Description
Ø	ID -	B	Card identification in column 1.
1	NGAGE		Number of gaging stations used in determining the starting elevations for water surface profile calculations (HEC-6 R-card) cannot be changed on subsequent B cards.
		Ø	R cards are not output with the histogram.
		1,2	Enter number of gaging stations (sets of Y-cards) input to compute R-card values.
2	GZ1	-,Ø,+	Gage zero of first gaging station if stages are input.
3	GS2	-,Ø,+	Gage zero of second gaging station if stages are input.
4	GWF		Weighting factor applied to first gaging station when computing representative stage between two gages.
		Ø	Defaults to Ø.5. (equal weighting for each gage)
		+	Enter value between Ø and 1.
5	DYM	+	Maximum allowable change in starting downstream water surface elevation. When DYM is equaled or exceeded, a new histogram event will be started.
		Ø	Defaults to 99999.Ø.
6	XDIV		The computational time step on the X-card (HEC-6 hydrologic input) is approximately equal to the number of days in the histogram event divided by XDIV.
		Ø	Defaults to 1.0. W-cards will be output.
		+	Enter an integer value greater than 1. X-cards will be output.
7	DTM	+	Maximum allowable change in water temperature in input units. When DTM is equalled or exceeded, a new histogram event will be started.
		Ø	Defaults to 99.

H card - Input control card. Required for each time period up to one year in length. The first H card comes before the Q or S cards. The rest of the H cards go after the last ER card. Place a blank H card after the last H card to terminate the job.

Field	Variable	Value	Description
Col 1	ID	H	Card identification.
Col 5-8	IYR	+	Year of hydrograph.
2	ITRB	Ø	No tributaries are present.
		+	Indicate number of tributary Q or S card sets of mean daily flow hydrograph are input (Note: Exclude the numbers of tributaries calculated using the F-card option). Stack the hydrographs in sequence from downstream to upstream. Place on ER card after each tributary hydrograph.
3	SWSED	+	Specific weight of sediment, lbs/cf.
		Ø	Default = 93 lb/cf.
4	AMAGIC	+	Weight of accumulated sediment for determining each histogram interval, tons.
5	SM	+	Number of first month of hydrograph time period (e.g. 2 is for February).
		Ø	Defaults to 1 (January).
6	EM	+	Number of last month of hydrograph time period.
		Ø	Default is 12 (December)
7	PUN	1	Create output file (I/O unit 10) of histogram for HEC-6 hydrologic input. IDH (H-9) must be 1 or 3.
		Ø	Do not create output file.
8	STZ	+	Elevation of gage zero if stages are input (S-cards).
9	IDH	Ø	Process data and display but do not calculate histogram or dominate discharge.
		1	Calculate histogram only and display.
		2	Calculate dominate discharge only and display.
		3	Calculate both histogram and dominate discharge only and display.
10	NGSF	Ø	Print daily calculations for time period.
		1	Print summary (monthly and yearly only) for time period.

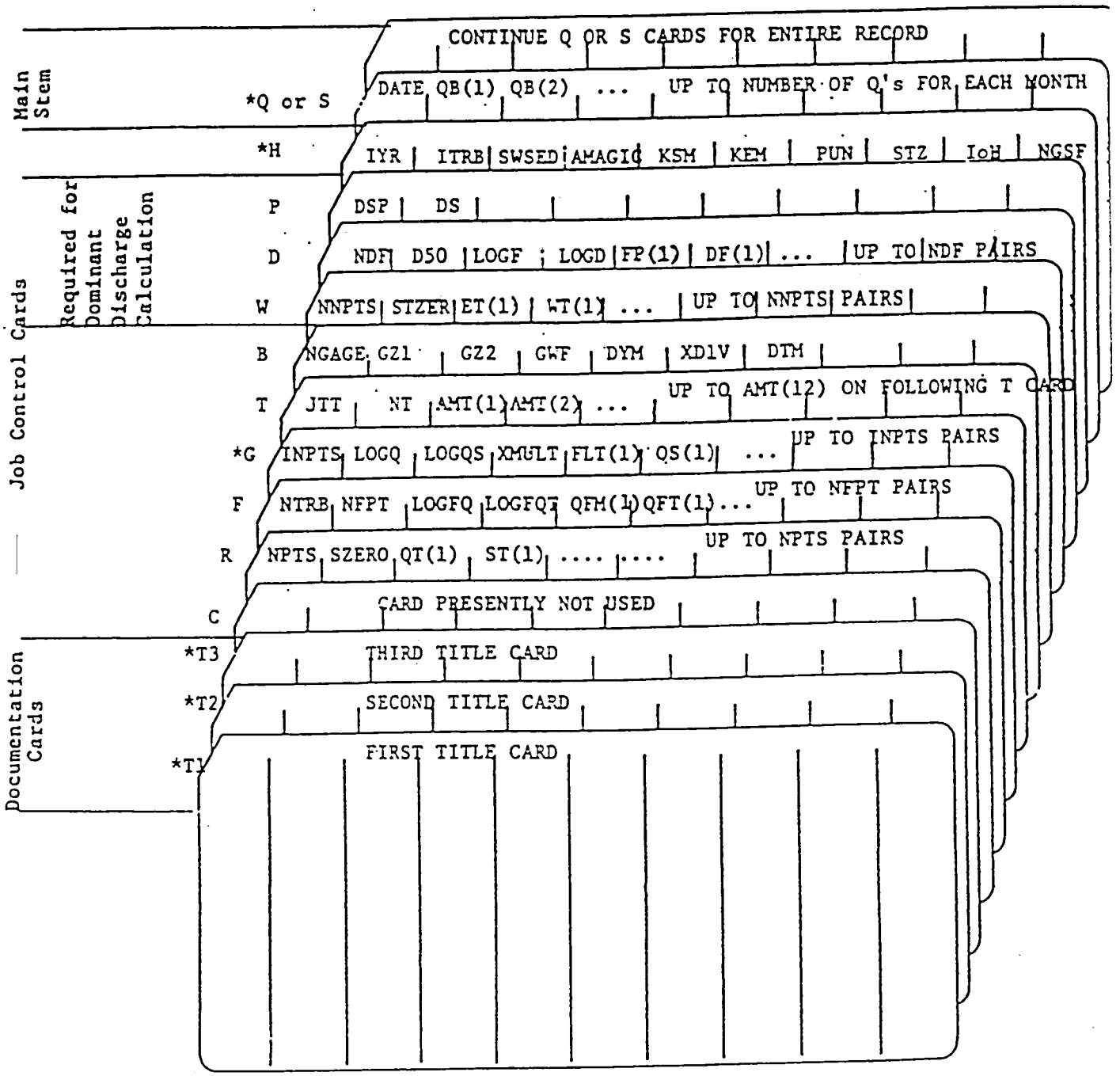
Q or S Card - Input hydrograph, mean daily flows or mean daily elevations/stages. Required.

Field	Variable	Value	Description
Col 1	ID	Q	Discharge in cfs are input.
		S	Stage in ft. are input.
Col 2-3	—	AN	Time identification (e.g. February 1972 is 1972-02).
2-10	Q(I)	+	Discharges or stages. Subsequent cards use fields 2-10 for values of Q or S. Must have four cards for each month.

If stage is input, there must be R cards present. A set of Q or S cards, terminated by an ER card, is required for the main stem and each tributary. If Q cards are changed to S cards, R cards must be placed before the H cards representing the S card time interval. Tributaries must use Q cards - S cards are not allowed.

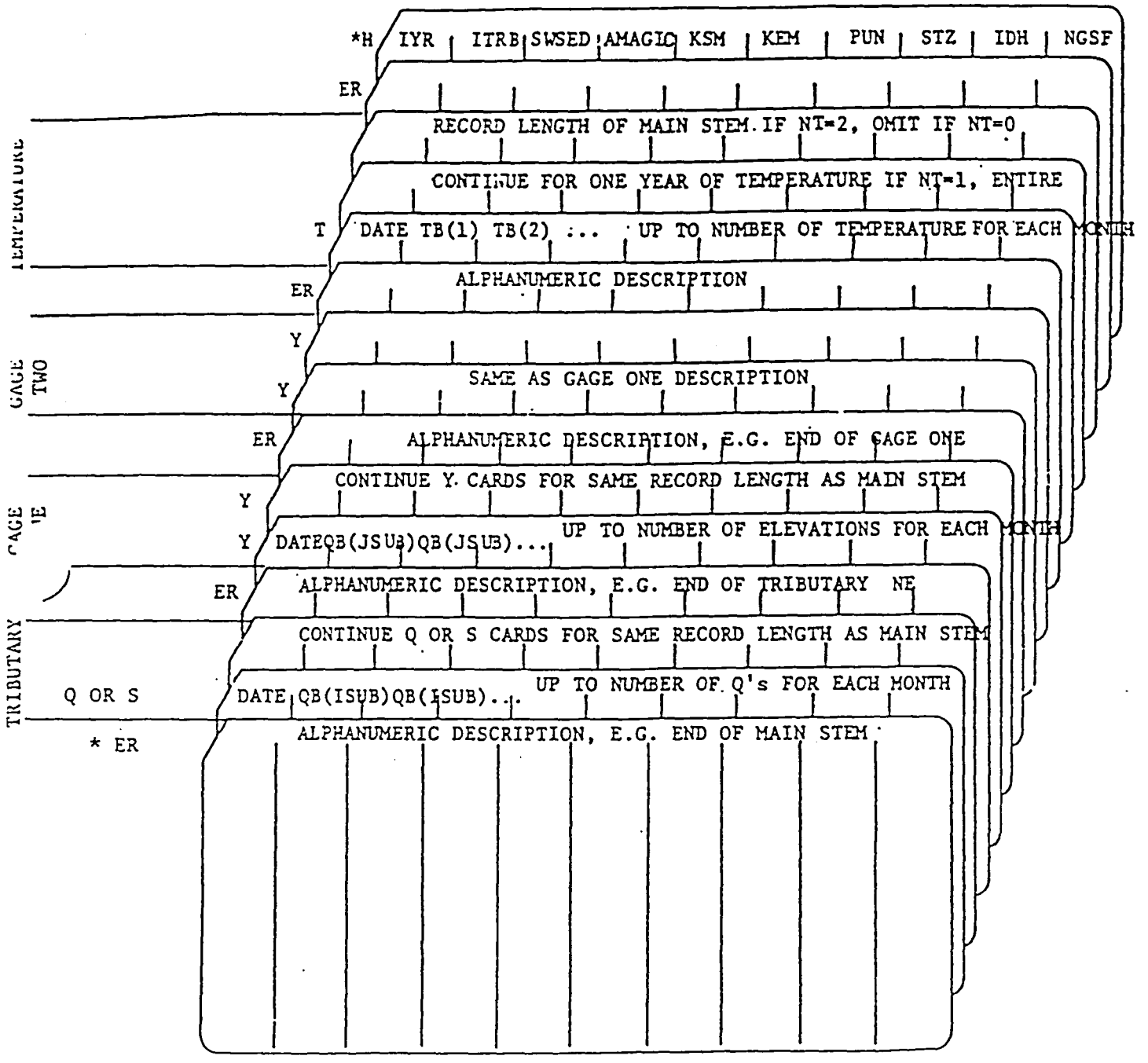
ER - Card - Separator for sets of data. Required after each set of Q, S, T, or Y cards.

Field	Variable	Value	Description
0	ID	ER	Card identification.
1-10	-	AN	Alphanumeric description of data set.

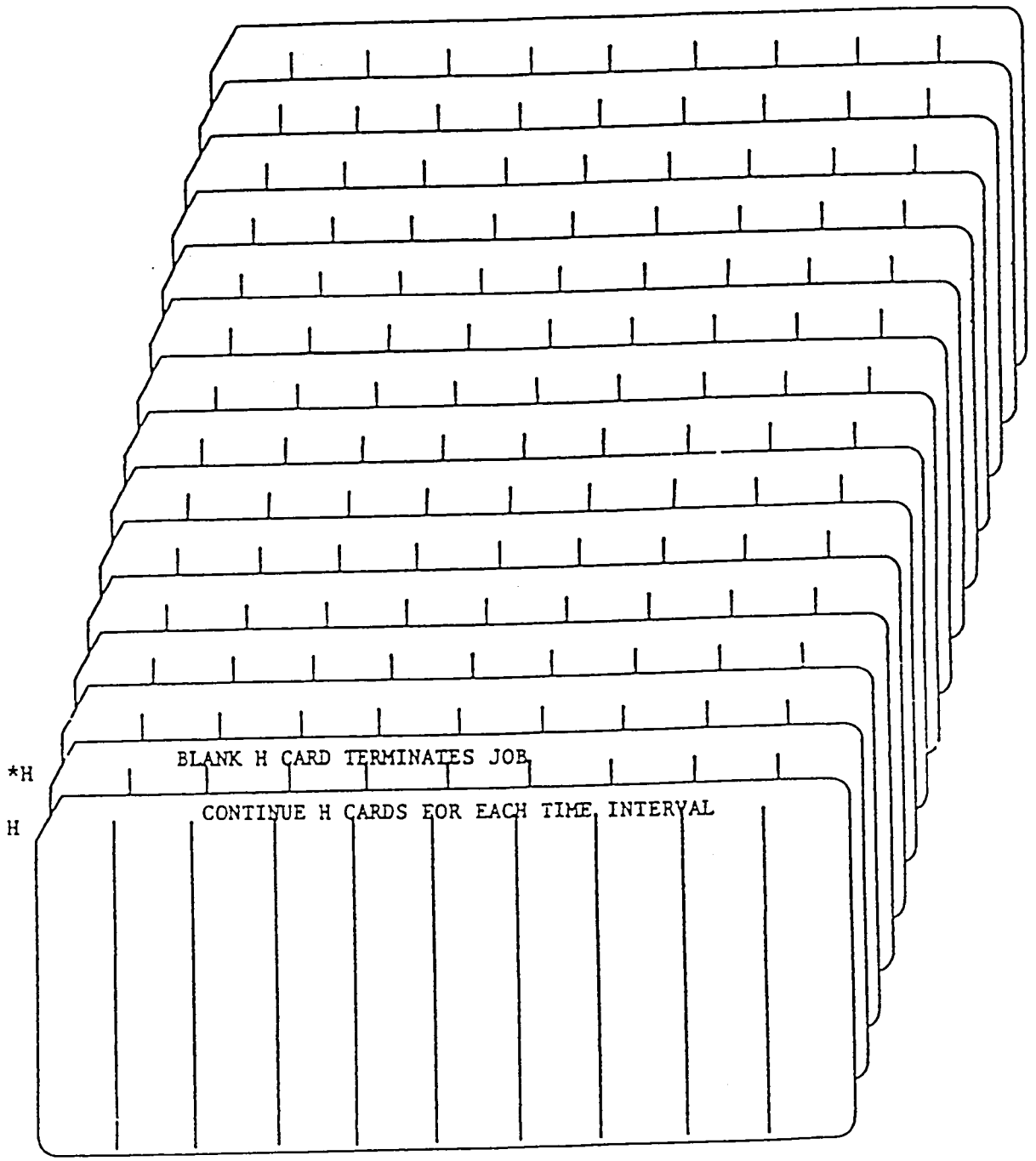


Any job control parameters can be changed for any H-card time period by placing the appropriate job control card before the H-card it applies to.

* Indicates cards required for basic application



* Indicates cards required for basic application



* Indicates cards required for basic application

```
T1      ROCHESTER,MN SEDIMENT STUDY
T2      LOAD CURVE IS QS=.00XQ (EXP 1.55)
T3      DAVID WILLIAMS, WES, MARCH 1982
G     2       1       1       1       1.      .08  30000. 696030.
T                    71      68      78      90      45      32      76      90
T    89      97      96      95      94      93
R                                                    15
H  1952       1           10000       1      12     (1)              1       1
01952- 1     85.     65.     85.     85.     85.     85.     85.     85.     87.
01952- 1     83.     81.     83.     83.     91.     91.     95.     90.     89.
01952- 1    104.     76.     85.     83.     78.     78.     79.     81.     78.
01952- 1     74.     72.     72.     78.
01952- 2     79.     79.     79.     81.     81.     79.     81.     81.     79.
01952- 2     83.     63.     89.     93.     95.     98.    104.    102.    102.
01952- 2     74.     78.     87.     83.     87.     83.     81.     87.     87.
01952- 2     87.     85.
01952- 3     81.     85.     83.     66.     72.     70.     76.     76.     74.
01952- 3     83.     85.    104.    115.    124.    131.    150.    189.    360.
01952- 3    459.    534.    466.    345.    168.    222.    200.    178.    171.
01952- 3    168.    322.   3260.   7300.
01952- 4   5300.   3430.   1100.    872.    900.    760.    912.    864.    806.
01952- 4    510.    479.    436.    432.    412.    937.    888.    660.    581.
01952- 4    520.    459.    412.    436.    370.    314.    284.    264.    250.
01952- 4    236.    225.    214.
01952- 5    205.    194.    197.    186.    176.    165.    186.    308.    270.
01952- 5    236.    228.    223.    204.    191.    191.    176.    166.    156.
01952- 5    148.    146.    140.    138.    146.    148.    143.    133.    143.
01952- 5    140.    133.    143.    136.
01952- 6    123.    118.    116.    113.    118.    111.    106.    101.     94.
01952- 6     88.    106.     94.    104.    116.    101.     96.     96.     84.
01952- 6     78.     86.     88.     80.   2340.   4730.   2230.   1090.    739.
01952- 6    798.    489.    379.
01952- 7    318.    295.    310.    279.    233.    207.    225.    220.    199.
01952- 7    184.    173.    171.    158.    168.    178.    160.    150.    148.
01952- 7    197.   1340.    761.    333.    246.    212.    186.    160.    163.
01952- 7    884.    516.    243.    197.
01952- 8    173.    160.    166.    254.    181.    160.    153.    237.   1060.
01952- 8    513.    273.    223.    199.    184.    205.    840.    302.    273.
01952- 8    273.    295.    321.    238.    202.    181.    160.    160.    156.
01952- 8    148.    148.    166.    173.
01952- 9    153.    140.    136.    130.    123.    120.    118.    118.    111.
01952- 9    106.    104.     99.     99.    106.     96.     94.     94.     96.
01952- 9     94.     90.     90.     88.     86.     86.     84.     82.     82.
01952- 9     80.     71.     66.
01952-10     74.     71.     71.     69.     69.     69.     71.     72.     74.
01952-10     74.     74.     72.     72.     72.     71.     69.     69.     69.
01952-10     68.     66.     66.     66.     66.     66.     66.     66.     66.
01952-10     66.     64.     66.     66.
01952-11     66.     64.     64.     64.     66.     63.     63.     63.     61.
01952-11     61.     61.     63.     63.     61.     61.     63.     88.     72.
01952-11     68.     66.     63.     63.     61.     61.     66.     61.     50.
01952-11     56.     55.     55.
01952-12     58.     60.     63.     63.     64.     66.     61.     66.     60.
01952-12     69.     66.     66.     58.     58.     60.     61.     58.     55.
01952-12     56.     58.     58.     60.     61.     60.     52.     58.     53.
```

```
T1      ROCHESTER,MN SEDIMENT STUDY
T2      LOAD CURVE IS QS=.08XQ (EXP 1.55)
T3      DAVID WILLIAMS, WES, MARCH 1982
```

THE INPUT SEDIMENT LOAD CURVE HAS 2 POINTS AND THE SEDIMENT IS TO BE MULTIPLIED BY 1.0 LOGQ = 1 AND LOGQS = 1
THE SEDIMENT LOAD CURVE TABLE FOLLOWS

FLOW IN CFS	1.0	30000.0
LOAD IN TONS/DAY	.080	696030.0

THE FOLLOWING MONTHLY TEMPERATURES (F) WILL BE USED

JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPT.	OCTOBER	NOVEMBER	DEC.
71.0	68.0	70.0	90.0	45.0	32.0	76.0	90.0	89.0	97.0	93.0	93.0

INFORMATION FROM B CARD

NGAGE	GZ1	GZ2	GWF	DYM	XDIV	DTM,F
0	0.00	0.00	.50	99999.00	1.00	15.00

****
****

START YEAR = 1952 START MONTH = 1 END MONTH = 12 AMAGIC = 10000. UNIT WT OF SED. = 93.0 ITRB = 1 IDH = 1
****

	CFS-DAYS	ACRE-FEET	*		TONS	ACRE-FEET
TOTAL WATER DISCHARGE	92292.0	183058.5	*	TOTAL SEDIMENT DISCHARGE	362615.6	177.0
CUMMULATIVE DISCHARGE	92292.0	183058.5	*	CUMMULATIVE DISCHARGE	362615.6	179.0

NUMBER OF DISCHARGE EVENTS IN THE HYDROGRAPH= 366

MAX. WATER DISCHARGE IS 7300.0
MIN. WATER DISCHARGE IS 50.0
MEAN WATER DISCHARGE IS 252.2

MONTHLY VALUES

MONTH	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPT.	OCTOBER	NOVEMBER	DEC.
Q CFSD	2593.	2487.	15825.	24253.	5495.	15012.	9430.	8265.	3047.	2140.	1892.	1858.
Q ACFT	5143.	4933.	31388.	48105.	10099.	29776.	18704.	16393.	6034.	4245.	3753.	3685.
QS TNS	2375.	2310.	109023.	115276.	7756.	70535.	22506.	17036.	3140.	1759.	1485.	1415.
QS AFT	1.2	1.1	53.8	56.9	3.8	38.8	11.1	8.4	1.6	.9	.7	.7

ACCUM DAY	QMAX	QMIN	DAY W-CARD	TIME X-CARD	DS WSE R-CARD	INTPL Q Q-CARD	ADT T-CARD	WATER YIELD ACTUAL	WATER YIELD HISTOGRAM	SEDIMENT YIELD	CRITERION EXCEEDED
30	104.	70.	29.82	29.824	0.0	84.	71.0	2515.	2515.	2306.	30 DAYS
60	104.	74.	29.81	29.806	0.0	86.	68.1	2565.	2565.	2370.	30 DAYS
89	534.	66.	21.72	21.717	0.0	247.	78.0	5265.	5356.	8862.	AMAGIC
90	3260.	3260.	1.00	1.000	0.0	3260.	78.0	3260.	3260.	22314.	AMAGIC
91	7300.	7300.	1.00	1.000	0.0	7300.	78.0	7300.	7300.	77847.	AMAGIC
92	5300.	5300.	1.00	1.000	0.0	5300.	90.0	5300.	5300.	47393.	AMAGIC
93	3420.	3420.	1.00	1.000	0.0	3420.	90.0	3420.	3420.	24034.	AMAGIC
95	1100.	872.	1.98	1.980	0.0	996.	90.0	1972.	1972.	7032.	AMAGIC
98	912.	760.	2.99	2.985	0.0	862.	90.0	2572.	2572.	8468.	AMAGIC
104	864.	432.	5.61	5.613	0.0	629.	90.0	3527.	3528.	9767.	AMAGIC
108	937.	412.	3.79	3.789	0.0	767.	90.0	2897.	2908.	8984.	AMAGIC
131	581.	214.	12.03	12.032	0.0	380.	90.0	4565.	4572.	9596.	TEMP.
151	308.	133.	20.73	20.732	0.0	186.	45.0	5359.	5354.	7594.	30 DAYS
174	136.	78.	22.64	22.641	0.0	104.	32.6	2353.	2353.	2421.	AMAGIC
175	2340.	2340.	1.00	1.000	0.0	2340.	32.0	2340.	2340.	13347.	AMAGIC
176	4730.	4730.	1.00	1.000	0.0	4730.	32.0	4730.	4730.	39731.	AMAGIC
177	2230.	2230.	1.00	1.000	0.0	2230.	32.0	2230.	2230.	12387.	AMAGIC
180	1090.	739.	2.93	2.930	0.0	897.	32.0	2627.	2627.	8839.	AMAGIC
182	489.	379.	1.98	1.976	0.0	439.	32.0	868.	868.	1973.	TEMP.
201	318.	148.	18.09	18.091	0.0	220.	76.0	3981.	3980.	6185.	AMAGIC
204	1540.	333.	2.51	2.511	0.0	1070.	76.0	2634.	2687.	9968.	AMAGIC
221	884.	153.	12.16	12.162	0.0	349.	82.6	4299.	4239.	8485.	AMAGIC
229	1060.	184.	6.07	6.072	0.0	591.	90.0	3497.	3586.	9593.	AMAGIC
259	382.	96.	26.25	26.250	0.0	192.	89.5	5043.	5037.	7260.	30 DAYS
289	96.	66.	29.69	29.686	0.0	79.	93.0	2358.	2358.	2092.	30 DAYS
319	69.	61.	29.97	29.971	0.0	65.	96.5	1948.	1948.	1540.	30 DAYS
349	88.	50.	29.74	29.741	0.0	64.	95.5	1895.	1895.	1489.	30 DAYS
366	61.	52.	16.97	16.973	0.0	57.	95.0	972.	972.	720.	END TIME

NO. OF EVENTS . 28

TOTALS OF HISTOGRAM

TOTAL DAYS = 342.
TOTAL SEDIMENT IN TONS = 362616.

****

****
****

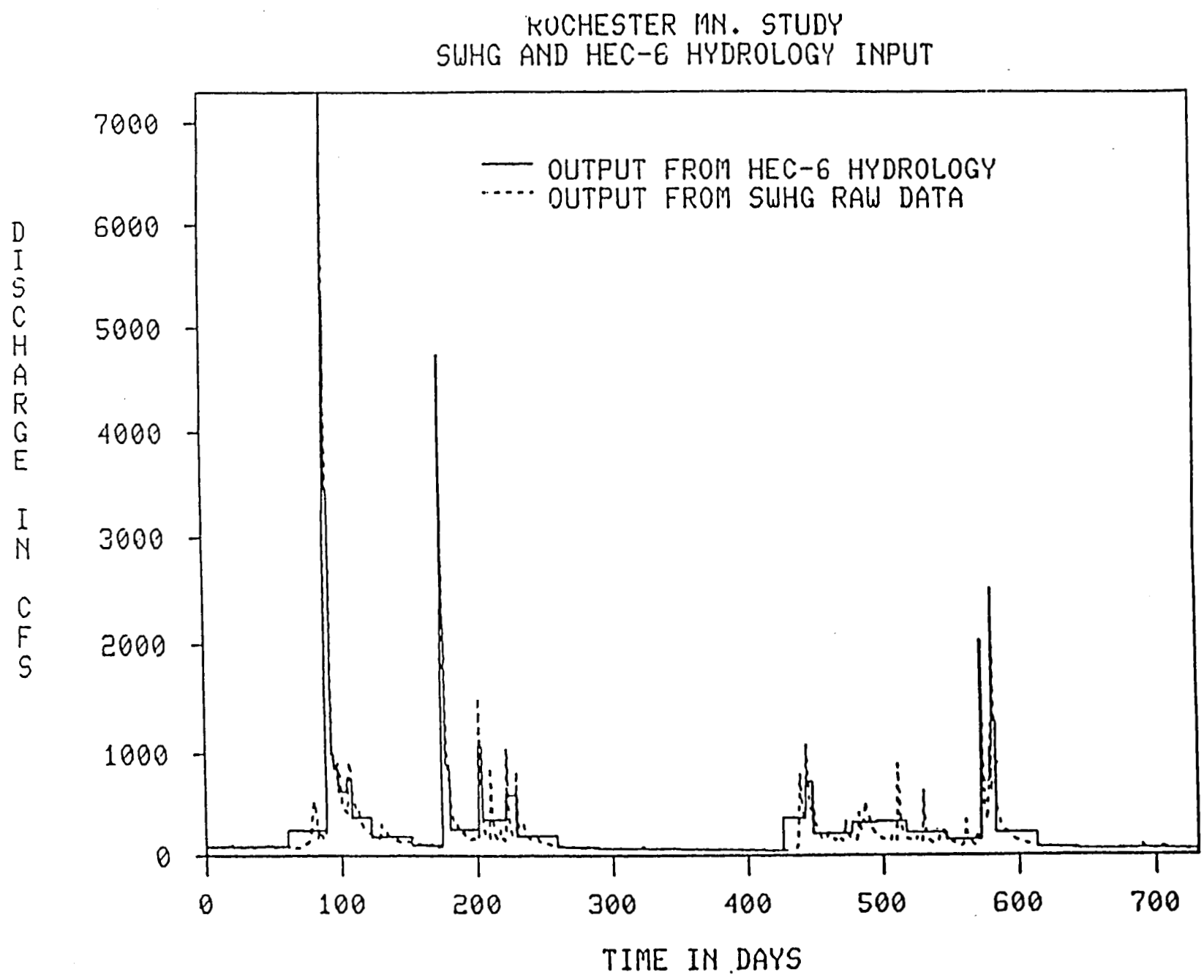
START YEAR = 1953 START MONTH = 1 END MONTH = 12 AMAGIC = 10000. UNIT WT OF SED. = 93.0 ITRB = 1 IDH = 1

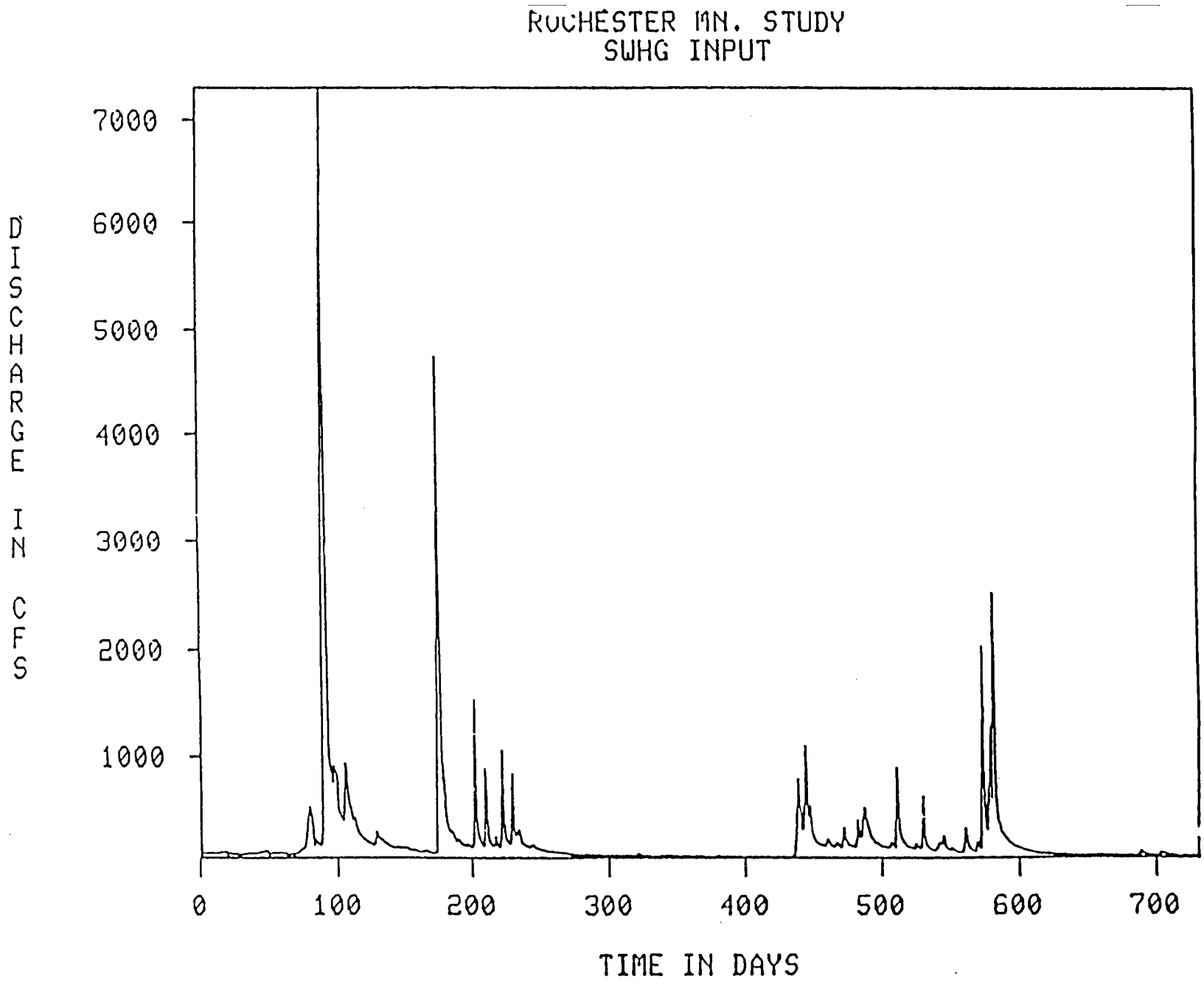
****

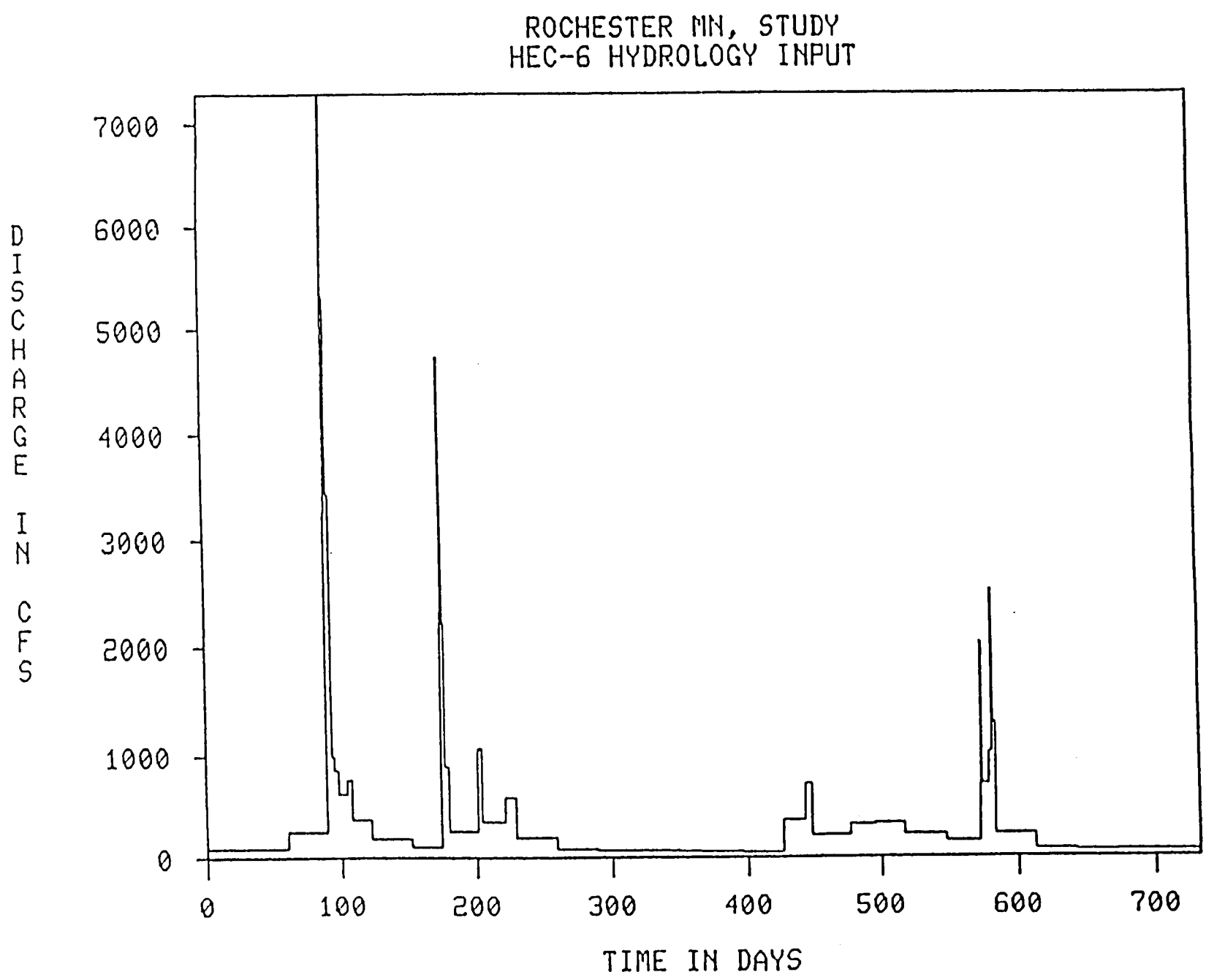
	CFS-DAYS	ACRE-FEET	*		TONS	ACRE-FEET
TOTAL WATER DISCHARGE	59789.0	118589.7	*	TOTAL SEDIMENT DISCHARGE	127300.3	62.9
CUMMULATIVE DISCHARGE	152081.0	301640.2	*	CUMMULATIVE DISCHARGE	490004.0	241.9

NUMBER OF DISCHARGE EVENTS IN THE HYDROGRAPH= 365

```
$HYD
*          EVENT ENDING JULIAN DAY AND YEAR     30 1952
Q     34.      55.
T    71.0     71.0
W   29.02
*          EVENT ENDING JULIAN DAY AND YEAR     60 1952
Q     32.      49.
T    68.1     60.1
W   29.01
*          EVENT ENDING JULIAN DAY AND YEAR     89 1952
Q    247.     377.
T    78.0     78.0
W   21.72
*          EVENT ENDING JULIAN DAY AND YEAR     90 1952
Q   3280.     170.
T    78.0     78.0
W    1.00
*          EVENT ENDING JULIAN DAY AND YEAR     91 1952
Q   3300.     173.
T    78.0     78.0
W    1.00
*          EVENT ENDING JULIAN DAY AND YEAR     92 1952
Q   5300.     167.
T    96.0     96.0
W    1.00
*          EVENT ENDING JULIAN DAY AND YEAR     93 1952
Q   3420.     139.
T    96.0     96.0
W    1.00
*          EVENT ENDING JULIAN DAY AND YEAR     95 1952
Q    776.     211.
T    95.0     95.0
W    1.98
*          EVENT ENDING JULIAN DAY AND YEAR     98 1952
Q    862.     192.
T    99.0     99.0
W    2.99
*          EVENT ENDING JULIAN DAY AND YEAR    104 1952
Q    629.     176.
T    99.0     99.0
W    5.61
*          EVENT ENDING JULIAN DAY AND YEAR    108 1952
Q    767.     245.
T    99.0     99.0
W    3.79
*          EVENT ENDING JULIAN DAY AND YEAR    121 1952
Q    339.     249.
T    99.0     50.0
W   12.93
*          EVENT ENDING JULIAN DAY AND YEAR    151 1952
Q    186.     274.
T    45.0     45.0
W   28.73
*          EVENT ENDING JULIAN DAY AND YEAR    174 1952
Q    104.     170.
```


ROCHESTER MN. STUDY
SWHG AND HEC-6 HYDROLOGY INPUT
OUTPUT FROM HEC-6 HYDROLOGY
OUTPUT FROM SWHG RAW DATA
DISCHARGE IN CFS
7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
700
TIME IN DAYS


ROCHESTER MN. STUDY
SWHG INPUT
DISCHARGE IN CFS
7000
6000
5000
4000
3000
2000
1000
0
100
200
300
400
500
600
700
TIME IN DAYS


ROCHESTER MN, STUDY
HEC-6 HYDROLOGY INPUT
DISCHARGE IN CFS
7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
700
TIME IN DAYS

VERIFICATION OF HEC-6

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

References:

[1] HEC-6 User Manual.

[2] Guidelines for the Calibration and Application of Computer Program HEC-6, The Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.

Objective: The student demonstrates skill in interpreting HEC-6 print out and adjusting input to reproduce field observations.

Input file is H6WRKSH3.DAT

1. PROBLEM.

A HEC-2 data set is being converted for HEC-6 computation. Sediment and hydrology data have already been added, and a trial execution has been made. The HEC6 model is now ready for verification.

2. END PRODUCT

The end product of this workshop will be an HEC-6 model that is verified for one water discharge.

3. MODEL VERIFICATION.

3.1 **Diagnosis.** The following diagnosis is made using printout from the trial #1 Run. The last event in that printout is shown on the next page.

3.1.1 <u>End of Run Results.</u> The first tables to scan to find out how well the sediment calculations represent the prototype are the SA- and SB-tables in the HEC=6 print out. These 2 tables will be printed for each hydrologic event which has a B in column 6 . The final event in this verification run is reproduced below. Notice the rather large trap efficiency, 9%, in the SA-1 table on the next page. This model is of a river which is in equilibrium. What should the trap efficiency be?

In this case, 9% trap efficiency is too large; there is a problem which must be resolved before this model is verified. The following steps illustrate the process.

3.1.2 <u>Most Active Cross Section.</u> First, scan every SB-2 table in the printout for the cross section having the largest BED CHANGE value. This cross section is referred to as "the most active section."

```
TIME STEP #       10
*    B  RUN 10

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Workshop Problem VII.  VERIFICATION OF HEC6 MODEL
       ACCUMULATED TIME (yrs)....      0.027
       FLOW DURATION (days)......      1.000

UPSTREAM BOUNDARY CONDITIONS
----------------------------------------------------------------------
Stream Segment # 1      |   DISCHARGE   | SEDIMENT LOAD | TEMPERATURE
Section No.  4570.000 |     (cfs)       |  (tons/day)   |   (deg F)
----------------------------------------------------------------------
                INFLOW |       90000.00 |       21942.14 |       50.00

TABLE SA-1. TRAP EFFICIENCY ON STREAM SEGMENT #  1
            Workshop Problem VII.  VERIFICATION OF HEC6 MODEL
            ACCUMULATED AC-FT ENTERING AND LEAVING THIS STREAM SEGMENT
******************************************************
    TIME        ENTRY *          SAND                 *
    DAYS        POINT *    INFLOW   OUTFLOW  TRAP EFF *
   10.00    4570.000 *    108.33                      *
   TOTAL=       0.000 *    108.33     98.96      0.09 *
******************************************************

TABLE SB-1:  SEDIMENT LOAD PASSING THE  BOUNDARIES OF STREAM SEGMENT #  1
--------------------------------------------------------------------------------
  SEDIMENT INFLOW at the Upstream Boundary:
      GRAIN SIZE       LOAD (tons/day) |    GRAIN SIZE      LOAD (tons/day)
  --------------------------------------------------------------------------
    VERY FINE SAND....        1797.84  | FINE GRAVEL.......        1693.78
    FINE SAND.........        1973.84  | MEDIUM GRAVEL.....        2619.76
    MEDIUM SAND.......        2986.06  | COARSE GRAVEL.....        3081.76
    COARSE SAND.......        2102.98  | VERY COARSE GRAVEL        4180.00
    VERY COARSE SAND..         594.66  | SMALL COBBLES.....           0.22
    VERY FINE GRAVEL..         911.24  | LARGE COBBLES.....           0.00
                         ------------                        ------------
                                                 TOTAL =       21942.14
  SEDIMENT OUTFLOW from the Downstream Boundary
      GRAIN SIZE       LOAD (tons/day) |    GRAIN SIZE      LOAD (tons/day)
  --------------------------------------------------------------------------
    VERY FINE SAND....        1885.65  | FINE GRAVEL.......        1172.45
    FINE SAND.........        2088.63  | MEDIUM GRAVEL.....        1790.50
    MEDIUM SAND.......        3093.14  | COARSE GRAVEL.....        2143.77
    COARSE SAND.......        2214.00  | VERY COARSE GRAVEL        2962.60
    VERY COARSE SAND..         515.22  | SMALL COBBLES.....           0.00
    VERY FINE GRAVEL..         654.71  | LARGE COBBLES.....           0.00
                         ------------                        ------------
                                                 TOTAL =       18520.66

TABLE SB-2:  STATUS OF THE BED PROFILE AT TIME =     10.000 DAYS
--------------------------------------------------------------------------------
  SECTION   BED CHANGE   WS ELEV   THALWEG         Q       TRANSPORT RATE (tons/day)
  NUMBER       (ft)        (ft)      (ft)        (cfs)        SAND
   4570.000       2.09    729.14    709.99     90000.     13718.
   2870.000      -1.63    726.07    701.57     90000.     17698.
   2280.000       0.54    725.55    703.24     90000.     17370.
    590.000      -0.92    723.04    704.38     90000.     18184.
      0.000       0.07    722.30    702.07     90000.     18521.

--------------------------------------------------------------------------------------------
$$END
```

Which is the most active cross section? _____

3.1.3 Numerical Stability Test. The next step is to determine whether or not the most active cross section is numerically stable by plotting a bed change hydrograph, i.e. BED CHANGE vs TIME.

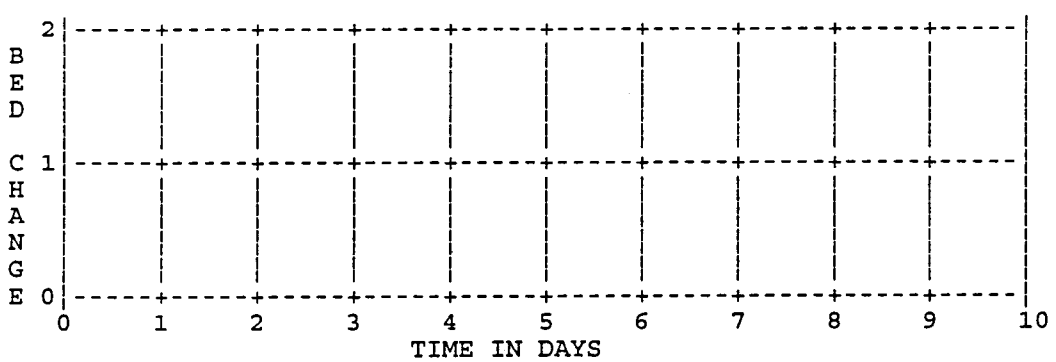
(HINT: There is no single table showing such a hydrograph. It has to be compiled by scanning the printout with an editor. In this case, scan the printout for cross section 4570, view every SB-2 table, and write the BED CHANGE value and its TIME in the spaces provided in Table 1 below. There are 10 events in the hydrograph, and each event flowed for 1 day. All 10 events are for the same water discharge - 90000 cfs and have SA & SB- tables. The BED CHANGE values are accumulative. All other values in table SB-2 are instantaneous. Plot the BED CHANGE values which you have just recorded in Table 1 on the graph below the table.)

Is the model numerically stable?

Table 1. Scan all SB-2 Tables Using Editor

SECTION NUMBER	BED CHANGE (ft)	WS ELEV (ft)	THALWEG (ft)	Q (cfs)	TRANSPORT RATE (tons/day) SAND	TIME DAYS
4570.000	_____ (1)	729.83	708.12	90000.	11740.	_____
4570.000	_____	729.77	708.36	90000.	11210.	_____
4570.000	_____	729.64	708.59	90000.	11288.	_____
4570.000	_____	729.55	708.81	90000.	11637.	_____
4570.000	_____	729.41	709.03	90000.	12083.	_____
4570.000	_____	729.34	709.23	90000.	12448.	_____
4570.000	_____	729.27	709.43	90000.	12785.	_____
4570.000	_____	729.23	709.62	90000.	13060.	_____
4570.000	_____	729.18	709.81	90000.	13391.	_____
4570.000	_____ (10)	729.14	709.99	90000.	13718.	_____

Notes:
(1) This is the bed change at the end of day 1
(10) This is the accumulated bed change at the end of day 10



3.1.4 Hydraulic Calculations. The next step is to check hydraulic computations for flow distribution. The following values were collected by scanning the HEC-6 print out for the string /FLOW DISTR/ using the utility "grep." Notice the hydraulic computations proceed from DOWNSTREAM TO UPSTREAM in direction whereas the sediment results in Table SB-2 are from UPSTREAM TO DOWNSTREAM in direction. (I added the Cross Section column for reference.)

Table 2. Calculated Flow Distribution, Initial Trial

Cross Section		Left Overbank	Main Channel	Right Overbank
0	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
590	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
2280	FLOW DISTRIBUTION (%) =	12.171	87.829	0.000
2870	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
4570	FLOW DISTRIBUTION (%) =	30.719	69.281	0.000

3.2 **Potential Problems.** There is a flow distribution problem at sections 2280 and 4570. For example, only 69.3% of the water is conveyed within the channel portion of cross section 4570, and 90,000 cfs is suppose to be the bank full flow. List some possible causes of such a problem.

3.3 **Task 2.** In this case the problem is a HEC-2 data set which has no X3-records. Insert X3-Records into the data set given to you. Use Method 1 option for defining ineffective flow area(X3-1, p A-10). A listing of the existing data set is shown in Table 3. Execute and tabulate the new flow distributions in Table 4.

Table 3. The HEC-6 Input Data File.

```
T1      Workshop Problem III.  VERIFICATION OF HEC6 MODEL
T2      WORKSHOP TO DEMONSTRATE HEC-6 MODEL VERIFICATION
T3      Sediment Transport in Rivers and Reservoirs
NC  .080    .080     .03      .3      .5
```

```
X1      0       20              653
GR 743.1        0     710       68     710      120   710.2      150   709.1      178
GR 711.6      214   711.9      264   710.5      320     709      360     707      390
GR   706      415   703.3      450   703.1      492     702      530   703.9      570
GR 703.1      610     705      635     711      647     715      649   743.1      653
H
X1   590       19             696     590      590     590
GR 743.1        0   711.5       62   710.3       78   711.7      102   710.9      137
GR   711      173   712.5      208   714.6      270   713.3      320   711.3      340
GR 708.8      402   707.3      458   706.3      475     706      493   705.3      513
GR   706      558   707.8      611     709      625   743.1      696
H
X1  2280       13     620     1122    1690     1690    1690
GR 743.1        0     717       53     717      550     730      620     704      710
GR 703.5      740   703.9      780   702.7      840   702.8      878   704.2      910
GR 705.8      990   717.4     1046   743.1     1122
H
X1  2870       13     570     1182     590      590     590
GR 743.1        0     743       53     743      500     740      570     707      710
GR 704.0      740   704.4      780   703.2      840   703.3      878   704.7      910
GR 708.8      990   717.4     1046   743.1     1182
H
X1  4570       17    1040     1593    1700     1700    1700
GR 743.3        0     717       52     717      964     715     1008     735     1040
GR   710     1074     708     1080   708.1     1140   707.9     1190   708.2     1230
GR   710     1304   711.7     1324   713.5     1360     715     1395     717     1450
GR   717     1540   743.3     1593
H
EJ
T4        Workshop Problem III.  Sediment Data
T5        A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6        B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7        C.  Transport Method is Laursen (Madden-1985)
T8        D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1            20
I4            13       1      12
LQ  Q       1000   10000   90000
LT QS        200    1200   22000
LF VFS   0.49999 0.50000 0.08172
LF FS    0.17065 0.03577 0.08972
LF MX    0.21649 0.04672 0.13573
LF CS    0.05499 0.07747 0.09559
LF VCS   0.00624 0.04373 0.02703
LF VFG   0.00147 0.00665 0.04142
LF FG    0.00460 0.02099 0.07699
LF MG    0.02008 0.06456 0.11908
LF CG    0.02548 0.10284 0.14008
LF VC    0.00000 0.10126 0.19000
LF SC          0       0 0.00001
LF LC          0       0       0
PF             0             150     128      95      64 53.3017      32 22.6062
PFC   16 11.9206       8  5.7197       4  3.1665       2  2.6834       1  2.6189
PFC    .5  2.2526     .25  1.0636    .125  0.4569   .0625       0
PF           590             150     128      94      64 56.4491      32 21.6422
PFC   16  9.5599       8  3.6605       4  1.6432       2  1.2737       1   1.211
PFC    .5  1.0523     .25  0.4937    .125  0.2132   .0625       0
PF          2280             150     128      96      64 66.9754      32 30.7065
PFC   16 16.0606       8  7.4191       4  3.5252       2  2.4365       1  2.2003
PFC    .5  1.6181     .25  0.8359   0.125  0.3613   .0625       0
PF          4570             150     128      95      64 69.5031      32 34.2786
PFC   16 19.4004       8  9.8218       4  4.9831       2  3.5241       1  3.1602
PFC    .5  2.0968     .25  1.1474    .125  0.4842   .0625       0
$HYD
$RATING
RC             6  20000.   10000       0   711.5     715     719   720.6   722.3
RC         723.6
*   AB  RUN 1.  STABILIZE THE MODEL FOR A WATER DISCHARGE = 2-YR FLOOD PEAK
Q  90000
T     50
W      1
*    B  RUN 2
Q  90000
W      1
*    B  RUN 3
Q  90000
W      1
```

```
*    B  RUN 4
Q  90000
W      1
*    B  RUN 5
Q  90000
W      1
*    B  RUN 6
Q  90000
W      1
*    B  RUN 7
Q  90000
W      1
*    B  RUN 8
Q  90000
W      1
*    B  RUN 9
Q  90000
W      1
*    B  RUN 10
Q  90000
W      1
$$END
```

Table 4 Calculated Flow Distribution, Task 2

Cross Section		Left Overbank	Main Channel	Right Overbank
0	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
590	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
2280	FLOW DISTRIBUTION (%) =	_____	_____	0.000
2870	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
4570	FLOW DISTRIBUTION (%) =	_____	_____	0.000

3.4 Calculated Hydraulic and Sedimentation Values.

3.4.1 <u>End of 10 days.</u> Fill in the calculated values in the space provided in table 5. These results are available for comparison with any measured data.

Table 5. Results from Sediment Calculations, TIME = 10 days

SECTION NUMBER	BED CHANGE ft	WS ELEV ft	THALWEG Q ft	SEDIMENT LOAD IN TONS/DAY cfs	SAND
4570	_____	_____	_____	90000.	_____
2870	_____	_____	_____	90000.	_____
2280	_____	_____	_____	90000.	_____
590	_____	_____	_____	90000.	_____
0	_____	722.30	_____	90000.	_____

3.4.2 Test for Equilibrium, Task 3. Ten days may not be long enough to develop the equilibrium case. Use X5 records and extend the hydrograph period to 50, 100, 200 and 300 days. How many days passed before the sediment transport rate at all cross sections became constant and equal to the inflow.

4. SENSITIVITY TESTS.

4.1 **Check Sensitivity to Hydraulic Roughness, Task 4.** Test sediment calculations to stream bed roughness using the Limerinos Method for calculating bed surface n-values. That option is selected by placing a $KL- Record after the $HYD. Modify your data file and execute the program producing C-Level print out in the Sediment Module for events 1 and 10. Using that C- Level print out, plus data from Table 3, fill in the following table. Did model performance improve when the n-value was calculated by Limerinos Method?

Table 6. n-Value Test

	n-values used in HEC-2			Channel n-values, Limerinos Method	
X-Section	LOB	ROB	CH	Event #1	Event #10
0	_____	_____	_____	_____	_____
590	_____	_____	_____	_____	_____
2280	_____	_____	_____	_____	_____
2820	_____	_____	_____	_____	_____
4570	_____	_____	_____	_____	_____

4.2 **Sensitivity to Tailwater Boundary Condition, Task 5.** Increase the tailwater +2.0 feet using a Shift Record (S-Record). The Hydrologic Data sequence is

```
*
Q
R
S
T
W
```

Did the model behave as expected?

5. OTHER WATER DISCHARGES. Assuming the model is now calibrated for 90,000, is it also calibrated for all flows?

VERIFICATION OF HEC-6 SOLUTIONS

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

References:

[1] HEC-6 User Manual

[2] Guidelines for the Calibration and Application of Computer Program HEC-6, The Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.

Objective: The student demonstrates skill in interpreting HEC-6 print out and adjusting input to reproduce field observations.

Solution output files are: H6WRK31S.DAT, H6WRK32S.DAT, H6WRK33S.DAT, H6WRK34S.DAT, H6WRK35S.DAT

1. PROBLEM.

A HEC-2 data set is being converted for HEC-6 computation. Sediment and hydrology data have already been added, and a trial execution has been made. The HEC6 model is now ready for verification.

2. END PRODUCT

The end product of this workshop will be an HEC-6 model that is verified for one water discharge.

3. MODEL VERIFICATION.

3.1 **Diagnosis.** The following diagnosis is made using printout from the trial #1 Run. The last event in that printout is shown on the next page.

3.1.1 <u>End of Run Results.</u> The first tables to scan to find out how well the sediment calculations represent the prototype are the SA- and SB-tables in the HEC=6 print out. These 2 tables will be printed for each hydrologic event which has a B in column 6 . The final event in this verification run is reproduced below. Notice the rather large trap efficiency, 9%, in the SA-1 table on the next page. This model is of a river which is in equilibrium. What should the trap effeciency be? **It should be 0 %.**

In this case, 9% trap efficiency is too large; there is a problem with the model which must be resolved before proceeding.

3.1.2 Most Active Cross Section. First, scan every SB-2 table in the printout for the cross section having the largest BED CHANGE value. This cross section is referred to as "the most active section."

```
TIME STEP #      10
*    B  RUN 10

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Workshop Problem VII.  VERIFICATION OF HEC6 MODEL
       ACCUMULATED TIME (yrs)....       0.027
       FLOW DURATION (days)......       1.000

UPSTREAM BOUNDARY CONDITIONS
-----------------------------------------------------------------------
Stream Segment # 1      |   DISCHARGE    | SEDIMENT LOAD | TEMPERATURE
Section No.   4570.000  |     (cfs)      |  (tons/day)   |   (deg F)
-----------------------------------------------------------------------
                INFLOW  |     90000.00   |     21942.14  |      50.00

TABLE SA-1. TRAP EFFICIENCY ON STREAM SEGMENT #  1
            Workshop Problem VII.  VERIFICATION OF HEC6 MODEL
            ACCUMULATED AC-FT ENTERING AND LEAVING THIS STREAM SEGMENT
*****************************************************
    TIME        ENTRY *              SAND            *
    DAYS        POINT *    INFLOW   OUTFLOW  TRAP EFF *
   10.00     4570.000 *    108.33                     *
   TOTAL=       0.000 *    108.33     98.96      0.09 *
*****************************************************

TABLE SB-1:  SEDIMENT LOAD PASSING THE  BOUNDARIES OF STREAM SEGMENT #  1
-------------------------------------------------------------------------------
  SEDIMENT INFLOW at the Upstream Boundary:
      GRAIN SIZE      LOAD (tons/day) |    GRAIN SIZE      LOAD (tons/day)
  -----------------------------------------------------------------------
    VERY FINE SAND....        1797.84 |  FINE GRAVEL.......        1693.78
    FINE SAND.........        1973.84 |  MEDIUM GRAVEL.....        2619.76
    MEDIUM SAND.......        2986.06 |  COARSE GRAVEL.....        3081.76
    COARSE SAND.......        2102.98 |  VERY COARSE GRAVEL        4180.00
    VERY COARSE SAND..         594.66 |  SMALL COBBLES.....           0.22
    VERY FINE GRAVEL..         911.24 |  LARGE COBBLES.....           0.00
                          -------------                        -------------
                                                     TOTAL =       21942.14
  SEDIMENT OUTFLOW from the Downstream Boundary
      GRAIN SIZE      LOAD (tons/day) |    GRAIN SIZE      LOAD (tons/day)
  -----------------------------------------------------------------------
    VERY FINE SAND....        1885.65 |  FINE GRAVEL.......        1172.45
    FINE SAND.........        2088.63 |  MEDIUM GRAVEL.....        1790.50
    MEDIUM SAND.......        3093.14 |  COARSE GRAVEL.....        2143.77
    COARSE SAND.......        2214.00 |  VERY COARSE GRAVEL        2962.60
    VERY COARSE SAND..         515.22 |  SMALL COBBLES.....           0.00
    VERY FINE GRAVEL..         654.71 |  LARGE COBBLES.....           0.00
                          -------------                        -------------
                                                     TOTAL =       18520.66

TABLE SB-2:  STATUS OF THE BED PROFILE AT TIME =    10.000 DAYS
-------------------------------------------------------------------------------
  SECTION    BED CHANGE   WS ELEV   THALWEG          Q       TRANSPORT RATE (tons/day)
  NUMBER        (ft)        (ft)      (ft)         (cfs)        SAND
   4570.000       2.09     729.14    709.99       90000.       13718.
   2870.000      -1.63     726.07    701.57       90000.       17698.
   2280.000       0.54     725.55    703.24       90000.       17370.
    590.000      -0.92     723.04    704.38       90000.       18184.
      0.000       0.07     722.30    702.07       90000.       18521.

-------------------------------------------------------------------------------------------
$$END
```

Which is the most active cross section? 4570

3.1.3 Numerical Stability Test. The next step is to determine whether or not the most active cross section is numerically stable by plotting a bed change hydrograph, i.e. BED CHANGE vs TIME.

(HINT: There is no single table showing such a hydrograph. It has to be compiled by scanning the printout with an editor. In this case, scan the printout for cross section 4570, view every SB-2 table, and write the BED CHANGE value and its TIME in the spaces provided in Table 1 below. There are 10 events in the hydrograph, and each event flowed for 1 day. All 10 events are for the same water discharge - 90000 cfs and have SA & SB- tables. The BED CHANGE values are accumulative. All other values in table SB-2 are instantaneous. Plot the BED CHANGE values which you have just recorded in Table 1 on the graph below the table.)

Is the model numerically stable? YES

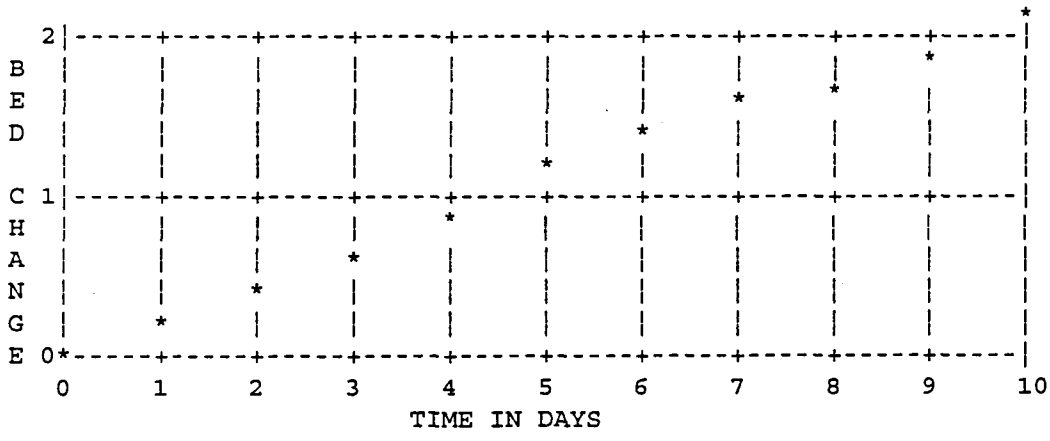
Table 1. Scan all SB-2 Tables Using Editor

SECTION NUMBER	BED CHANGE (ft)	WS ELEV (ft)	THALWEG (ft)	Q (cfs)	TRANSPORT RATE (tons/day) SAND	TIME DAYS
4570.000	0.22(1)	729.83	708.12	90000.	11740.	1
4570.000	0.46	729.77	708.36	90000.	11210.	2
4570.000	0.69	729.64	708.59	90000.	11288.	3
4570.000	0.91	729.55	708.81	90000.	11637.	4
4570.000	1.13	729.41	709.03	90000.	12083.	5
4570.000	1.33	729.34	709.23	90000.	12448.	6
4570.000	1.53	729.27	709.43	90000.	12785.	7
4570.000	1.72	729.23	709.62	90000.	13060.	8
4570.000	1.91	729.18	709.81	90000.	13391.	9
4570.000	2.09(10)	729.14	709.99	90000.	13718.	10

Notes:

(1) This is the bed change at the end of day 1

(10) This is the accumulated bed change at the end of day 10



3.1.4 Hydraulic Calculations. The next step is to check hydraulic computations for flow distribution. The following values were collected by scanning the HEC-6 print out for the string /FLOW DISTR/. Notice the hydraulic computations proceed from DOWNSTREAM TO UPSTREAM in direction whereas the sediment results in Table SB-2 are from UPSTREAM TO DOWNSTREAM in direction. (I added the Cross Section Column for reference.)

Table 2. Calculated Flow Distribution, Initial Trial

Cross Section		Left Overbank	Main Channel	Right Overbank
0	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
590	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
2280	FLOW DISTRIBUTION (%) =	12.171	87.829	0.000
2870	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
4570	FLOW DISTRIBUTION (%) =	30.719	69.281	0.000

3.2 **Potential Problems.** There is a flow distribution problem at sections 2280 and 4570. For example, only 69.3% of the water is conveyed within the channel portion of cross section 4570, and 90,000 cfs is suppose to be the bank full flow. List some possible causes of such a problem.

1) Error in coding GR-Records,
2) Error in tailwater rating curve,
3) Error in n-values,
4) Error in effective flow area,
5) Error in Bankfull Discharge.

3.3 **Task 2.** In this case the problem is a HEC-2 data set which had no X3-records. Insert X3-Records into the data set given to you. Use Method 1 option for defining ineffective flow area(X3-1, p A-10). A listing of the data set is shown in Table 3. Execute and tabulate the new flow distributions in Table 4.

Table 3. The HEC-6 Input Data File.

```
T1      Workshop Problem III.  VERIFICATION OF HEC6 MODEL
T2      WORKSHOP PROBLEM TO DEMONSTRATE HEC-6 MODEL VERIFICATION
T3      Sediment Transport in Rivers and Reservoirs
NC  .080    .080     .03      .3      .5
X1    0      20             653
```

```
X3       10
GR 743.1        0     710      68     710     120   710.2     150   709.1     178
GR 711.6      214   711.9     264   710.5     320     709     360     707     390
GR   706      415   703.3     450   703.1     492     702     530   703.9     570
GR 703.1      610     705     635     711     647     715     649   743.1     653
H
X1   590       19             696     590     590     590
X3       10
GR 743.1        0   711.5      62   710.3      78   711.7     102   710.9     137
GR   711      173   712.5     208   714.6     270   713.3     320   711.3     340
GR 708.8      402   707.3     458   706.3     475     706     493   705.3     513
GR   706      558   707.8     611     709     625   743.1     696
H
X1  2280       13     620    1122    1690    1690    1690
X3       10
GR 743.1        0     717      53     717     550     730     620     704     710
GR 703.5      740   703.9     780   702.7     840   702.8     878   704.2     910
GR 705.8      990   717.4    1046   743.1    1122
H
X1  2870       13     570    1182     590     590     590
X3     10
GR 743.1        0     743      53     743     500     740     570     707     710
GR 704.0      740   704.4     780   703.2     840   703.3     878   704.7     910
GR 708.8      990   717.4    1046   743.1    1182
H
X1  4570       17    1040    1593    1700    1700    1700
X3       10
GR 743.3        0     717      52     717     964     715    1008     735    1040
GR   710     1074     708    1080   708.1    1140   707.9    1190   708.2    1230
GR   710     1304   711.7    1324   713.5    1360     715    1395     717    1450
GR   717     1540   743.3    1593
H
EJ
T4        Workshop Problem III.  Sediment Data
T5        A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6        B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7        C.  Transport Method is Laursen (Madden-1985)
T8        D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1            20
I4            13       1      12
LQ  Q       1000   10000   90000
LT QS        200    1200   22000
LF VFS   0.49999 0.50000 0.08172
LF FS    0.17065 0.03577 0.08972
LF MX    0.21649 0.04672 0.13573
LF CS    0.05499 0.07747 0.09559
LF VCS   0.00624 0.04373 0.02703
LF VFG   0.00147 0.00665 0.04142
LF FG    0.00460 0.02099 0.07699
LF MG    0.02008 0.06456 0.11908
LF CG    0.02548 0.10284 0.14008
LF VC    0.00000 0.10126 0.19000
LF SC          0       0 0.00001
LF LC          0       0       0
PF             0             150     128      95      64 53.3017      32 22.6062
PFC   16 11.9206       8  5.7197       4  3.1665       2  2.6834       1  2.6189
PFC   .5  2.2526     .25  1.0636    .125  0.4569   .0625       0
PF           590             150     128      94      64 56.4491      32 21.6422
PFC   16  9.5599       8  3.6605       4  1.6432       2  1.2737       1   1.211
PFC   .5  1.0523     .25  0.4937    .125  0.2132   .0625       0
PF          2280             150     128      96      64 66.9754      32 30.7065
PFC   16 16.0606       8  7.4191       4  3.5252       2  2.4365       1  2.2003
PFC   .5  1.6181     .25  0.8359   0.125  0.3613   .0625       0
PF          4570             150     128      95      64 69.5031      32 34.2786
PFC   16 19.4004       8  9.8218       4  4.9831       2  3.5241       1  3.1602
PFC   .5  2.0968     .25  1.1474    .125  0.4842   .0625       0
$HYD
$RATING
RC             6  20000.   10000       0   711.5     715     719   720.6   722.3
RC         723.6
*   AB  RUN 1.  STABILIZE THE MODEL FOR A WATER DISCHARGE = 2-YR FLOOD PEAK
Q  90000
T     50
W      1
*    B  RUN 2
Q  90000
```

```
W       1
*     B  RUN 3
Q   90000
W       1
*     B  RUN 4
Q   90000
W       1
*     B  RUN 5
Q   90000
W       1
*     B  RUN 6
Q   90000
W       1
*     B  RUN 7
Q   90000
W       1
*     B  RUN 8
Q   90000
W       1
*     B  RUN 9
Q   90000
W       1
*     B  RUN 10
Q   90000
W       1
$$END
```

Table 4 Calculated Flow Distribution, Task 2

Cross Section		Left Overbank	Main Channel	Right Overbank
0	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
590	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
2280	FLOW DISTRIBUTION (%) =	0%	100%	0.000
2870	FLOW DISTRIBUTION (%) =	0.000	100.000	0.000
4570	FLOW DISTRIBUTION (%) =	0%	100%	0.000

3.4 Calculated Hydraulic and Sedimentation Values.

3.4.1 <u>End of 10 days.</u> Fill in the calculated values in the space provided in table 5. These results are available for comparison with any measured data.

Table 5. Results from Sediment Calculations, TIME = 10 days

SECTION NUMBER	BED CHANGE ft	WS ELEV ft	THALWEG ft	Q cfs	SEDIMENT LOAD IN TONS/DAY SAND
4570.000	0.38	728.65	708.28	90000.	21728.
2870.000	-0.28	726.33	702.92	90000.	22917.
2280.000	0.29	725.41	702.99	90000.	21888.
590.000	-0.80	723.31	704.50	90000.	22581.
0.000	0.95	722.30	702.95	90000.	22694.

3.4.2 Test for Equilibrium, Task 3. Ten days may not be long enough to develop the equilibrium case. Use X5 records and extend the hydrograph period to 50, 100, 200 and 300 days. How many days passed before the sediment transport rate at all cross sections became constant and equal to the inflow.

Between 100 and 200 days the model reached equilibrium.

4. SENSITIVITY TESTS.

4.1 **Check Sensitivity to Hydraulic Roughness, Task 4 .** Test sediment calculations to stream bed roughness using the Limerinos Method for calculating bed surface n-values. That option is selected by placing a $KL- Record after the $HYD. Modify your data file and execute the program producing C-Level print out in the Sediment Module for events 1 and 10. Using that C- Level print out, plus data from Table 3, fill in the following table. Did model performance improve when the n-value was calculated by Limerinos Method?

Table 6. n-Value Test

	n-values used in HEC-2			Channel n-values, Limerinos Method	
X-Section	LOB	ROB	CH	Event #1	Event #10
0	0.080	0.080	0.030	0.033	0.029
590	"	"	"	0.033	0.034
2280	"	"	"	0.032	0.033
2820	"	"	"	0.032	0.031
4570	"	"	"	0.032	0.029

Not particularly. The water surface is slightly higher with Limerinos n-value. In the absence of water surface profile measurements I would favor the Limerinos values in this case.

4.2 **Sensitivity to Tailwater Boundary Condition, Task 5.** Increase the tailwater +2.0 feet using a Shift Record (S-Record). Did model behave as expected?

Yes. Deposition occurred. The BED CHANGE calculated for the base test was 0.38 ft at cross section 4570, end of 10 days. In Task 5, the bed change increased to 0.96 ft. Trap efficiency increased from -4 % to 20 %. When Task 5 was run to 300 days, the model reached equilibrium between 200 and 300 days. The BED CHANGE at section 4570 stabilized at 1.92 ft.

5. OTHER WATER DISCHARGES. If the model is calibrated for 90,000, is it now ready for all flows?

Not necessarily. The 90,000 cfs flow was selected because it represents the channel forming discharge. A channel which is in equilibrium will pass the channel forming discharge with no significant bed changes. When detailed field data are not available, the historical trends of channel behavior are very useful. If the trend is for no significant deposition or erosion in the study reach, then the model should so indicate when running the channel forming discharge.

After verifying the model behavior for the channel forming discharge, always test a low flow and the flood peak before accepting that model as verified. Follow the same procedure as illustrated in this workshop for each of these tests.

USE OF FEATURES OF HEC-6

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

Reference:

[1] HEC-6 User Manual

Objective: The student demonstrates skill in combining existing main stem and tributary data sets into a stream network model for HEC-6.

Input file is H6WRKSH4.DAT

1. END PRODUCT

The end product is an example execution.

2. PROBLEM

One Main stem and one tributary data set have been formed and debugged for HEC-6. A schematic of the system is shown in figure 1. The main stem data set starts at River Mile 100.67 and goes to 101.16. The tributary data set starts at the confluence with the main stem and contains cross sections at River Mile 0.67, 0.78, 0.92 and 1.16. Combine these into a stream network model and provide the special output according to instructions in paragraph 3, *Procedure*.

```
                                  |
                                  -     101.16
                                  |
                                  |
                                  |
                                  -     100.92
   |--------|------|-------|->|
1.16     0.92   0.78    0.67 |
                                  |
                                  -     100.78
                                  |
                                  |
                                  -     100.67
                                  |
                                  V
```

Figure 1. Schematic of the Stream Network

3. PROCEDURE

3.1 Summary of Tasks. Locate the basic, HEC-6, data file provided for this workshop, H6WRKSH4.DAT. A copy is shown below.

3.2 HEC-6 Input Data File.

```
T1       Workshop Problem IV.  USE OF FEATURES OF HEC-6, Main Stem Branch
T2       STREAM NETWORK EXAMPLE PROBLEM
T3       Sediment Transport in Rivers and Reservoirs
NC  .080     .080      .03       .3       .5
X1100.67       20               653
X3     10
GR 743.1        0      710       68      710      120    710.2      150    709.1      178
GR 711.6      214    711.9      264    710.5      320      709      360      707      390
GR   706      415    703.3      450    703.1      492      702      530    703.9      570
GR 703.1      610      705      635      711      647      715      649    743.1      653
H 100.67    697.0       64      648
X1100.78       19               696      590      590      590
X3     10
GR 743.1        0    711.5       62    710.3       78    711.7      102    710.9      137
GR   711      173    712.5      208    714.6      270    713.3      320    711.3      348
GR 708.8      402    707.3      458    706.3      475      706      493    705.3      513
GR   706      558    707.8      611      709      625    743.1      696
H 100.78    700.3       56      638
X1100.92       13              1122      690      690      690
X3     10
GR 743.1        0      717       53      717      550      715      573      715      630
GR 707.5      740    707.9      780    706.7      840    706.8      878    708.2      910
GR 708.8      990    707.4     1046    743.1     1122
H 100.92    701.7       40     1066
X1101.16       17              1593     1290     1290     1290
X3     10
GR 743.3        0      717       52      717      964      715     1008      710     1040
GR   710     1074      708     1080    708.1     1140    707.9     1190    708.2     1230
GR   710     1304      711     1310    713.5     1360      715     1395      717     1450
GR   717     1540    743.3     1593
H 101.16    702.9       40     1542
EJ
T4      Workshop Problem IV.   MAIN STEM SEDIMENT DATA.
T5       A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6       B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7       C.  Transport Method is Laursen (Madden-1985)
T8       D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1             20
I4             13
LQ   CFS     1000    10000   100000   200000
LT   T/D      2.9      100    25000   185227
LF VFS      .0917    .0917    .0917    .0917
LF FS       .1016    .1016    .1016    .1016
LF MS       .1515    .1515    .1515    .1515
LF CS       .1428    .1428    .1428    .1428
LF VCS      .1462    .1462    .1462    .1462
LF VFG      .1717    .1717    .1717    .1717
LF FG       .1383    .1383    .1383    .1383
LF MG       .0386    .0386    .0386    .0386
LF CG       .0173    .0173    .0173    .0173
LF VCG      .0004    .0004    .0004    .0004
PF   AVG   100.67               150       95      128       61       64       27       32
PFC   14       16     6.65       8     3.32        4     2.48        2     2.30        1
PFC 1.75      0.5     0.89     0.25     0.38    0.125
$HYD
$RATING
RC              6   20000.    10000        0    711.5      715      719    720.6    722.3
RC          723.6
*   AB  RUN 1.
Q 100000
T     50
W     .5
```

```
*    B  RUN 2
Q 100000
W     .5
*    B  RUN 3
Q 100000
W     .5
*    B  RUN 4
Q 100000
W     .5
*    B  RUN 5
Q 100000
W     .5
*    B  RUN 20
Q 100000
X     20      .5
*    B  RUN 40
Q 100000
X             .5      20
$JOB
T1       Workshop Problem IV. TRIBUTARY GEOMETRY
T2       STREAM NETWORK EXAMPLE PROBLEM
T3       Sediment Transport in Rivers and Reservoirs
NC  .080    .080     .03      .3      .5
X1  0.67      20             653
X3    10
GR 743.1       0     710      68     710     120   710.2     150   709.1     178
GR 711.6     214   711.9     264   710.5     320     709     360     707     390
GR   706     415   703.3     450   703.1     492     702     530   703.9     570
GR 703.1     610     705     635     711     647     715     649   743.1     653
H   0.67   697.0      64     648             705     320     570             2.0
X1   .78      19            696     590     590     590
X3    10
GR 743.1       0   711.5      62   710.3      78   711.7     102   710.9     137
GR   711     173   712.5     208   714.6     270   713.3     320   711.3     340
GR 708.8     402   707.3     458   706.3     475     706     493   705.3     513
GR   706     558   707.8     611     709     625   743.1     696
H   0.78   700.3      56     638             705     208     258             2.0
X1   .92      13     710    1122    1690    1690    1690
X3    10
GR 743.1       0     717      53     717     550     715     673     735     710
GR 707.5     740   707.9     780   706.7     840   706.8     878   708.2     910
GR 708.8     990   707.4    1046   743.1    1122
H   0.92   701.7      40    1066             705     740     990             2.0
X1  1.16      17    1040    1593    2290    2290    2290
X3    10
GR 743.3       0     717      52     717     964     715    1008     735    1040
GR   710    1074     708    1080   708.1    1140   707.9    1190   708.2    1230
GR   710    1304   711.7    1324   713.5    1360     715    1395     717    1450
GR   717    1540   743.3    1593
H   1.16   702.9      40    1542             705    1074    1324             2.0
EJ
T4       Workshop Problem IV.  TRIBUTARY SEDIMENT DATA
T5       A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6       B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7       C.  Transport Method is Laursen (Madden-1985)
T8       D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1            20
I4            13
LQ  Q       1000   10000   90000
LT QS        200    1200   25000
LF VFS     .0017   .0017   .0017
LF FS      .1516   .1516   .1516
LF MS      .1515   .1515   .1515
LF CS      .0828   .0828   .0828
LF VCS     .1862   .1862   .1862
LF VFG     .1617   .1617   .1617
LF FG      .1483   .1483   .1483
LF MG      .1086   .1086   .1086
LF CG      .0073   .0073   .0073
LF VC      .0004   .0004   .0004
PF   AVG    0.67            150      95     128      61      64      27      32
PFC   14      16    6.65      8    3.32       4    2.48       2    2.30       1
PFC 1.75     0.5    0.89    0.25    0.38   0.125
$HYD
*   AB  RUN 1.
Q  80000
```

```
R    721
T     50
W    .25
*    B  RUN 2
Q  80000
W    .25
*    B  RUN 3
Q  80000
W    .25
*    B  RUN 4
Q  80000
W    .25
*    B  RUN 20
Q  80000
X     20       .5
*    B  RUN 40
Q  80000
X              .5       20
$$END
```

A. Geometric Data Set: Cut and paste the HEC-6 file to form the geometric model for a stream network model.

B. Sediment Data Set: Cut and paste the HEC-6 file to form the sediment data set for the stream network model.

C. Hydrologic Data Set: Form the hydrologic data set to run the 5 events shown below. Each has a duration of 1 day. Request an A-level print out from hydraulics for the first event. Request a B-level print out from sediment for first 4 events, and request a C-level print out from sediment for the 5'th event.

Event No	Discharge CFS, at the D/S Boundary		Water Temperature Degrees F		Starting Water Surface Elevation
	Main	Tributary	Main Stem	Tributary Stem	
1	100,000	90,000	50	50	(Main Stem Rating
2	100,000	90,000	50	50	Curve- provided)
3	100,000	90,000	50	50	"
4	100,000	10,000	50	50	"
5	100,000	10,000	50	50	"

- Add the necessary data records to calculate dredging after the 5'th event in the Hydrologic Data Set. The dredging template is already coded in the geometric data (H-Cards).

- Add the data cards necessary for restricting the detailed print out, requested for event #5, to X-Section #2 on the tributary(See $PRT-CP-PN-END coding instructions).

- Execute the job, highlight the requested output in the printed results from the run, and be prepared to discuss the results in the review.

USE OF FEATURES OF HEC-6
Solution

Note: This workshop was originally developed by W. A. Thomas, Mobile Boundary Hydraulics, Vicksburg, MS

1. Completed Input Data File.

```
T1       Workshop Problem IV.  USE OF FEATURES OF HEC-6, Main Stem Branch
T2       STREAM NETWORK EXAMPLE PROBLEM
T3       Sediment Transport in Rivers and Reservoirs
NC  .080     .080      .03       .3       .5
X1100.67       20               653
X3     10
GR 743.1        0      710       68      710      120    710.2      150    709.1      178
GR 711.6      214    711.9      264    710.5      320      709      360      707      390
GR   706      415    703.3      450    703.1      492      702      530    703.9      570
GR 703.1      610      705      635      711      647      715      649    743.1      653
H 100.67    697.0       64      648
X1100.78       19               696      590      590      590
X3     10
GR 743.1        0    711.5       62    710.3       78    711.7      102    710.9      137
GR   711      173    712.5      208    714.6      270    713.3      320    711.3      348
GR 708.8      402    707.3      458    706.3      475      706      493    705.3      513
GR   706      558    707.8      611      709      625    743.1      696
H 100.78    700.3       56      638
QT      2
X1100.92       13              1122      690      690      690
X3     10
GR 743.1        0      717       53      717      550      715      573      715      630
GR 707.5      740    707.9      780    706.7      840    706.8      878    708.2      910
GR 708.8      990    707.4     1046    743.1     1122
H 100.92    701.7       40     1066
X1101.16       17              1593     1290     1290     1290
X3     10
GR 743.3        0      717       52      717      964      715     1008      710     1040
GR   710     1074      708     1080    708.1     1140    707.9     1190    708.2     1230
GR   710     1304      711     1310    713.5     1360      715     1395      717     1450
GR   717     1540    743.3     1593
H 101.16    702.9       40     1542
EJ
$TRIB
CP
T1       Workshop Problem IV. TRIBUTARY GEOMETRY
T2       STREAM NETWORK PROBLEM
T3       Sediment Transport in Rivers and Reservoirs
NC  .080     .080      .03       .3       .5
X1   0.67      20               653
X3     10
GR 743.1        0      710       68      710      120    710.2      150    709.1      178
GR 711.6      214    711.9      264    710.5      320      709      360      707      390
GR   706      415    703.3      450    703.1      492      702      530    703.9      570
GR 703.1      610      705      635      711      647      715      649    743.1      653
H    0.67   697.0       64      648               705      320      570               2.0
X1    .78      19               696      590      590      590
X3     10
GR 743.1        0    711.5       62    710.3       78    711.7      102    710.9      137
GR   711      173    712.5      208    714.6      270    713.3      320    711.3      340
GR 708.8      402    707.3      458    706.3      475      706      493    705.3      513
GR   706      558    707.8      611      709      625    743.1      696
H    0.78   700.3       56      638               705      208      258               2.0
X1    .92      13      710     1122     1690     1690     1690
X3     10
GR 743.1        0      717       53      717      550      715      673      735      710
GR 707.5      740    707.9      780    706.7      840    706.8      878    708.2      910
GR 708.8      990    707.4     1046    743.1     1122
H    0.92   701.7       40     1066               705      740      990               2.0
X1   1.16      17     1040     1593     2290     2290     2290
X3     10
GR 743.3        0      717       52      717      964      715     1008      735     1040
```

```
GR   710    1074     708    1080   708.1    1140   707.9    1190   708.2    1230
GR   710    1304   711.7    1324   713.5    1360     715    1395     717    1450
GR   717    1540   743.3    1593
H   1.16   702.9      40    1542              705    1074    1324              2.0
EJ
T4       Workshop Problem IV.   MAIN STEM SEDIMENT DATA.
T5        A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6        B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7        C.  Transport Method is Laursen (Madden-1985)
T8        D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1            20
I4            13
LQ   CFS    1000   10000  100000  200000
LT   T/D     2.9     100   25000  185227
LF VFS     .0917   .0917   .0917   .0917
LF FS      .1016   .1016   .1016   .1016
LF MS      .1515   .1515   .1515   .1515
LF CS      .1428   .1428   .1428   .1428
LF VCS     .1462   .1462   .1462   .1462
LF VFG     .1717   .1717   .1717   .1717
LF FG      .1383   .1383   .1383   .1383
LF MG      .0386   .0386   .0386   .0386
LF CG      .0173   .0173   .0173   .0173
LF VCG     .0004   .0004   .0004   .0004
PF   AVG  100.67            150      95     128      61      64      27      32
PFC   14      16    6.65      8    3.32       4    2.48       2    2.30       1
PFC 1.75     0.5    0.89    0.25    0.38   0.125
$TRIB
T4       Workshop Problem IV.  TRIBUTARY SEDIMENT DATA
T5        A.  Inflowing Load is Calculated from the Bed Gradation:  DATASET # 1
T6        B.  Bed Gradations from Field Samples of Top 1-ft.        DATASET # 1
T7        C.  Transport Method is Laursen (Madden-1985)
T8        D.  Sediment Model # 1   Dated 1 June 1988,  WA Thomas,  WES
I1            20
I4            13
LQ  Q       1000   10000   90000
LT QS        200    1200   25000
LF VFS     .0017   .0017   .0017
LF FS      .1516   .1516   .1516
LF MS      .1515   .1515   .1515
LF CS      .0828   .0828   .0828
LF VCS     .1862   .1862   .1862
LF VFG     .1617   .1617   .1617
LF FG      .1483   .1483   .1483
LF MG      .1086   .1086   .1086
LF CG      .0073   .0073   .0073
LF VC      .0004   .0004   .0004
PF   AVG    0.67            150      95     128      61      64      27      32
PFC   14      16    6.65      8    3.32       4    2.48       2    2.30       1
PFC 1.75     0.5    0.89    0.25    0.38   0.125
$HYD
$RATING
RC            6  20000.   10000       0   711.5     715     719   720.6   722.3
RC        723.6
*   AB  RUN 1.
Q 100000   90000
T     50      50
W      1
*    B  RUN 2
Q 100000   90000
W      1
*    B  RUN 3
Q 100000   90000
W      1
*    B  RUN 4
Q 100000   10000
W      1
$PR
CP     2
PS  0.78
END
*    C  RUN 5
Q 100000   10000
W      1
$DREDGE
$NO DREDGE
$$END
```

Chapter 3

Methods for Estimating Sediment Yield

3.1 Background

In the United States, soil erosion and soil losses from watersheds were first investigated intensively in association with agriculture. Tillage was found to dramatically increase erosion rates and thus loss of valuable agricultural soils. Early estimates were based on observations that various cultural and land use practices differed in their ability to control soil erosion. These initial estimating procedures involved single factor equations to represent local conditions where other contributing factors were nearly constant. Multiple factor relationships were developed as more data became available and researchers were able to describe multiple contributing factors. A variety of field-plot erosion studies were carried out beginning in 1917 (Smith, 1966), to attempt to quantify erosion rates based on precipitation, crop patterns, soils, and slope characteristics. Zingg (1940) related soil loss to slope steepness and length. Soil erodibility and land management practices were later incorporated into quantitative techniques (Smith, 1941, Smith and Whitt, 1947, and Van Doren and Bartelli, 1956). Musgrave (1947) added a rainfall parameter to develop an empirical relation using factors for erodibility and vegetative cover, the land slope and slope length, and the 30-minute, 2-year frequency rainfall amount.

The Universal Soil Loss Equation (Wischmeier and Smith, 1960) was developed to overcome deficiencies in Musgrave's equation in predicting erosion rates by storm, season, or crop year based on average annual rainfall patterns. The USLE became the basic equation for estimating soil loss from sheet erosion, and data for estimating the various factors were tabulated for a wide variety of field conditions and geographic locations. Revisions of the USLE (MUSLE, RUSLE) have been developed to extend its applicability (Williams, 1975 and Weltz et al., 1987). The general accuracy of the USLE equation for estimating soil loss from field plots has been confirmed by a large number of data in various environmental conditions (Vanoni, 1975), however, its applicability to complex watersheds has been questioned (Haan et al., 1994).

Although sheet and rill erosion are primary sources of sediment in most watersheds, other sources as described in Chapter 2 may be significant. In addition, transport of eroded sediments downstream to a specified point is influenced by a complex set of interacting geomorphic processes including erosion, entrainment, transportation, deposition and compaction.

Researchers have focused on development of physically-based relations to replace the empirical form of the USLE for computation of sheet and rill erosion. However, the application of physically-based models to complex watersheds is not a common practice. Physically-based models typically contain equations with constants and exponents which must be determined for each watershed or basin and location-specific hydrologic conditions, and the data requirements are often overwhelming. A variety of empirical and semi-empirical models have also been developed and utilized. Refer to Appendix A "Progress Report on Land Surface Erosion," for a summary of several of the more common models.

Attempts are currently underway by researchers to combine soil loss and hydrologic models so that sediment movement within and from watersheds can be estimated. However, no single numerical modeling technique has emerged as a suitable technology for use in estimating sediment yield for the purposes of river or reservoir sedimentation studies.

Many of the existing models were developed for application to agricultural lands and have limited applicability in other types of watersheds. Furthermore, calibration data is often unavailable, or available only for moderate hydrologic conditions. The applicability of these models to extreme hydrologic events, typically required in many Corps of Engineers analyses, would be extremely limited due to the lack of calibration data. Because erosion and sediment transport processes are not fully described as yet, a process-based sediment yield estimation procedure is not likely to be developed for some time.

3.2 Recommended Approach to Sediment Yield Estimation

In practice, sediment yield must often be estimated on an average annual or single event basis for complex watersheds with limited available data. A general approach in use by many investigators is to utilize a number of techniques to estimate yield, and then cross-check results against one another and against engineering judgement. In the absence of a verified, widely applicable specific technique, this approach is recommended.

Investigators should select techniques for estimation of sediment yield based on an understanding of the dominant geomorphic and hydrologic processes occurring in a watershed. Particular attention should be given to determining which sources of sediment are likely to be predominant, and the ability of the drainage system to transport produced sediment to the point at which yield must be estimated.

Selected techniques will vary depending on the purpose of the investigation and the availability of measured data. For example, estimation of single event sediment loads in a river channel for an extreme hydrologic event may differ significantly from average annual estimates.

In general terms, total sediment yield can be estimated by summing potential sources and then reducing the estimate to reflect the transport capability in the fluvial system. This general approach is illustrated in Figure 3.1.

3.3 Estimating Sediment Sources

For each of the categories shown in Figure 3.1, several potential methods are available for use in qualitative estimates. Multiple methods should be selected for comparative purposes. Selection of methods should be based on their applicability to particular type of problems, or geographic areas, and the investigators' familiarity with the methods. Because all of the methods involve judgement in selection of parameters, familiarity with application of a particular method is an important consideration.

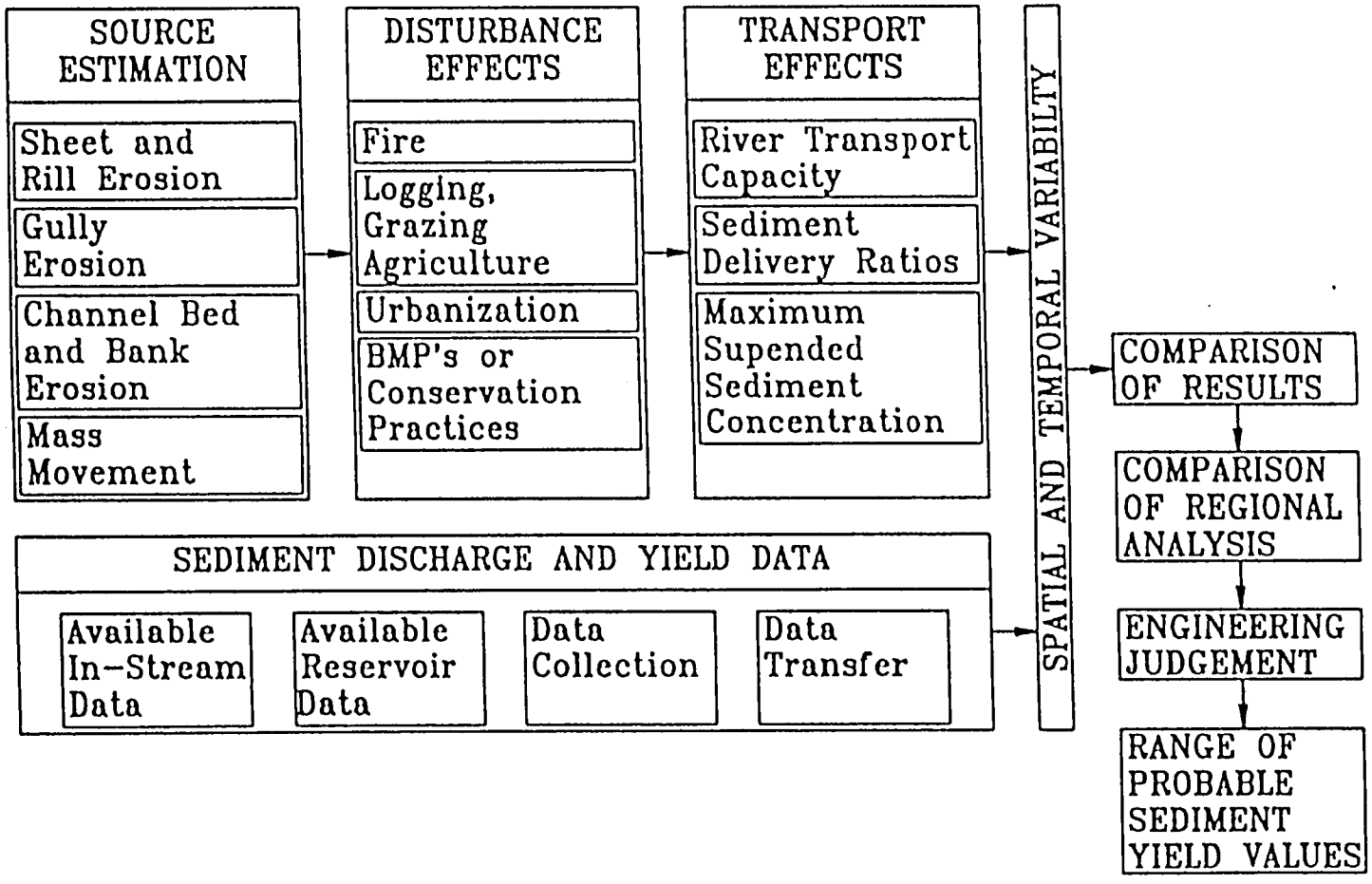


Figure 3.1 – Schematic Representation of Estimating Sediment Yield

5002.3-1.1.2

Table 3.1 lists estimation techniques that may be considered for particular applications. The table includes several empirical computation methods, two comparative methods (aerial photography and topographic surveys), and three regional relationship methods (Dendy and Bolton, 1976, Strand and Pemberton, 1982, and SCS Yield Rate Maps and local or regional soil loss/yield rate estimates from soil and water conservation agencies). Several of the methods are briefly described below.

Table 3.1
Sediment Source Estimation Techniques

Method	Sheet and Rill Erosion	Gully Erosion	Channel Bed and Bank Erosion	Mass Movement	Average Annual Yield	Single Event Yield
USLE					•	
MUSLE						•
BUSCLE					•	
PSIAC					•	
Aerial Photography					•	•
Topographic Surveys					•	•
Thompson or SCS TR32					•	
Dendy and Bolton					•	
Strand and Pemberton, USBR					•	
SCS Yield Rate Map					•	

3.4 USLE Method

The Universal Soil Loss Equation (USLE) is perhaps the most widely used method for estimating soil erosion. The equation was originally developed for application to agricultural fields, but its use has been greatly extended in practice. The USLE was derived for estimating average annual yield, and not single event volumes. In spite of its wide historical application, investigators should be careful to recall that the equation was intended for estimation of sheet and rill erosion, on relatively small agricultural plots. Its accuracy for application to complex watersheds, especially for forest and rangeland, depends on the experience of the user. However, the method has the advantage that large amounts of data are available for parameter estimation based on practice. (See Kirkby and Morgan, 1980, Haan et al., 1994 and Barfield et al., 1981.) The equation has the form

$$A = R * K * LS * C * P \tag{3.1}$$

where:

A = average annual sheet and rill erosion (mass/area)
R = Rainfall erosion index (length*mass/area*intensity)
K = soil erodibility factor (mass/area/unit of R)

LS = slope length and steepness factor (dimensionless)
C = vegetative cover factor (dimensionless)
P = erosion control practice factor (dimensionless)

The equation has traditionally been applied in English units, and the various factors contain some embedded units based on experimental methodology. Therefore, application of the equation in English units, and conversion of the results to metric units may be more practical than conversion of all the factors to metric units. To calculate erosion, each of these factors is assigned a numerical value. Mitchell and Bubenzer (in Chapter 2 of Kirkby and Morgan, 1980) discuss the application of the USLE using metric units.

3.5 MUSLE Method

The Modified Universal Soil Loss Equation (MUSLE) was developed by Williams (1975), and Williams and Berndt (1976) to predict erosion from a single storm event. Williams modified 'R' in the USLE to be a storm runoff energy factor. The value of Williams' modified *R* represents the product of runoff volume and peak discharge for an event, and is given by:

$$R_m = a + (V * Q)^b \tag{3.2}$$

where: R_m = Williams' modified *R* factor
V = the storm event runoff volume
Q = the storm event peak discharge
a and b = empirical constants

Williams and Berndt (1972) used data from experimental watersheds from 3 acres to 7 mi^2 in size to estimate a = 95 and b = 0.56 (for V and Q in English units). These values are widely used. Typical accuracy of the MUSLE is shown in Figure 3.2 from Williams (1975). The spread in the data is typical of most predictive procedures and can be even larger depending on basin complexity and significance of episodic processes. Williams' MUSLE Method is simple to use; however, like the other methods described here, it does not predict a time distribution (sedigraph) or a size distribution of sediment. Mass wasting, gullying, floodplain erosion and channel erosion processes are also not considered.

3.6 RUSLE Method

The Revised Universal Soil Loss Equation (RUSLE) was developed by Weltz et al. (1987) to extend and update the USLE for non-agricultural applications, and to incorporate data collected in a variety of geographic areas since the development of the USLE.

Various improvements are incorporated into the calculation of the equation factors, but the form of the equation remains that of the USLE. Revisions include new methods for estimating *R* in the western United States, adjustments for splash erosion on flat slopes, development of a seasonally variable *K* term, a subfactor method for calculating *C*, new *LS* calculation methods based on rill/interrill erosion ratio, and new methods for calculating *P*.

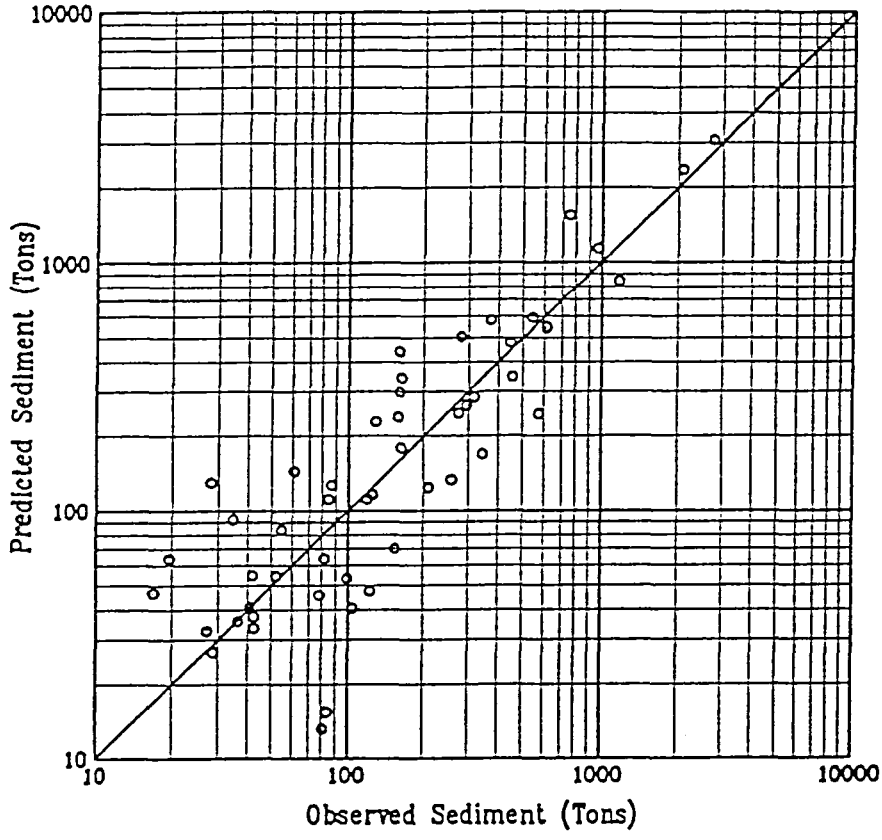


Figure 3.2 – Comparison of Observed and Predicted Sediment Yields for Watersheds W–3 and W–5 (From Williams, 1975)

50002.3_2.1.1

Readers should refer to Chapter 8 in Haan et al. (1994) for further information on the limitations and application of RUSLE.

3.7 PSIAC Method

The Pacific Southwest Interagency Committee Method (PSIAC, 1968) provides a guide for estimating yields from a watershed rating procedure based on climatic and physical characteristics. The method is intended primarily for planning purposes and results in a range of expected annual sediment yield values. The procedure was developed for basins in the western United States and is typically applicable for areas greater than 30 km^2 (10 mi^2); however, it has been successfully applied to smaller basins.

Nine factors are used to account for land use, channel erosion and transport, runoff, geology, topography, upland erosion, soils, ground cover, and climate. The PSIAC technique has compared well with actual watershed data (Shown, 1970, and Renard, 1980). Unlike the USLE and its variations, the PSIAC method estimates total annual sediment yield, rather than sheet and rill erosion. The method can be used to estimate changes in sediment yield due to land use changes.

3.8 Aerial Photography and Topographic Surveys

Comparison of sets of historical photos and surveys to present watershed conditions can often provide a means to estimate special types of sediment production such as gullying, channel bank erosion, and mass wasting. It is important to separate and quantify slow accretionary processes from more rapid and episodic avulsionary processes. Channel cross sections are necessary to make accurate estimates of bed degradation or aggradation.

Where historical aerials are not available, current aerial photography may still provide valuable supportive information such as length of eroding banks, extent of gullying, or extent and location of mass wasting processes.

Sequences of aerial photographs can be used to estimate channel bank or gully erosion by measuring aerial differences between sets of photos and computing volume based on average bank heights from field reconnaissance. Aerial photographs may also be useful in estimating bank erosion losses for single hydrologic events or longer term erosion and bank migration rates, if photos are available for periods before and after comparable historical events. Examination of historical aerial photographs is recommended for all levels of sedimentation investigations. Sediment production rates and volumes estimated from examining historical photographs can be compared to values obtained from empirical estimation formulas discussed above.

3.9 Gully Erosion Estimates

Estimates of gully erosion are best developed from field surveys, examination of historical cross section data or the examination of detailed aerial photographs if they are

available. If no data are available, gully erosion estimates can be made using an equation developed by Thompson (1964) or the procedure outlined in Technical Release 32 (SCS, 1966). Both are empirical methods that estimate gully head advancement based on drainage area and rainfall parameters. In both cases, the average depth and width of gullies must be estimated to compute the volume for a single gully, and this value must be multiplied by the number of gullies in the watershed to estimate total gully erosion.

These methods have obvious limitations in accuracy, but may be effectively used in concert with aerial photography and field reconnaissance and geomorphic assessments. Where gullying is a significant fraction of total sediment production, more detailed field measurements may be necessary. Consultation with the local SCS is advised.

3.10 Regional Analysis

Regional sediment yield analyses have been conducted for some areas of the United States. As shown in Figure 3.1, these methods are recommended as a check on other computations rather than as primary computation methods. They are also useful in providing quick preliminary estimates of yield. Discussions of several of the more widely applied regional methods are presented in Chapter 3 and Appendix C of the EM 1110-2-4000 (USACE, 1989).

Dendy and Bolton (1976) developed two regression equations relating unit sediment yield to drainage area and mean annual runoff based on sedimentation data from about 800 reservoirs throughout the continental United States. Strand and Pemberton (1982) developed a similar regional relationship for use in the semi-arid areas of the United States. The Soil Conservation Service (SCS, 1974) has developed a map of generalized sediment yield rates for the Western United States. Tatum (1963) proposed a method for computing sediment yield and debris volumes from arid, brush-covered mountainous areas in Southern California. Calculations are made from nomographs using an equation with adjustment factors for size, shape and slope of the drainage area, 3-hour precipitation, the portion of the area that may have burned and the years since the last burn and flood. Refer to Appendix C of EM 1110-2-4000 (USACE, 1989). All of these regional relationships are useful in providing general estimates for relatively large areas for the purpose of establishing a range of reasonable values. However, they should be used with caution for specific sites, especially where watershed conditions are unique or extreme.

3.11 Effects of Disturbance

Watershed sediment production, transport and yield are influenced by a complex set of geomorphic processes that are spatially and temporally dynamic. As a completely integrated system, the watershed sediment and water flow budgets represent a complex balance of forces. Once disturbed, erosion forces can outweigh erosion resistant and stabilizing forces resulting in dramatic increases in sediment production and yield. Typical events and activities that most often lead to increases in sediment yield include logging, mining, clearing and cultivation for agriculture, grazing, road construction, clearing and grading associated with urbanization, brush and forest fires, and extreme drought followed by extreme runoff events.

The effects of urbanization can lead to a number of sediment problems. Urbanization usually involves site preparation, grading, and excavation activities. Accelerated soil loss in the project area with sediment deposition in downstream flood control channels is common during construction. Therefore, during the construction phase of urbanization projects, the soil surface is typically exposed and disturbed leading to measurable increases in erosion and sediment production. Once constructed, paved and landscaped, however, sediment production from an urbanized area may drop below its original undisturbed amount, especially in basins utilizing concrete-lined drainage channels and local storm water detention ponds or debris basins.

3.12 Adjustment for Transport Capacity

Usually, a part of the soil eroded in a watershed is temporarily or permanently stored so that sediment yield out of a catchment is less than the amount of sediment production. The ratio of yield to gross production (erosion) is called the sediment delivery ratio (SDR). SDR is a dimensionless number less than or equal to one. The gross erosion and sediment delivery ratio method for estimating sediment yield is a two-step procedure. First the gross erosion (sediment production) in a catchment of given area is computed. Gross erosion includes interill, rill, gully and stream erosion. Then a sediment delivery ratio is estimated from empirical curves available in the literature (Kirkby and Morgan, 1980, and Barfield et al., 1981). Sediment yield from the catchment is obtained from the product of gross erosion and SDR.

Typically, specific sediment yield is observed to decease with increasing area. There are a few locations in the world, however, where yield is observed to increase with area. This anomalous condition has been observed in the Middle Yellow River Basin in China (Vanoni, 1975), where fine loessol soils are easily eroded and carried by runoff of even low intensity. There is greater production in the lower watershed with little loss resulting in an increase in specific yield and delivery ratio with area. The same anomalous condition has been reported for catchments in Canada and North America comprised of fine glacial materials. Urbanized catchments that are highly channelized with very efficient concrete lined drainage channels also tend to have higher sediment delivery ratios.

Sediment delivery ratio equations have been developed from studies of watersheds in particular regions, but have limited applicability elsewhere. Reservoir sedimentation data may be useful in estimating SDRs for watersheds with similar hydrologic and geomorphic characteristics to the study watershed. Sediment delivery ratio adjustments must normally be applied to methods where sheet and rill erosion are estimated using USLE or RUSLE.

Measured flow sediment data may be utilized to check the accuracy of sediment yields computed, based on erosion sources (see Section 3.13). Even where data are limited, an estimate of yield from flow and suspended sediment concentration data can assist in establishing reasonable bounds. For single event analyses, computed results should be checked against practical limits for maximum suspended sediment concentration. Where a maximum expected suspended sediment concentration can be selected, maximum yield can be calculated as:

$$Y_s max = Cmax\ V \tag{3.3}$$

where:

$Y_s$max is the maximum sediment yield (mass),
Cmax is the maximum expected concentration (mass/volume)
and V is the volume of clear water runoff (volume)

3.13 Use of Measured Flow and Sediment Load Data

Rigorous determination of sediment yield requires that field data be utilized for hydrologic, hydraulic, and sediment characteristics of the study area. The empirical methods described above should only be relied upon to establish trends or make reasonable estimates of expected ranges of yields. Unfortunately, detailed historical water and sediment discharge data are seldom available, and collection of data is often beyond the budgetary limitations of investigations. Limited data, in conjunction with empirical or regional analysis, will significantly improve the accuracy of estimates. A good discussion of estimating sediment yield based on field measurements, is provided in EM 1110-2-4000 (USACE, 1989). Direct measurements are divided into categories of in-stream sampling and reservoir sedimentation investigations.

In-stream sampling is the most reliable approach for determining sediment yield, provided sufficient data are available over a suitable time period and range of hydrologic conditions. Where available, long-term sediment gage records provide a reliable means of calculating yield. It is the measured suspended sediment load that is usually reported. Therefore, an adjustment must be made to account for larger materials moving as bed load, and sediment moving within about 0.2m of the bed. Field sampling methods are discussed in Guy and Norman (1976), Vanoni (1975), and USGS (1978). The unmeasured portion of the load is usually between 5 and 15 percent of the measured load, and can be estimated by empirical techniques (Colby, 1957). Adjusted long-term sediment discharge records can be used directly to estimate average annual yield and single event yield. However, adjustments may be necessary to account for watershed changes and hydrologic variation.

One of the most common methods used to estimate average annual yield is the flow-duration sediment-discharge rating curve method. The flow duration curve is integrated with the sediment discharge rating curve at the basin outflow point. This procedure can be easily utilized to predict changes in sediment yield due to changes in hydrologic regime via the flow duration curve or due to changes in watershed sediment production via the sediment-discharge rating curve. The sediment-discharge rating curve can also be modified to account for only those particles within a specific size range (e.g., sand and gravel). Unfortunately, the sediment-discharge rating curve is very difficult to develop without extensive flow and measured sediment load data. Sediment-discharge rating curves are not linear and often display looped curve characteristics making them very difficult to estimate without measured data from the basin being studied. The general flow-duration sediment-discharge curve procedure is illustrated in Figure 3.3. A detailed discussion of this computational technique is provided in EM 1110-2-4000 (USACE, 1989). The manual also provides a number of cautions regarding use of the method, and provides guidance on appropriate methods for analysis of data.

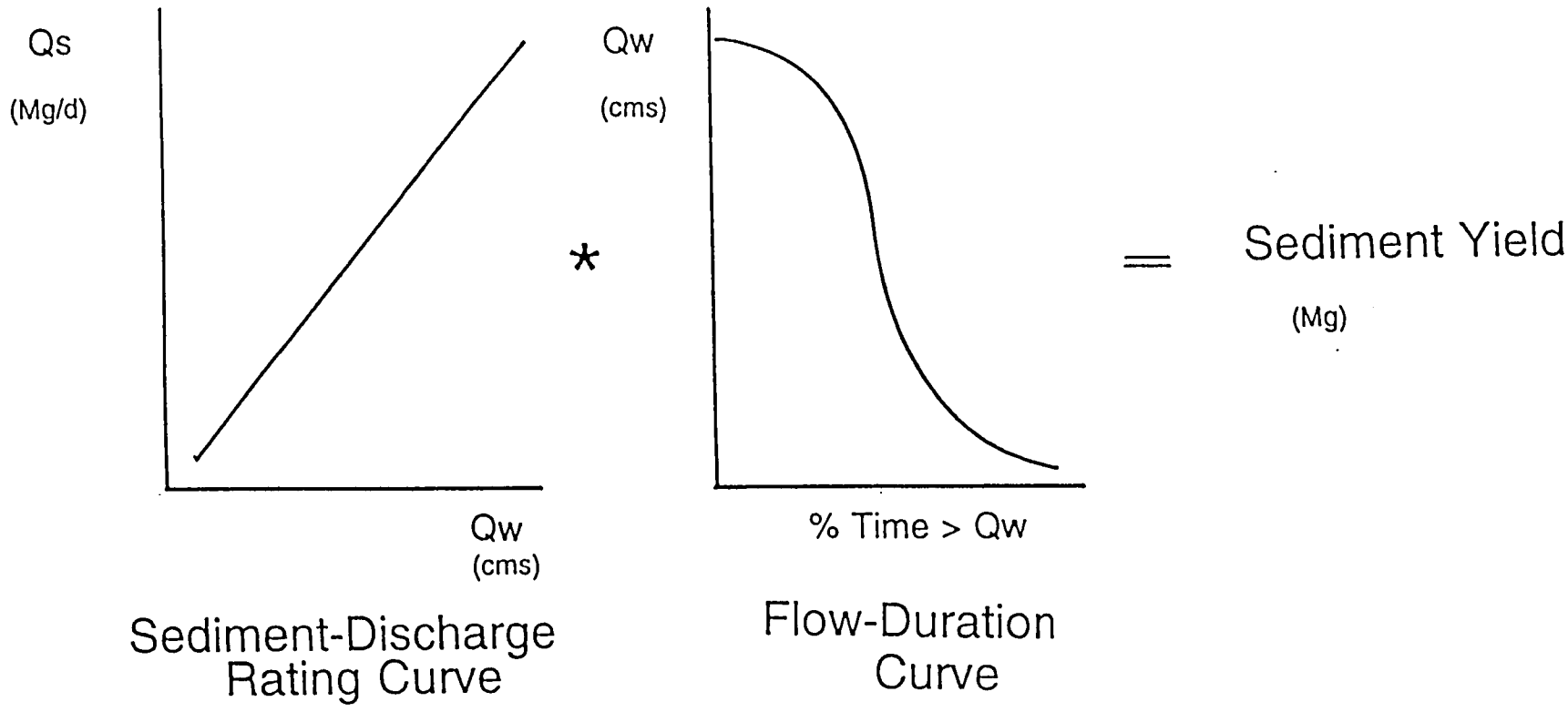


Figure 3.3 Illustration of Procedure to Estimate Sediment Yield from the Flow-Duration and Sediment-Discharge Curves.

3.14 Reservoir Sedimentation Data

Several regional sediment yield equations are based on relationships derived from reservoir sedimentation measurements (e.g., Tatum, 1963, Dendy and Bolton, 1976, and Strand and Pemberton, 1982). In some cases, reservoir sedimentation data may be available within the study watershed or in an adjacent watershed with similar characteristics. Care should be taken to ensure that soils, topography, precipitation, land use, agricultural development, and other basic characteristics are similar enough to warrant transfer of data from one watershed or region to another.

For areas east of the Rocky Mountains, the USDA (1978) has a developed procedure for transferring data. Specific sediment yield is adjusted for basin size according to the following guidelines, where A_e = area of the basin for which yield will be estimated and A_m = area of the basin for which measured data exists:

for $0.5 < A_e / A_m < 2.0$	direct transfer	
for $A_e / A_m < 0.1$ or $A_e / A_m > 10.0$	no transfer	
for other ratios of A_e / A_m	$Y_e = Y_m (A_e / A_m)^{0.8}$	(3.4)

where: Y_e = the total annual estimated yield in the unmeasured basin
and Y_m = the total annual measured yield at the reservoir site.

These guidelines do not apply to mountainous areas or other watersheds which, based on dominant geomorphic processes, would not be expected to exhibit a relatively smooth relationship between specific sediment yield and drainage area. Examples of these types of areas are sites where significant deposition may occur upstream of the estimate point, or where channel bank erosion contributes significantly to sediment yield in the lower portions of a watershed.

As with other methods, accuracy in transfer of reservoir data is limited by variability between watersheds, but is often useful in establishing reasonable bounds for estimates. Investigators should utilize all available data and compare results from as many different estimating procedures as possible. Comparison of results from regional procedures, yield maps, reservoir measurements and empirical formulas should establish reasonable bounds for yield (MacArthur et al., 1990).

3.15 Transfer of In-Stream Data

In-stream sampling data from various points in a study watershed may be integrated to give annual yield. This procedure will normally result in a relationship between annual yield and drainage area which may be extrapolated to other points in the basin. In the case where considerable scatter in the plotted yield vs. drainage area plots are evident, investigators should look for geomorphic factors that could influence the data and attempt to isolate those factors. These techniques, plus limited in-stream sampling at the estimate point, may provide a reasonable basis for both annual yield and single event estimates.

Transfer of in-stream data between watersheds can be attempted using a procedure similar to that described in Section 3.14, but with low expected accuracy. Cautions relating to watershed characteristics similar to those for transfer of reservoir sedimentation data should be applied. Data should be transferred only for annual sediment yield and not for single event measurements.

3.16 Temporal and Spatial Variability

Regardless of the analyses used or the watershed type, it is essential that temporal and spatial variability of sediment yield be considered in making estimates. These considerations should be based on watershed reconnaissance, and a basic understanding of basin geomorphology. The following hypothetical examples illustrate the need for thoughtful application of estimates based on variability.

1) In-stream sampling in a mountain gorge is used to calculate average annual and event-based sediment yields for a small stream. Just downstream of the gorge, the stream becomes braided as the gradient decreases on an alluvial fan. Sediment yield estimates based on upstream measurements, will likely be significantly in error below the alluvial fan for specific events due to temporary storage of sediments at low flow, and the potential for avulsive changes in channel location during extreme flows.

2) Reservoir sedimentation data from the past 50 years are used to estimate sediment yield for a new reservoir in a forested watershed. More careful examination of historical land use patterns would reveal that grazing was initiated in the last 10 years, and that urban development is expected to increase by 100% over the next 10 years. A long-term estimate of sediment storage volume for a reservoir might be significantly in error.

3) An empirical method is used to estimate average annual sediment yield for a chaparral watershed. The following years, a fire occurs in the watershed which increases sediment yield by a factor of 8. Analysis of historical data might indicate that the watershed could experience a fire on the average of once every 50 years, thus significantly affecting 'average' annual sediment yield, and drastically affecting yield from individual events.

These examples are intended only to illustrate the potential for temporal and spatial variability in watershed yield estimates, and not to typify specific design conditions. Each watershed will have a unique set of characteristics which vary in space and time, and the investigator must apply engineering judgement to arrive at a reasonable estimate.

3.17 Comparison and Engineering Judgement

Although the state of the science in computer modeling of erosion and sediment transport processes continues to advance, variability between watersheds is extremely high, and data requirements for calibration are often out of reach. Therefore, methods with recognized limitations in accuracy are often adopted. As outlined in Figure 3.1, one of the

most important elements in making reasonable estimates of sediment yield is utilization of several methods or techniques based on as much measured information as one can find, and comparison of all the results. This approach is essential where in-stream data is limited or lacking.

In any sediment yield estimate, engineering judgement will play a part in screening data and selecting computational factors. In addition, judgement must often be applied to account for temporal and spatial variability in the watershed characteristics which affect sediment yield. Judgement must also applied to account for the effects of watershed disturbances or the coincidence of hydrologic events with other events or processes (e.g., fire, landslides, channel avulsion) which significantly effect sediment production and yield. Investigators should always visit the project area, review the areas upstream and downstream from the project site and examine as much of the drainage basin above the site as possible. If possible, it is advisable to make an aerial reconnaissance of the basin prior to making yield estimates so that otherwise unnoticeable basin geomorphic or land use characteristics might be observed. Investigators should consider the historical and geomorphic evolution of the basin and determine whether the system is reasonably stable or adjusting to an imbalance of forces or past activities.

Chapter 4

Estimating Basin Sediment Yield and Total Inflowing Load Characteristics

4.1 Background

Sediment transport computer models for streams and reservoirs require the specification of the inflowing sediment load as an upstream boundary condition. For models such as HEC-6 it is necessary not only to know total inflowing sediment load for a range of discharges (the sediment-discharge rating curve), but also to subdivide the load into various grain size classes. Obviously, it is most desirable to obtain measured sediment load and gradation data for various flow conditions, and to base model input on measured data. However, these data are frequently unavailable or incomplete. This chapter describes the steps required to develop the total inflowing sediment load and gradation assuming little measured data are available for the study site.

4.2 General Procedures

The first step is to acquire relevant background information for the subject watershed including basin geomorphology, soil characteristics, dominant erosion and transport processes, descriptions of historical events and past floods. Measured flow and sediment load data are often not available for the study site, but may be available for adjacent basins and watersheds. Available data and reports should be obtained and carefully examined. It is also beneficial to contact people who actually collected and prepared that data to discuss what they saw, and any difficulties, shortcomings or limitations in the data. Occasionally, the data may be of the quality that it can be transposed to the study area for use in calibrating or circumstantiating the basin yield and total load relationships. Effort spent early in a study to establish what sediment production and yields are reasonable or not reasonable for various flood magnitudes, is critical to the rest of the investigation.

Prior to adopting a method for calculating sediment yield, it is very important to conduct a field reconnaissance of the project site and of the general watershed area upstream from the site. It is important to determine whether significant portions of the annual yield are coming from individual localized mechanisms such as gullying, bank caving or mass wasting. Has the basin been burned, clear cut, over-grazed or altered by other disturbances that can affect sediment production? The field reconnaissance allows the engineer to determine the main source of sediment entering the project. It is very beneficial to involve an experienced fluvial geomorphologist in the initial field reconnaissance studies. From that inspection and a review of available data for the basin, the most appropriate method or methods for estimating sediment yield and grain size distributions can be selected. If *sedimentation is critical* to the recommended project alternative, *a rigorous sediment yield analysis is recommended early in the project planning process.*

Once the initial data review and field reconnaissance are accomplished, procedures outlined herein and in Chapter 3 of Engineering Manual 1110-2-4000 (USACE, 1989) can be applied to estimate basin yield. The following outline can be used for general study purposes. Because every basin and river system is unique, specific study procedures may require adjustment and refinement to accomplish the objectives of the investigation. The procedures presented herein are discussed in more detail and illustrated with an example problem in Chapter 6.

4.3 General Steps for Estimating Sediment Yield

Potential methods for estimating sediment yield in ungaged catchments include: (1) application of regression equations based on detailed basin characteristics like rainfall intensities, soil properties, ground cover, etc., (2) use of regional relationships based on global basin characteristics like drainage area, altitude and slope-aspect ratio; (3) transposition of data from similar basins where reliable data are available; (4) integration of annual or single event yields from stream sediment rating curves and flow-duration curves or hydrographs; and (5) application of empirical methods described in Chapter 3. Any estimate should account for: (1) sheet, rill and interrill erosion from upland land surfaces; (2) gully erosion, stream bed and bank erosion; and (3) mass wasting processes in the basin. The following general steps are necessary to estimate basin sediment yield. Several of these steps may require iterative applications and adjustment in order to develop reasonable estimates.

(1) Perform field inspection and review of available data. Discuss observations and results from previous studies with local SCS field office, USGS field survey people, County flood control and channel maintenance personnel, and Corps of Engineers hydrology and hydraulics personnel.

(2) If little or no data are available, prepare a field sampling program to at least collect several bed material and bank material samples from sediment source areas and stream channel locations upstream and through the study area. Perform standard sieve analyses and settling tests on the samples.

(3) Examine published long-term daily discharge records and sediment gage records. The standard procedure used by the USGS is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as prescribed by Porterfield (1972). Results from this exercise are expressed in t/day. Before comparing sediment yields, the period-of-record data should be examined for homogeneity. Adjustments for upstream reservoirs, hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

(4) Develop the daily water discharge - suspended sediment load rating curve from gage data. Integrate the flow duration curve with the measured sediment load - discharge rating curve to develop a good representation of the process-based average annual yield. (Details of how to prepare these curves and compute these values are summarized in Section 3-6 in EM 1110-2-4000 (USACE, 1989).

(5) When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is highly recommended early in the planning phases of the study. This level of short duration sampling is often referred to as "flood water sampling." Caution is necessary, however, because the short record data set will not necessarily provide a representative sample of watershed processes for the full range of possible hydrologic conditions. Therefore, these data are less dependable than the flow duration sediment discharge rating technique. The lack of large flood data may bias the yield results.

(6) Apply several regional analysis procedures (Tatum, 1963, Dendy and Bolton, 1976, and PSIAC, 1968) to estimate average annual yield. Compare the results to published information or reports obtained from other studies in the area. Compare the yields by plotting yield vs. effective drainage area. Figure 3.1 summarizes a generalized yield estimating procedure. Attempt to establish upper and lower bounds on the yield - drainage area curve for low, average and high sediment production years (MacArthur et al., 1990). Use this range of yield values during the sediment load sensitivity studies.

(7) Use one or more yield estimating equations to estimate the average annual and single event sediment yields for a range of events (e.g., USLE, RUSLE, PSIAC, MUSLE).

(8) Multiply your gross sediment yields by an appropriate sediment delivery ratio (SDR) if necessary to give the net sediment yield at the project location. For more information on how to estimate the sediment delivery ratio and when to apply it, please refer to Section 3-14 in EM 1110-2-4000 (USACE, 1989) and pages 293-294 in Design Hydrology and Sedimentology for Small Catchments (Haan et al., 1994).

(9) A quick method for estimating single event sediment yields involves application of several reliable "annual yield" estimating methods to establish the average annual yield first. Then, assume that an equivalent amount of sediment to the average annual yield occurs during a 2-year event. Also assume that greater single event yields can be approximated by the linear extrapolation of the annual value by multiplying the annual yield by the ratio of the peak single event water flow to the 2-year flows.

$$\text{Yield}_i = \text{Yield}_{AvgAnn} * Q_i/Q_2 \qquad (4.1)$$

where Yield_i is the single event yield for an ith-year storm event and Q_i is the peak water discharge for the ith-year event.

This method is only recommended as a procedure for establishing rough estimates of single event yields and for cross-checking values developed by other methods.

(10) Another procedure for estimating single event and average annual yields is through the application of the MUSLE single event yield method. Use the MUSLE procedure to develop single event yield estimates for the 5-, 10-, 50-

and 100-year events. Convert the single event sediment yields to an average annual value (if applicable) by integrating the sediment yield vs. probability curve. Compare this value with observed reservoir annual yield data and/or computed annual yield values. Select the most reliable value for annual yield. (This procedure is demonstrated in the example problem discussed in Chapter 6.)

(11) Decide whether gully, stream bank erosion or mass wasting processes are active in your study basin. Determine whether your selected annual and single event estimating procedures adequately account for these processes. No generalized analytical procedures are presently available to explicitly calculate these types of sediment production for the full range of possible events. Measured data are obviously the most reliable source to use; otherwise application of empirical relationships and the careful examination of pre- and post-flood event photographs are necessary.

When time, data, and budget permit, process-based erosion and yield models can be used to develop average annual and single event yields. A review of watershed erosion models is presented in Appendix A. Application of process-based erosion and yield models is generally complex and requires detailed data collection for development of model input parameters and calibration. Application of models of this type is beyond the scope of this report.

4.4 General Steps for Estimating Sediment Discharge Curves and Grain Size Distribution Relationships for Use In Mobile Boundary Models

(1) Collect representative bed material sediment samples through the project reach (see Chapter 3, USGS, 1978). Develop grain size distribution curves for each bed and bank sample and plot the representative grain sizes (D_{50}, D_{84} and D_{10}) with distance from downstream to upstream.

(2) Develop a sediment gradation curve for the wash load using measured data or watershed soil surveys. If there are no data, apply Einstein's (1950) assumption that the largest representative size present in the wash load is approximately equivalent to the D_{10} of the bed material load. Using this assumption and soil survey data regarding the approximate percentages of sands, gravels, silts, and clays, develop an approximate grain size distribution curve for the wash load fraction of the total load. (Refer to Chapter 6 for an example of this procedure.)

(3) Estimate the fraction of the total sediment load that travels as bed material load and the fraction that travels as wash load. Two methods are presented in the example problem discussed in Chapter 6. *Method one* is the presently preferred method for use with computer program HEC-6. It involves using HEC-6 through an iterative procedure to synthesize its own inflowing bed material load and gradation from the grain size distribution curves measured in the field. Wash load is then computed as the difference of the total

sediment yield volume or weight (estimated from procedures discussed in Section 4.3) and the HEC-6 estimated bed material load. *Method 2* develops the bed material load by starting with the estimated total sediment load from the computed basin yield. The approximate percentage of bed material load to total load is estimated from information and data measured in the study area. Because there are no established rules of thumb for the ratio of bed material load to total load, one assumes a value based on field observations or measured information and checks to see if that assumption is reasonable (see step number 6). If it is not, new percentages are assumed and checked until the estimated bed material load produces reliable results. Chapter 6 presents an example application of the Method 2 procedure for estimating inflowing load and the grain size distribution of that load.

(4) Develop a composite total load gradation curve by combining the bed material gradation data and curves with the wash load gradation data and curves.

(5) Apply the Corps' SAM procedures (Thomas et al., 1992) to estimate bed form-dependent *n* values. Also utilize SAM to select the most appropriate transport function for a particular river type. Check to see if the river is capable of carrying the estimated single event sediment load using SAM or HEC-6. Determine whether the river through your study reach is "supply limited" during large events or "transport limited." If it is sediment supply limited, channel bed and bank erosion may be important. If it becomes transport limited during large events, sediment accumulation and possible channel avulsion may occur.

(6) Once the total inflowing load curve is complete and an appropriate transport function(s) is selected, use them in HEC-6 or other stream sedimentation models to determine if the estimated load and gradations are in balance with the stream hydraulics and basin yield estimates. If significant deposition or scour occurs in the first few upstream cross sections, then the inflowing load may require adjustment. Once the model performs properly and the computed HEC-6 results appear stable, compare the volumes of total load, bed material load and wash load to observed data. Make adjustments to the load, grain size distribution or transport function according to procedures outlined in the HEC-6 User's Manual, CPD-6, (HEC, 1993) and TD-13 (HEC, 1992).

(7) Perform model calibration and sensitivity studies according to guidelines provided in Chapters 3, 5 and 6 of CPD-6 (HEC, 1993) and Section 3.5 in TD-13 (HEC, 1992).

Chapter 5

Evaluation of Sediment Yield Results

5.1 General

Due to the diverse nature of Corps projects and geographic location, a standard method for estimating sediment yield is not employed throughout the Corps. Instead, individual district offices select their own procedures based on the type of project being investigated, the availability of data and the potential significance that sedimentation processes have on project performance (USACE, 1989). Consequently, a variety of procedures are used throughout the Corps, but are all related closely to one of three basic approaches for estimating sediment yield, including: (1) determining sediment yield directly from sampling and monitoring programs or from river and reservoir surveys, (2) transposition and/or extrapolation of measured data from watersheds with similar characteristics to the study area, and (3) application of empirical relationships (predictive equations) and regional equations to estimate annual or single event yields. The following sections discuss the inherent difficulties associated with developing yield estimates and offer advice for checking and evaluating estimated results.

5.2 Limitations of Sediment Estimating Procedures

Estimating basin sediment yield for average annual and single event conditions requires the application of several yield estimating procedures in order to establish a reasonable range of results. Estimation of sediment transport load curves and grain size distributions for those load relationships may also involve the application of several methods in order to check and cross-check the sensitivity and reliability of estimates. Ask for input *early* in the study from others experienced with the basin being investigated and check your estimates with measured information from the area or from similar basins to circumstantiate your results. Some general considerations and limitations to remember:

(1) The variability of sediment yield from year to year, and perhaps from decade to decade, is likely to be high. This is especially true in flashy ephemeral watersheds. In extreme events like a 100-year flood, there may be a wide range of possible yields depending on antecedent basin conditions. The occurrence or non-occurrence of infrequent intense storm events can greatly affect measured annual yield rates. Spatial variability is also likely to be high, and relatively local sources can contribute large amounts of sediment (e.g., disturbed areas or mass wasting processes). Establishment and use of long-term continuous data records are important, but even long-term data may fail to account for spatial and temporal variability in extreme events.

(2) The lack of local data affects estimation of grain sizes as well as yields. Grain size distributions of delivered sediment loads are difficult to estimate. There are no presently available direct methods for computing the grain size distribution of sediment loads estimated directly from basin yields. Direct

measurement methods are the most reliable; however, soil survey information can be used to make estimates when no measured data are available. Refer to *Field Methods for Measurement of Fluvial Sediments*, by the USGS (Guy and Norman, 1976).

(3) The geomorphic behavior of the basin during a severe (e.g., 100-year) event, particularly the response of steep unstable canyon areas and exposed channel banks is difficult to predict. It is important to attempt to establish an historical geomorphic understanding of the study basin and how it may have responded in the past during significant runoff events.

(4) Seismic activity and land surface subsidence can result in significant basin responses (plan and profile adjustments). This may greatly affect sediment production, yield and channel stability. Determine whether these processes are affecting the study area.

(5) In light of these limitations and complications, there will be uncertainty associated with sediment yield and load estimates. Therefore, always perform sensitivity tests to evaluate the impact of your assumptions and of the uncertainty in the yield, load curve, or grain size distribution estimates on the project evaluations. If halving, doubling or tripling the sediment load does not greatly affect the performance of the project being evaluated, then additional data and analysis may not be necessary.

5.3 Evaluation Procedures

When little or no measured yield data are available, it may not be possible to calibrate or verify estimated values. It therefore becomes necessary to evaluate results using a variety of checking and sensitivity procedures. The general procedures outlined in Figure 3.1 are recommended. Herein, "calibration" refers to the development of representative data and model (estimation procedure) parameters based on known or deduced prototype behavior. "Verification" involves the demonstration of the calibrated model's (or estimation procedure's) ability to simulate prototype behavior for a time record different from that used during calibration. A calibrated model (or procedure) is not necessarily a verified model (or procedure). The following partial list of suggested evaluation procedures may be useful. Many additional checks and evaluation procedures are described in EM 1110-2-4000 (USACE, 1989), EM 1110-2-1416 (USACE, 1993), CPD-6 (HEC, 1993), and TD-13 (HEC, 1992).

Evaluation procedures can be generally divided into the evaluation of data and information during the early stages of an investigation, and the evaluation of computed results. The following procedures apply to data and information:

(1) Data should be reviewed to assess its accuracy and applicability based on internal consistency, collection methods, and watershed conditions during collection.

(2) Review of the history and geomorphology of the basin is necessary to interpret trends in the data and its reliability for use under present conditions. Review of

reports and literature, field reconnaissance, and interviews with individuals who have previous field and analysis experience in the study area are essential components of the historical review. Data can also be correlated to watershed conditions using historical aerial photography.

(3) It is advisable to conduct at least limited field sampling to determine whether reported data can be duplicated or verified, and to identify changes, conditions, or sampling techniques which may significantly influence accuracy or reliability of available data.

(4) Evaluate data in a temporal context to determine whether the period of record for the data is likely to accurately depict important parameters and meet study objectives.

(5) Evaluate data needs based on study requirements. For example, river sedimentation models are likely to require less accuracy in sediment yield estimates than reservoir sedimentation studies.

(6) Establish reasonable ranges for accuracy in the data, and use these ranges in sensitivity analyses.

(7) Methods for preparing and checking sediment data for use in computer program HEC-6 are discussed in Chapters 3, 5, and 6 of CPD-6 (HEC, 1993) and in Chapters 3 through 7 of TD-13 (HEC, 1992).

The following procedures apply to the evaluation of computed results:

(1) Compare computed results to measured data, even if available data are limited.

(2) Assess the accuracy of computed results based on field observations or measurements while the fluvial transport system is active (i.e., during a significant runoff event). If possible, verify computed results with field measurements.

(3) Evaluate results from a geomorphic perspective to determine whether computed results are consistent with observed or documented geomorphic trends.

(4) Evaluate computed results developed from a number of different methods, and consider potential explanations for the differences. Differences in computed results for sediment yield are often on the order of 50 to 200 percent. Selection of values for use should be based on their potential impact on project performance.

(5) Utilize initial results to decide what types of sensitivity tests are appropriate.

(6) Compare results to data or results from previous studies, and for other basins (e.g., computed results or reservoir sedimentation surveys).

(7) Establish reasonable bounds for sediment estimates, and evaluate results against this acceptable range. If methods appear to under or over estimate acceptable values, review the approach to isolate potential weak areas, and conduct sensitivity analyses to refine the method.

(8) Present the results with an explanation of expected accuracy and limitations. Clearly document assumptions, boundary conditions, data analysis, and methodology.

APPENDIX A

PACIFIC SOUTHWEST INTER-AGENCY COMMITTEE (PSIAC)
METHOD FOR PREDICTING WATERSHED SOIL LOSS

Note: The information presented in APPENDIX A is from the following source: "Pacific Southwest Inter-Agency Committee, Report of the Water Management Subcommittee on Factors Affecting Sediment Yield in the Pacific Southwest Area and Selection and Evaluation of Measures for Reduction of Erosion and Sediment Yield," October, 1968.

Introduction

The material that follows is suggested for use in the evaluation of sediment yield in the Pacific Southwest. It is intended as an aid to the estimation of sediment yield for the variety of conditions encountered in this area.

The classifications and companion guide material are intended for broad planning purposes only, rather than for specific projects where more intensive investigations of sediment yield would be required. For these purposes it is recommended that map delineations be for areas no smaller than 10 square miles.

It is suggested that actual measurements of sediment yield be used to the fullest extent possible. This descriptive material and the related numerical evaluation system would best serve its purpose as a means of delineating boundaries between sediment yield areas and in extrapolation of existing data to areas where none is available.

This may involve a plotting of known sediment yield data on work maps. Prepared materials such as geologic and soil maps, topographic, climatic, vegetative type and other references would be used as aids in delineation of boundaries separating yield classifications. A study of the general relationships between known sediment yield rates and the watershed conditions that produce them would be of substantial benefit in projecting data to areas without information.

Sediment Yield Classification

It is recommended that sediment yields in the Pacific Southwest area be divided into five classes of average annual yield in acre-feet per square mile. These are as follows:

Classification	1	> 3.0	acre-feet/square	mile
	2	1.0 - 3.0	"	"
	3	0.5 - 1.0	"	"
	4	0.2 - 0.5	"	"
	5	< 0.2	"	"

Nine factors are recommended for consideration in determining the sediment yield classification. These are geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and sediment transport.

Characteristics of each of the nine factors which give that factor high, moderate, or low sediment yield level are shown on Table A-1. The sediment yield characteristic of each factor is assigned a numerical value representing its relative significance in the yield rating. The yield rating is the sum of values for the appropriate characteristics for each of the nine factors. Conversion to yield classes should be as follows:

Rating	Class
> 100	1
75 - 100	2
50 - 75	3
25 - 50	4
0 - 25	5

Guidelines which accompany the table are an integral part of the procedure. They describe the characteristics of factors which influence sediment yield and these are summarized in the space provided on the table.

The factors are generally described, for purposes of avoiding complexity, as independently influencing the amount of sediment yield. The variable impact of any one factor is the result of influence by the others. To account for this variable influence in any one area would require much more intensive investigational procedures than are available for broad planning purposes.

To briefly indicate the interdependence of the factors discussed separately, ground cover is used as an example. If there is no vegetation, litter or rock fragments protecting the surface, the rock, soil, and topography express their uniqueness on erosion and sediment yield. If the surface is very well protected by cover, the characteristics of the other factors are obscured by this circumstance. In similar vein, an arid region has a high potential for erosion and sediment yield because of little or no ground cover, sensitive soils and rugged topography. Given very low intensity rainfall and rare intervals of runoff, the sediment yield could be quite low.

Each of the 9 factors shown on Table A-1 are paired influences with the exception of topography. That is, geology and soils are directly related as are climate and runoff, ground cover and land use, and upland and channel erosion. Ground cover and land use have a negative influence under average or better conditions. Their impact on sediment yield is therefore indicated as a negative influence when affording better protection than this average.

It is recommended that the observer follow a feedback process whereby he checks the sum of the values on the table from A through G with the sum of H and I. In most instances high values in the former should correspond to high values in the latter. If they do not, either special erosion conditions exist or the A through G factors should be re-evaluated.

Although only the high, moderate and low sediment yield levels are shown on the attached table, interpolation between these levels may be made.

Surface Geology

Over much of the southwest area, the effect of surface geology on erosion is readily apparent. The weaker and softer rocks are more easily eroded and generally yield more sediment than do the harder more resistant types. Sandstones and similar coarse-textured rocks that disintegrate to form permeable soils erode less than shales and related mudstones and siltstones under the same conditions of precipitation. On the other hand, because of the absence of cementing agents in some soils derived from sandstone, large storms may produce some of the highest sediment yields known.

The widely distributed marine shales, such as the Mancos and shale members of the Moenkopi Formation, constitute a group of highly erodible formations. The very large areal extent of the shales and their outwash deposits

gives them a rank of special importance in relation to erosion. Few of the shale areas are free from erosion. Occasionally, because of slope or cover conditions, metamorphic rocks and highly fractured and deeply weathered granites and granodiorites produce high sediment yield. Limestone and volcanic outcrop areas are among the most stable found within the western lands. The principal reason for this appears to be the excellent infiltration characteristics, which allow most precipitation to percolate into the underlying rocks.

In some areas, all geologic formations are covered with alluvial or colluvial material which may have no relation to the underlying geology. In such areas the geologic factor would have no influence and should be assigned a value of 0 in the rating.

Soils

Soil formation in the Pacific Southwest generally has not had climatic conditions conducive to rapid development. Therefore, the soils are in an immature stage of development and consist essentially of physically weathered rock materials. The presence of sodium carbonate (black alkali) in a soil tends to cause the soil particles to disperse and renders such a soil susceptible to erosion.

There are essentially three inorganic properties--sand, silt, and clay--which may in any combination give soil its physical characteristics. Organic substances plus clay provide the binding material which tends to hold the soil separates together and form aggregates. Aggregate formation and stability of these aggregates are the resistant properties of soil against erosion. Unstable aggregates or single grain soil materials can be very erodible.

Climate and living organisms acting on parent material, as conditioned by relief or topography over a period of time, are the essential factors for soil development. Any one of these factors may overshadow or depress another in a given area and cause a difference in soil formation. For instance, climate determines what type of vegetation and animal population will be present in an area, and this will have a definite influence or determine the type of soil that evolves. As an example, soils developing under a forest canopy are much different from soils developing in a grassland community.

The raw, shaley type areas (marine shales) of the Pacific Southwest have very little, if any, solid development. Colluvial-alluvial fan type areas are

usually present at the lower extremities of the steeper sloping shale areas. Infiltration and percolation are usually minimal on these areas due to the fine textured nature of the soil material. This material is easily dispersed and probably has a high shrink-swell capacity. Vegetation is generally sparse, and consists of a salt desert shrub type.

There are areas that contain soils with definite profile development, and also, stony soils that contain few fines, which constitutes an improved physical condition for infiltration and plant growth over the fine textured shaley areas. These areas usually occur at higher and more moist elevations where bare, hard crystalline rocks provide the soil parent material. Vegetation and other ground cover, under these circumstances, provide adequate protection against the erosive forces and thus low sediment yield results.

In arid and semi-arid areas, an accumulation of rock fragments (desert pavement) or calcareous material (caliche) is not uncommon. These layers can offer substantial resistance to erosion processes.

The two extreme conditions of sediment yield areas have been described. Intermediate situations would contain some features of the two extremes. One such situation might be an area of predominately good soil development that contains small areas of badlands. This combination would possibly result in an intermediate classification.

Climate and Runoff

Climatic factors are paramount in soil and vegetal development and determine the quantity and discharge rate of runoff. The same factors constitute the forces that cause erosion and the resultant sediment yield. Likewise, temperature, precipitation, and particularly the distribution of precipitation during the growing season, affect the quantity and quality of the ground cover as well as soil development. The quantity and intensity of precipitation determine the amount and discharge rates of runoff and resultant detachment of soil and the transport media for sediment yield. The intensity of prevailing and seasonal winds affects precipitation pattern, snow accumulation and evaporation rate.

Snow appears to have a minor effect on upland slope erosion since raindrop impact is absent and runoff associated with snow melt is generally in resistant mountain systems.

Frontal storms in which periods of moderate to high intensity precipitation occur can produce the highest sediment yields within the Southwest. In humid and subhumid areas the impact of frontal storms on sediment may be greatest on upland slopes and unstable geologic areas where slides and other downhill soil movement can readily occur.

Convective thunderstorm activity in the Southwest has its greatest influence on eroison (sic) and sedimentation in Arizona and New Mexico and portions of the adjoining states. High rainfall intensities on low density cover or easily dispersed soils produces high sediment yields. The average annual sediment yield is usually kept within moderate bounds by infrequent occurrence of thunderstorms in any one locality.

High runoff of rare frequency may cause an impact on average annual sediment yield for a long period of time in a watershed that is sensitive to erosion, or it may have little effect in an insensitive watershed. For example, sediment that has been collecting in the bottom of a canyon and on side slopes for many years of low and moderate flows may be swept out during the rare event, creating a large change in the indicated sediment yield rate for the period of record.

In some areas the action of freezing and thawing becomes important in the erosion process. Impermeable ice usually forms in areas of fine textured soils where a supply of moisture is available before the advent of cold weather. Under these conditions the ice often persists throughout the winter and is still present when the spring thaw occurs. In some instances water tends to run over the surface of the ice and not detach soil particles, but it is possible for the ice in a surface layer to thaw during a warm period and create a very erodible situation. Spring rains with ice at shallow depth may wash away the loose material on the surface.

In some areas of the Pacific Southwest, particularly those underlain by marine shale, freezing and thawing alters the texture of soil near the surface, and thus changes the infiltration characteristics. These areas generally do not receive enough snow or have cold enough temperatures to build a snow pack for spring melt. Later in the year soil in a loosened condition is able to absorb a large part of the early rainfall. As rains occur during the summer, the soil becomes compacted on the surface, thus allowing more water to run off and affording a greater chance for erosion.

Topography

Watershed slopes, relief, floodplain development, drainage patterns, orientation and size are basic items to consider in connection with topography. However, their influence is closely associated with geology, soils, and cover.

Generally, steep slopes result in rapid runoff. The rimrock and badlands, common in portions of the Pacific Southwest, consist of steep slopes of soft shales usually maintained by the presence of overlying cap rock. As the soft material is eroded, the cap rock is undercut and falls, exposing more soft shales to be carried away in a continuing process. However, high sediment yields from these areas are often modified by the temporary deposition of sediment on the intermediate floodplains.

The high mountain ranges, although having steep slopes, produce varying quantities of sediment depending upon the type of parent materials, soil development, and cover which directly affect the erosion processes.

Southerly exposed slopes generally erode more rapidly than do the northerly exposed slopes due to greater fluctuation of air and soil temperatures, more frequent freezing and thawing cycles, and usually less ground cover.

The size of the watershed may or may not materially affect the sediment yield per unit area. Generally, the sediment yield is inversely related to the watershed size because the larger areas usually have less overall slope, smaller proportions of upland sediment sources, and more opportunity for the deposition of upstream derived sediments on floodplains and fans. In addition, large watersheds are less affected by small convective type storms. However, under other conditions, the sediment yield may not decrease as the watershed size increases. There is little change in mountainous areas of relatively uniform terrain. There may be an increase of sediment yield as the watershed size increases if downstream watersheds or channels are more susceptible to erosion than upstream areas.

Ground Cover

Ground cover is described as anything on or above the surface of the ground which alters the effect of precipitation on the soil surface and profile. Included in this factor are vegetation, litter, and rock fragments. A

good ground cover dissipates the energy of rainfall before it strikes the soil surface, delivers water to the soil at a relatively uniform rate, impedes the flow of water, and promotes infiltration by the action of roots within the soil. Conversely, the absence of ground cover, whether through natural growth habits or the effect of overgrazing or fire, leave the land surface open to the worst effects of storms.

In certain areas, small rocks or rock fragments may be so numerous on the surface of the ground that they afford excellent protection for any underlying fine material. These rocks absorb the energy of falling rain and are resistant enough to prevent cutting by flowing water.

The Pacific Southwest is made up of land with all classes of ground cover. The high mountain areas generally have the most vegetation, while many areas in the desert regions have practically none. The abundance of vegetation is related in a large degree to precipitation. If vegetative ground cover is destroyed in areas where precipitation is high, abnormally high erosion rates may be experienced.

Differences in vegetative type have a variable effect on erosion and sediment yield, even though percentages of total ground cover may be the same. For instance, in areas of pinyon-juniper forest having the same percentage of ground cover as an area of grass, the absence of understory in some of the pinyon-juniper stands would allow a higher erosion rate than in the area of grass.

Land Use

The use of land has a widely variable impact on sediment yield, depending largely on the susceptibility of the soil and rock to erosion, the amount of stress exerted by climatic factors and the type and intensity of use. Factors other than the latter have been discussed in appropriate places in this guide.

In almost all instances, use either removes or reduces the amount of natural vegetative cover which reflects the varied relationships within the environment. Activities which remove all vegetation for parts of each year for several years, or permanently, are cultivation, urban development, and road construction. Grazing, logging, mining, and fires artifically (sic) induce permanent or temporary reduction in cover density.

High erosion hazard sites, because of the geology, soils, climate, etc., are also of high hazard from the standpoint of type and intensity of use. For

example, any use which reduces cover density on a steep slope with erodible soils and severe climatic conditions will strongly affect sediment yield. The extent of this effect will depend on the area and intensity of use relative to the availability of sediment from other causes. Construction of road or urban development with numerous cut and fill slopes through a large area of widespread sheet or gully erosion will probably not cause a change in sediment yield classification. Similar contruction (sic) and continued disturbance in an area of good vegetative response to a favorable climate can raise yield by one or more classifications.

Use of the land has its greatest potential impact on sediment yield where a delicate balance exists under natural conditions. Alluvial valleys of fine, easily dispersed soils from shales and sandstones are highly vulnerable to erosion where intensive grazing and trailing by livestock have occurred. Valley trenching has developed in many of these valleys and provides a large part of the sediment in high yield classes from these areas.

A decline in vegetative density is not the only effect of livestock on erosion and sediment yield. Studies at Badger Wash, Colorado, which is underlain by Mancos shale, have indicated that sediment yield from ungrazed watersheds is appreciably less than from those that are grazed. This difference is attributed to the absence of soil trampling in the ungrazed areas, since the density of vegetation has not noticeably changed since exclusion began.

Areas in the arid and semi-arid portions of the Southwest that are surfaced by desert pavement are much less sensitive to grazing and other use, since the pavement affords a substitute for vegetative cover.

In certain instances the loss or deterioration of vegetative cover may have little noticeable on-site impact but may increase off-site erosion by acceleration of runoff. This could be particularly evident below urbanized areas where accelerated runoff from pavement and rooftops has increased the stress on downstream channels. Widespread destruction of cover by poor logging practices or by brush and timber fires frequently increases channel erosion as well as that on the directly affected watershed slopes. On the other hand, cover disturbances under favorable conditions, such as a cool, moist climate, frequently result in a healing of erosion sources within a few years.

Upland Slope Erosion

This erosion form occurs on sloping watershed lands beyond the confines of valleys. Sheet erosion, which involves the removal of a thin layer of soil over an extensive area, is usually not visible to the eye. This erosion form is evidenced by the formation of rills. Experience indicates that soil loss from rill erosion can be seen if it amounts to about 5 tons or more per acre. This is equivalent in volume per square mile to aproximately (sic)2 acre-feet.

Wind erosion from upland slopes and the deposition of the eroded material in stream channels may be a significant factor. The material so deposited in channels is readily moved by subsequent runoff.

Downslope soil movement due to creep can be an important factor in sediment yield on steep slopes underlain by unstable geologic formations.

Significant gully erosion as a sediment contributor is evidenced by the presence of numerous raw cuts along the hill slopes. Deep soils on moderately steep to steep slopes usually provide an environment for gully development.

Processes of slope erosion must be considered in the light of factors which contribute to its development. These have been discussed in previous sections.

Channel Erosion and Sediment Transport

If a stream is ephemeral, runoff that traverses the dry alluvial bed may be drastically reduced by transmission losses (absorption by channel alluvium). This decrease in the volume of flow results in a decreased potential to move sediment. Sediment may be deposited in the streambed from one or a series of relatively small flows only to be picked up and moved on in a subsequent larger flow. Sediment concentrations, determined from field measurements at consecutive stations, have generally been shown to increase many fold for instances of no tributary inflow. Thus, although water yield per unit area will decrease with increasing drainage area, the sediment yield per unit area may remain nearly constant or may even increase with increasing drainage area.

In instances of convective precipitation in a watershed with perennial flow, the role of transmission losses is not as significant as in watersheds with ephemeral flow, but other channel factors, such as the shape of the channel, may be important.

For frontal storm runoff, the flow durations are generally much longer than for convective storms, and runoff is often generated from the entire basin. In such instances, sediment removed from the land surfaces is generally carried out of the area by the runoff. Stream channel degradation and/or aggradation must be considered in such cases, as well as bank scour. Because many of the stream beds in the Pacific Southwest are composed of fine-grained alluvium in well defined channels, the potential for sediment transport is limited only by the amount and duration of runoff. Large volumes of sediment may thus be moved by these frontal storms because of the longer flow durations.

The combination of frontal storms of long duration with high intensity and limited areal-extent convective activity will generally be in the highest class for sediment movement in the channels. Storms of this type generally produce both the high peak flows and the long durations necessary for maximum sediment transport.

Sediment yield may be substantially affected by the degree of channel development in a watershed. This development can be described by the channel cross sections, as well as by geomorphic parameters such as drainage density, channel gradients and width-depth ratio. The effect of these geomorphic parameters is difficult to evaluate, primarily because of the scarcity of sediment transport data in the Pacific Southwest.

If the cross section of a stream is such as to keep the flow within defined banks, then the sediment from an upstream point is generally transported to a downstream point without significant losses. Confinement of the flow within alluvial banks can result in a high erosional capability of a flood flow, especially the flows with long return periods. In most channels with wide floodplains, deposition on the floodplain during floods is often significant, and the transport is thus less than that for a within bank flow. The effect of this transport capability can be explained in terms of tractive force which signifies the hydraulic stress exerted by the flow on the bed of the stream. This average bed-shear stress is obtained as the product of the specific weight of the fluid, hydraulic radius, and energy gradient slope. Thus, greater depth results in a greater bed shear and a greater potential for moving sediment. By the same reasoning, steep slopes (the energy slope and bed slope are assumed to be equivalent) also result in high bed-shear stress.

The boundary between sediment yield classifications in much of the Pacific Southwest may be at the mountain front, with the highest yield

designation on the alluvial plain if there is extensive channel erosion. In contrast, many mountain streams emerge from canyon reaches and then spread over fans or valley flats. Here water depths can decrease from many feet to only a few inches in short distances with a resultant loss of the capacity to transport sediment. Sediment yield of the highest classification can thus drop to the lowest in such a transition from a confined channel to one that has no definition.

Channel bank and bed composition may greatly influence the sediment yield of a watershed. In many areas within the Pacific Southwest, the channels in valleys dissect unconsolidated material which may contribute significantly to the stream sediment load. Bank sloughing during periods of flow, as well as during dry periods, piping, and bank scour generally add greatly to the sediment load of the stream and often change upward the sediment yield classification of the watershed. Field examination for areas of head cutting, aggradation or degradation, and bank cutting are generally necessary prior to classification of the transport expectancy of a stream. Geology plays a significant role in such an evaluation. Geologic controls in channels can greatly affect the stream regimen by limiting degradation and headcuts. Thus, the transport capacity may be present, but the supply of sediment from this source is limited.

Man-made structures can also greatly affect the transport characteristics of the stream. For example, channel straightening can temporarily upset the channel equilibrium and cause an increase in channel gradient and an increase in the stream velocity and the shear stress. Thus, the sediment transport capacity of the stream may be temporarily increased. Structures such as debris darns, lined channels, drop spillways, and detention dams may drastically reduce the sediment transport.

AN EXPLANATION OF THE USE OF THE RATING CHART (TABLE A-1) FOR EVALUATING FACTORS AFFECTING SEDIMENT YIELD IN THE PACIFIC SOUTHWEST FOLLOWS

Table A.1. Factors Affecting Sediment Yield in the Pacific Southwest

PSIAC - Table A-1

Sediment Yield Levels	A SURFACE GEOLOGY (10)*	B SOILS (10)	C CLIMATE (10)	D RUNOFF (10)	E TOPOGRAPHY (20)	F GROUND COVER (10)	G LAND USE (10)	H UPLAND EROSION (25)	I CHANNEL EROSION & SEDIMENT TRANSPORT (25)
High	a. Marine shales and related mudstones and siltstones.	a. Fine textured easily dispersed; saline-alkaline; high shrink-swell characteristics b. Single grain silts and fine sands	a. Storms of several days' duration with short periods of intense rainfall. b. Frequent intense convective storms c. Freeze-thaw occurrence	a. High peak flows per unit area b. Large volume of flow per unit area	a. Steep upland slopes (in excess of 30%) High relief; little or no floodplain development	Ground cover does not exceed 20% a. Vegetation sparse; little or no litter b. No rock in surface soil	a. More than 50% cultivated b. Almost all of area intensively grazed c. All of area recently burned	a. More than 50% of the area characterized by rill and gully or landslide erosion	a. Eroding banks continuously or at frequent intervals with large depths and long flow duration b. Active headcuts and degradation in tributary channels
**									
Moderate	(5) a. Rocks of medium hardness b. Moderately weathered c. Moderately fractured	(5) a. Medium textured soil b. Occasional rock fragments c. Caliche layers	(5) a. Storms of moderate duration and intensity b. Infrequent convective storms	(5) a. Moderate peak flows b. Moderate volume of flow per unit area	(10) a. Moderate upland slopes (less than 20%) b. Moderate fan or floodplain development	(10) Cover not exceeding 40% a. Noticeable litter b. If trees present understory not well developed	(0) a. Less than 25% cultivated b. 50% or less recently logged c. Less than 50% intensively grazed d. Ordinary road and other construction	(10) a. About 25% of the area characterized by rill and gully or landslide erosion b. Wind erosion with deposition in stream channels	(10) a. Moderate flow depths, medium flow duration with occasionally eroding banks or bed
**									
Low	(0) a. Massive, hard formations	(0) a. High percentage of rock fragments b. Aggregated clays c. High in organic matter	(0) a. Humid climate with rainfall of low intensity b. Precipitation in form of snow c. Arid climate, low intensity storms d. Arid climate; rare convective storms	(0) a. Low peak flows per unit area b. Low volume of runoff per unit area c. Rare runoff events	(0) a. Gentle upland slopes (less than 5%) b. Extensive alluvial plains	(-10) a. Area completely protected by vegetation, rock fragments, litter. Little opportunity for rainfall to reach erodible material	(-10) a. No cultivation b. No recent logging c. Low intensity grazing	(0) a. No apparent signs of erosion	(0) a. Wide shallow channels with flat gradients, short flow duration b. Channels in massive rock, large boulders or well vegetated c. Artificially controlled channels

* THE NUMBERS IN SPECIFIC BOXES INDICATE VALUES TO BE ASSIGNED APPROPRIATE CHARACTERISTICS. THE SMALL LETTERS, a, b, c, REFER TO INDEPENDENT CHARACTERISTICS TO WHICH FULL VALUE MAY BE ASSIGNED.

** IF EXPERIENCE SO INDICATES, INTERPOLATION BETWEEN THE 3 SEDIMENT YIELD LEVELS MAY BE MADE.

Use of the Rating Chart of Factors Affecting Sediment Yield in the Pacific Southwest

The following is a summary of the sediment yield classification presented for this methodology.

Classification	Rating	Sediment Yield AF/sq. ml.
1	> 100	3.0
2	75 - 100	1.0 - 3.0
3	50 - 75	0.5 - 1.0
4	25 - 50	0.2 - 0.5
5	0 - 25	< 0.2

In most instances, high values for the A through G factors should correspond to high values for the H and/or I factors.

An example of the use of the rating chart is as follows:

A watershed of 15 square miles in western Colorado has the following characteristics and sediment yield levels:

Factors	Sediment Yield Levels	Rating
A Surface geology	Marine Shales	10
B Soils	Easily dispersed, high shrink-swell characteristics	10
C Climate	Infrequent convective storms, freeze-thaw occurrence	7
D Runoff	High peak flows; low volumes	5
E Topography	Moderate slopes	10
F Ground cover	Sparse, little or no litter	10
G Land use	Intensively grazed	10
H Upland erosion	More than 50% rill and gully erosion	25
I Channel erosion	Occasionally eroding banks and bed but short flow duration	5
	TOTAL	92

This total rating of 92 would indicate that the sediment yield is in Classification 2. This compares with a sediment yield of 1.96 acre-feet per square mile as the average of a number of measurements in this area.

SCOUR ANALYSIS OF THE

2026 GAS PIPELINE CROSSING OF THE

GILA RIVER NEAR COOLIDGE, AZ

FOR

EL PASO NATURAL GAS COMPANY
EL PASO, TEXAS

BY

WEST Consultants, Inc.
2111 Palomar Airport Road, Suite 180
Carlsbad, CA 92009-1419
(619) 431.8113

May 17, 1993

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INTRODUCTION

Purpose

El Paso Natural Gas Company (EPNG) is proposing to replace a gas pipeline that ruptured (2026 line) during the January 1993 floods. The new line would be buried beneath the Gila River near Coolidge, AZ between Mile Posts 13-15 as measured using EPNG stationing. The purpose of this study was to determine 100 year flood scour depths due to general and local scour in the river, and the possible lateral extent of the scour. This was used to obtain recommended pipe burial depths and limits. An area map is shown in Figure 1 and a project site map in Figure 2.

Scope

WEST Consultants conducted a detailed scour analysis of the pipeline crossing and the results are documented in this report. This analysis was performed using the sediment transport computer program, HEC-6, "Scour and Deposition in Rivers and Reservoirs" to compute general scour. An analytical local scour analysis was then conducted to determine the total scour potential. Channel migration patterns from aerial photographs were analyzed to estimate probable lateral movement of the river near the proposed pipeline alignment.

Acknowledgements

Mr. David Williams of WEST Consultants was the project manager for this study. He also developed the technical approach used, and performed the HEC-6 modeling. Mr. Brian Doeing helped in the HEC-6 analysis and conducted the field reconnaissance. Dr. Jeffrey Bradley provided help with analysis of the sediment data and hydrologic analysis, provided independent technical review, and wrote a majority of this report. Mr. Norman Wetz was the engineer-in-charge for the geotechnical consultant, Sergent, Hauskins and Beckwith Geotechnical Engineers, Inc. (SHB) and helped in the determination of sediment sampling and drilling sites at the pipeline stream crossing. Mr. Samuel Carreon, Jr. of El Paso Natural Gas Company (EPNG) provided the overall technical supervision for this study. Mr. Jesus Soto was the EPNG project manager for this site and provided support in the study. Their contributions to this study are gratefully acknowledged.

PROJECT DESCRIPTION

General

The Gila River originates in southeastern Arizona and is tributary to the Colorado River with the confluence of the two rivers at Yuma, Arizona (Figure 1). The project site is located on the mainstem Gila River near the town of Coolidge, Arizona. Upstream flow regulation occurs as a result of Coolidge Dam on the Gila River. Coolidge Dam is used primarily for irrigation and is owned by the Bureau of Indian Affairs, but is operated by the Bureau of Reclamation. Approximately half of the drainage area upstream of Coolidge is regulated by Coolidge Dam. The San Pedro river is the major tributary drainage between the pipeline crossing and the dam. Completely dry river beds are a common occurrence in the Gila River during portions of the year. Thunderstorms and flash floods are also common in the summer months. The largest floods are most likely to occur from mid-December through March and are the result of regional rain storms, or rain on snow events.

January 1993 Flood

A 6 inch O.D. gas pipeline (2026 line) crossing the Gila River between Mile Posts 13 and 15 near Coolidge ruptured during the early January 1993 storm. This crossing is approximately twenty-five miles downstream of the USGS stream gage on the Gila River at Kelvin, however, no major tributaries enter between Kelvin and the pipeline crossing. The contributing drainage area upstream of Kelvin is 18,011 square miles. The provisional January 1993 storm hydrograph is presented in Figure 3. The peak at the pipeline crossing would lag that time shown in Figure 3 by approximately 4 hours, the travel time from Kelvin to Coolidge. The peak flow should be approximately the same. That peak flow of approximately 50,000 cfs, which would correspond to a flow slightly greater than the 25 year flood (Roeske, 1978), was estimated provisionally by the USGS. Figures 4 and 5 show this and other upstream and downstream flood frequency estimates made below Coolidge Dam (Roeske, 1978).

The meander belt at this crossing, which is at approximately a 30 degree angle to the pipeline crossing, is approximately 6700 feet across. The stream channel migrated laterally during the January 1993 flood and during previous floods. Complicating factors caused great changes in stream location during the January 1993 flood, including failure of the Attaway Road Bridge (completed by Pinal County in 1988/89) north and south abutments just upstream of the pipeline crossing, and a chute cutoff of a meander immediately upstream of Attaway Road. The channel shifted laterally over two thousand feet during the flood. Failure of the pipeline occurred as a result of the lateral channel shift which undercut the pipe in a location that had previously been perceived as an overbank area outside of the flood channel. Pipeline burial depth was more shallow in that location. The proposed pipeline alignment is shown in Figure 2.

Background Information and Field Reconnaissance

WEST Consultants conducted a background information survey in order to obtain any pertinent information concerning the hydraulics, hydrology, and sedimentation issues for the site. The agencies that provided information were Pinal County, the U.S. Army Corps of Engineers (Los Angeles District), and the U.S. Geological Survey. In conjunction with this effort, WEST Consultants conducted a field reconnaissance of the site.

The field reconnaissance crew consisted of sedimentation engineers from WEST Consultants and geotechnical engineers from Sergent, Hauskins and Beckwith (SHB), the geotechnical engineering firm that conducted the surface and subsurface soils analyses. The WEST Consultants personnel determined the locations of surface samples to be taken and used in the sediment model described later. Exploratory drilling locations were generally along the proposed burial alignment.

Field and Laboratory Activities

Sediment samples were collected at sites determined in the field by WEST Consultants. SHB collected and analyzed the samples under separate contract to EPNG. The sediment samples were analyzed for grain size distribution (sieve analysis) down to approximately 0.0625 mm. Samples from the borings were characterized and analyzed to determine depth of bedrock or strongly cemented (flow resistant) soils. This information was documented by boring logs. The information was helpful in determining the trenching requirements for pipeline placement and the likely maximum depth of scour. The results of the geotechnical investigation were documented in a separate report by SHB.

HYDROLOGIC ANALYSIS

General

The long term hydrologic information used in this study was obtained from the USGS stream gage, Gila River at Kelvin, Arizona. This USGS data was extracted from CD-ROM optical discs and associated software obtained from U. S. WEST (1988). The development of the 100 year flood used in the sediment transport model is described in detail later.

Historic Streamflows

The USGS stream gage on the Gila River at Kelvin has been in continuous operation since 1913. Upstream regulation of the river for peak flows has existed since completion of Coolidge Dam in 1941. The record from 1913 through 1986 was utilized to establish long term hydrologic trends at the project site. Flows are normally low from April through mid-December with some thunderstorm peak floods occurring in August through October. The historic wet period begins in mid to late December and continues through March. In order to present a range of possible flow conditions during the potential construction season Figures 6-10 are used to portray the average mean daily flow and the maximum mean daily flow observed during the period of record for May through September, respectively.

The 100 year flood peak flow of 130,000 cfs for the site was obtained by using the streamflow record from the Gila River at Kelvin streamgage and the USGS regional flood frequency analysis which includes Coolidge regulation (Roeske, 1978). The shape of the hydrograph was obtained by using the USGS provisional estimate for the January 1993 storm which had a peak of 50,000 cfs (USGS provisional estimate). The hydrograph was increased to reflect the difference between this event and the 100 year flood. The 100-year design hydrograph is shown in Figure 11. For comparative purposes peak annual instantaneous flows of record are presented in Table 1.

Flow During Construction Period

As noted in the previous section, mean daily flows can vary from essentially zero to flood conditions. Mean daily flow variances possible during a possible construction window from May to September are presented in Figures 6-10. It is apparent from these figures that the optimal construction season is from May through June. Large thunderstorms are quite normal during July, August and September. Peak instantaneous flows can be significantly larger than mean daily flows particularly during thunderstorm events. In order to provide a better estimate of the larger flows that can be expected during a construction period, a flood frequency analysis was performed to determine the 5 and 10 year peak flows. These peaks are 3360 cfs and 3970 cfs in May, 4050 cfs and 4650 cfs in June, 10,990 cfs and 12,060 cfs in July, and 17,330 cfs

and 21,200 cfs in August for the 5 and 10 year floods, respectively. It is recommended, based upon historic streamflows, that construction activities be initiated and completed before July, if possible. Following that date, streamflows increase significantly and can maintain relatively high levels due to thunderstorms through September and into October. Flows do decrease in later October and November until increasing again during the regional storm events during the winter.

Due to dam instability and ongoing construction at Coolidge Dam, the Bureau of Reclamation is planning to release at high levels until the Coolidge pool level is reduced to one-half the full pool volume. They plan to release 4200 cfs until May 1, 2000 cfs from May 1 to June 1, and 1500 cfs from June 1 through August. The previous analysis for the 5 and 10 year peak flows takes this information into account. The aforementioned flows are targets and are variable on a week to week basis.

SCOUR AND SEDIMENT TRANSPORT MODELING AND ANALYSIS

A detailed scour and sediment transport analysis was conducted at this site in order to provide criteria for pipeline construction, design and permitting.

Purpose of Sediment Transport Modeling

There are essentially two kinds of scour - general (degradation) and local. General scour is associated with general streambed lowering over a significant stream reach length. This occurs under conditions such as depletion of upstream sediment sources (e.g., scour downstream of reservoirs), and changes in stream gradient. Local scour is associated with streambed erosion at specific locations across and, to some extent, along the stream. Examples of local scour include the deepening incision of the low flow channel, constriction or pier scour at bridges or between bridge abutments, flow concentrations at severe stream bends, and impinging flows at stream confluences.

Traditional computation of scour depth addresses only the local scour component of the total scour and does not include the general lowering of the streambed during the design event and/or long term general scour trends. A more comprehensive approach is to determine the general scour of the streambed using the design hydrograph (supplemented with a long term hydrograph) and add the local scour component to the general scour to obtain the total scour depth. The concept of local and general scour is illustrated in Figure 12. The general scour portion of the total scour requires information on the geometry of the stream upstream and downstream of the pipeline crossing, hydraulic parameters (depth ,velocity, width, etc.) of each discharge of the design hydrograph and long term hydrograph, the sediment gradation of the bed surface, volume and composition of the sediment entering the reach for each discharge, and the flow and duration of each portion of the design hydrograph.

This type of analysis requires the use of a numerical sediment transport model. The sediment transport model, HEC-6, "Scour and Deposition in Rivers and Reservoirs," (U. S. Corps of Engineers, 1977) was selected to model the general scour of the stream crossing.

Description of HEC-6 Model

HEC-6 is a one-dimensional, movable boundary, open channel flow model designed to simulate streambed profile changes over fairly long time periods. Since its initial nationwide distribution by the Hydrologic Engineering Center (HEC) of the Corps of Engineers in 1973 and again in 1977, 1987 and 1991, it has been the most widely used one-dimensional sediment transport model in the U. S. and particularly, with the Corps of Engineers.

In general terms, the model first calculates the hydraulics of each discharge increment in a

hydrograph to determine hydraulic parameters such as flow depth, water velocity, and effective flow width for each cross section. It then computes the sediment transport potential at each cross section using the hydraulics of the main channel. Sediment contribution at the upstream end of the reach being modeled is simulated by the use of a sediment vs. discharge relation and is specified by the user. This load is compared to the sediment transport potential of the cross section. If the inflowing load is larger than its transport potential, the difference is deposited in the cross section. If the inflowing load is less than the transport potential, it is picked up (scoured) from the bed, taking into account the availability of material in the bed (e.g., bedrock, armoring, etc.). The sediment load leaving the cross section then becomes the inflowing load to the next downstream cross section. This continues until the most downstream cross section is simulated. For the next discharge in the hydrograph, the hydraulics are again computed using the new cross sectional geometry formed by the previous discharge. The cycle is repeated until the entire hydrograph is simulated. Further details of the model are presented in the HEC-6 User's Manual (USACOE, 1991) and MacArthur et. al. (1990).

The creation of HEC-6 input files for each river segment containing the pipeline crossing requires the development of channel geometry from field surveys, hydraulic analysis for the water discharges being simulated, the input of representative streambed material size distributions, the creation of an inflowing sediment rating curve, and development of a design hydrograph containing the design event and a representative long term hydrograph. The procedures used in developing the HEC-6 inputs are described in the following sections.

Development of Geometry and Hydraulics

The streambed and overbank geometry are required for input in the sediment transport model. Surveys were conducted by El Paso Natural Gas contract survey crews and provided to WEST Consultants. A flow of approximately 8000 cfs existed in the river at the time of the survey. Accordingly, the survey crews were unable to survey the channel bottom that was covered by water. In order to estimate the actual underwater geometry we assumed a thalweg shape consistent with previous observations and conducted a normal depth computation for 8000 cfs at each cross section such that the water surface elevation met that which was observed for this flow during the field survey. Cross sectional geometry was then input into the HEC-6 model. Cross sections as surveyed throughout the reach and computed water surface elevations for the 100-year peak flow are presented in Appendix B.

Streambed Gradation

A field sediment data collection program was conducted at the site. Bed sediment samples and gradations within the study reach are also a requirement for sediment transport modeling. These streambed gradations were input to the HEC-6 model. At cross sections that do not have samples taken, the upstream and downstream cross section gradations were linearly interpolated to produce a representative gradation. This interpolation is performed automatically in HEC-6.

Limits of Erodible Bed

From the field reconnaissance and plots of the cross sections, the lateral limits of scour were determined and input to the HEC-6 model. The model assumes that erosion is uniform between these limits but deposition can occur outside these limits but within the wetted portions of the channel. In general, the limits of scour are within what is termed the "active bed" and are often located just within the main channel limits.

Inflowing Sediment Load

Generally, no information was available on the sediment entering the stream crossings from upstream sources. To develop a sediment rating curve (the relation between water discharge and sediment discharge by grain size), it was assumed that the upstream cross sections were in quasi-equilibrium. This means that the sediment gradation of the streambed determines the sediment loads passing the cross sections and the amount of sediment entering the reach is generally equal to the amount of sediment exiting the reach. For a range of flows, the inflowing sediment for the HEC-6 model was assumed and the amount of sediment passing the upstream cross sections noted. The sediment load passing these cross sections was then used as the inflowing sediment load. This iterative process was continued until the inflowing sediment load is consistent with the sediment load passing the upstream cross sections and no significant scour or deposition occurred in these cross sections (consistent with the equilibrium assumption). The inflowing sediment loads from the last iteration were used as a basis for later analysis.

Development of Streamflow Hydrograph

In order to use HEC-6 for sedimentation analysis, a 100-year flood hydrograph must be developed which comprises a long term event as well as the hydrograph of the design event. The 100-year storm hydrograph was developed using the same pattern as observed in the January 1993 hydrograph at Kelvin. The hydrograph was shifted upward to represent the difference between the observed peak of the 1993 storm of 50,000 cfs as compared to the 100-year peak flow (Roeske, 1978) of 130,000 cfs. Using an in house computer program called the Sediment Weighted Histogram Generator, an output file of the representative 100-year flood histogram was created in HEC-6 input format.

Results of Scour Analysis

The HEC-6 model computed a maximum average scour depth of 6.3 feet at cross section 5000. Due to the extreme skew of the pipeline crossing to the river, the alignment actually crosses sections 3000 through 8000 (Figure 2). The maximum general scour at each cross section was used to compute total scour depth. It must be understood that the results of the simulation are representative of the general scour and that the actual local scour must be added to the general

scour to obtain the total scour, as depicted in Figure 12. Determination of local scour is theoretically beyond the capabilities of HEC-6 or any 1-dimensional sediment transport model; however, analytical methods can be used to approximate it.

Lacey (U.S Bureau of Reclamation, 1984) estimated that the local scour for a straight reach should be about 25% of the flow depth, 50% for a moderate bend and 75% for a severe bend. Blench (USBR, 1984) suggests that this value should be 60% of the flow depth, even for reaches that range from straight to severe bends. This implies that the local scour is just as great in a straight reach as in a severe bend. Since the general scour was already conservative (maximized scour conditions), Lacey's relation was chosen to determine the local scour and thus the total scour depth. The pipeline crossing site has moderate flow angles to the main stream and would be classified as a moderate bend in the Lacey method.

For the peak discharge of the 100-year flood (130,000 cfs), the flow depths along the pipeline crossing from cross sections 3000 to 8000 vary from approximately 10 to 15 feet. Assuming Lacey's relation for a moderate bend, the local scour would vary from 5 to 7.5 feet. A safety factor of 3 feet was added to reflect the effect of antidunes as were observed during the January 1993 storm.

Using the aforementioned computational techniques the total scour depth for the 100-year design event at the crossing was estimated along the entire crossing. Due to the extreme skew of the crossing to the river channel and assuming that the actual incised stream channel can migrate over the entire width of the meander belt total scour potential in feet mean sea level elevations are presented below. This crossing, therefore, has a possibility of maximum scour over the entire meander belt.

EPNG STATION	TOP OF PIPE BURIAL ELEVATION
719+75	1381
732+00	1383
746+00	1385
753+00	1386
760+00	1387
767+00	1388
773+00	1389
780+00	1390
787+00	1391

Lateral Scour

A lateral scour analysis, based upon use of historic aerial photographs and other site specific information, was then conducted in order to determine the maximum extent of pipe burial depth.

Meander belt width and activity were taken into consideration in the assessment of lateral migration of the alluvial channel. The lateral limits of maximum scour are estimated to occur between engineering stations 719+75 (approximate centerline of a field road) and 787+00.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are outgrowths of this study.

1. General scour depth as computed by HEC-6 for the design event is a maximum of 6.3 feet in the vicinity of pipeline crossing.

2. The local scour was estimated at vary from 5.4 to 6.7 feet, resulting in a total estimated scour depth at the proposed pipeline crossing varying from 8.6 to 14.7 feet. These total scour depths include a safety factor to incorporate the effects of antidunes. Based upon the scour depth, the pipeline should be buried below elevations as presented on page 9.

3. Lateral movement of the channel is anticipated during large flood events. The active meander belt width is approximately 6700 feet and extends from engineering stations 719+75 to 787+00.

4. Construction should begin as soon as possible as there is a greater probability of higher streamflows during thunderstorms in August and September. Ideally, the construction should be completed by 1 July.

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GILA RIVER NEAR KELVIN

100-YEAR FLOOD HYDROGRAPH

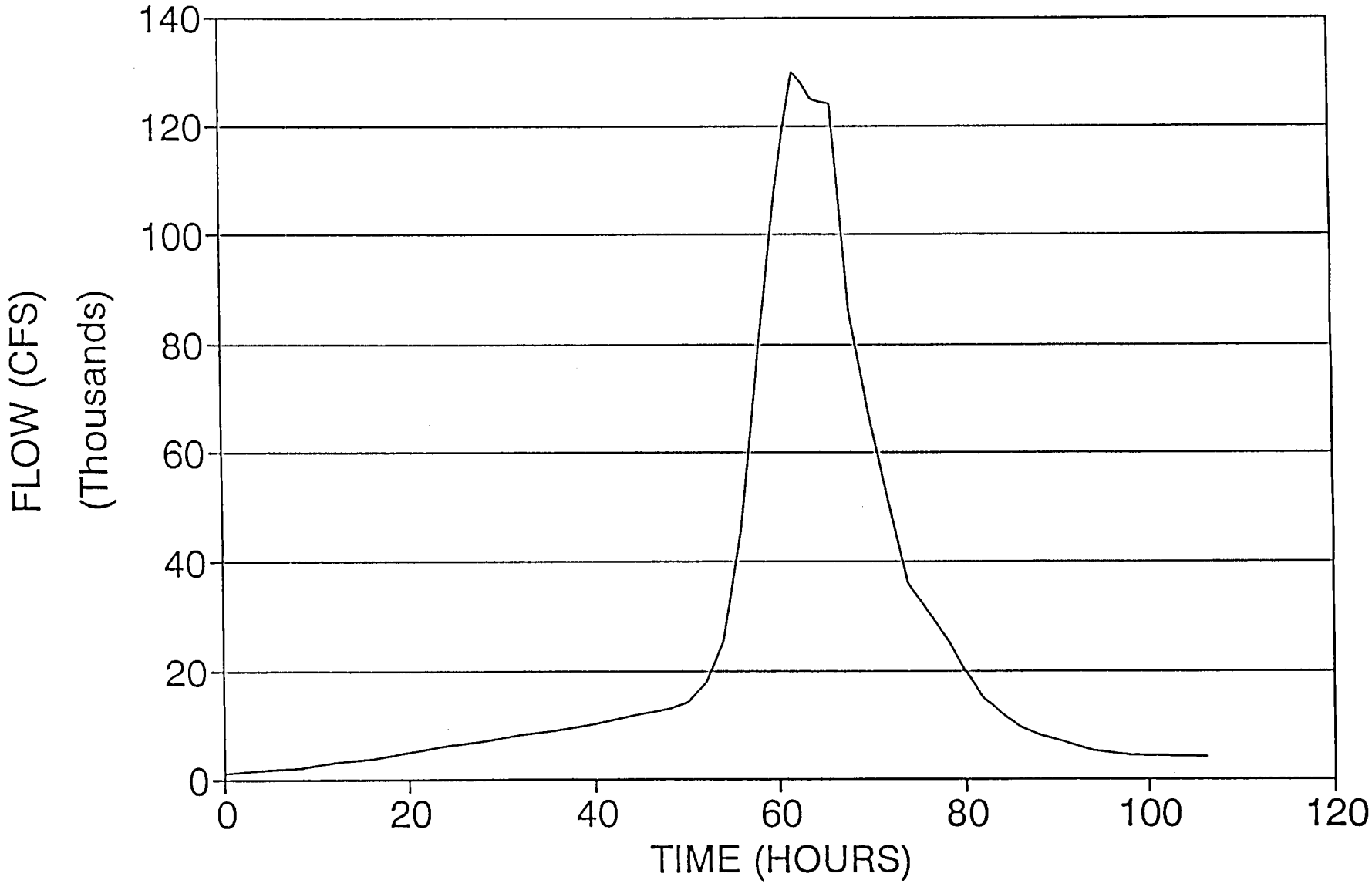
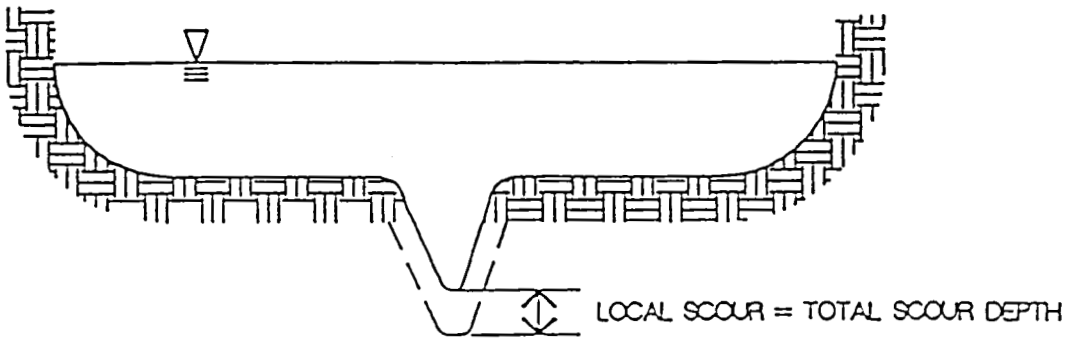


Figure 11. 100-Year Hydrograph

EXAMPLE OF LOCAL SCOUR



EXAMPLE OF GENERAL & LOCAL SCOUR

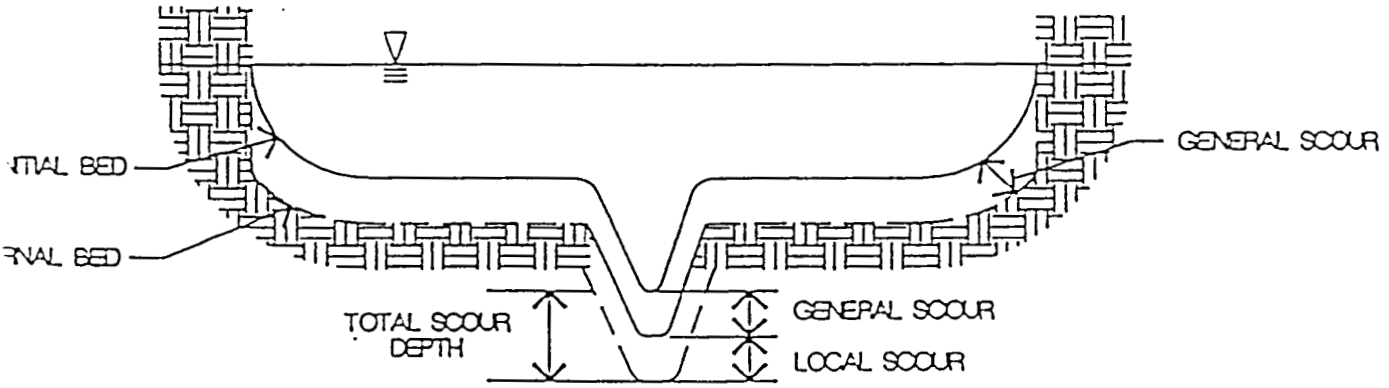


Figure 12 .Examples of Local and General Scour