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SRH-1D 4.0 User's Manual

Sedimentation and River Hydraulics – One Dimension, Version 4.0

US Department of Interior
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14. ABSTRACT

The sediment transport model SRH-1D 4.0 (Sedimentation and River Hydraulics – One Dimension Version 4.0) is documented. The model is for use in alluvial rivers where the one dimension assumption is appropriate. The model can simulate both cohesive and non-cohesive sediment transport using steady or unsteady flow solutions. Simple or complex networks can be simulated as well as a variety of hydraulic structures. The technical background, data requirements, and data formats are detailed.

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SRH-1D 4.0 User's Manual

Sedimentation and River Hydraulics – One Dimension, Version 4.0

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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1 Introduction

1.1 Background

SRH-1D (Sedimentation and River Hydraulics – One Dimension) is a one-dimensional hydraulic and sediment transport model for use in natural rivers and manmade canals. It is a mobile bed model with the ability to simulate steady or unsteady flows, internal boundary conditions, looped river networks, cohesive and non-cohesive sediment transport, and lateral inflows. The Environmental Protection Agency (EPA) and Bureau of Reclamation (Reclamation) were funding partners in the original development of the SRH-1D model.

1.2 SRH-1D Capabilities

SRH-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. Some of the model's capabilities are:

- Computation of water surface profiles in a single channel or multi-channel looped networks.
- Steady and unsteady flows.
- Subcritical flows in a steady hydraulic simulation.
- Subcritical, supercritical, and transcritical flows in an unsteady hydraulic simulation.
- Transport of cohesive and non-cohesive sediments.
- Cohesive sediment aggregation, deposition, erosion, and consolidation.
- Multiple non-cohesive sediment transport equations that are applicable to a wide range of hydraulic and sediment conditions.
- Cross stream variation in hydraulic roughness.
- Fractional sediment transport, bed sorting, and armoring.
- Point and non-point sources of flow and sediments.
- Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates.
- Bedrock control and erosion

1.3 Limits of Application

SRH-1D is a general numerical model developed to simulate and predict cohesive and non-cohesive sediment transport and related river morphological changes due to natural or human influences. SRH-1D is an engineering tool for solving fluvial hydraulic problems with the following limitations:

(1) SRH-1D is a one-dimensional model for flow simulation. It should not be applied to situations where a two-dimensional or three-dimensional model is needed for detailed simulation of local hydraulic conditions. Phenomena such as secondary currents, lateral diffusion, superelevation, and transverse sediment movement are ignored.

(2) Many of the sediment transport modules and concepts used in SRH-1D are simplified approximations of real phenomena. Those approximations and their limits of validity are embedded in the model.

(3) SRH-1D is currently compiled to run on the Windows 7 64-bit operating system.

(4) There are no specific system requirements, but the size of the problem may be limited by the computer memory or operating system limitations.

1.4 Acquiring SRH-1D

The latest information about SRH-1D is placed on the Web and can be found by accessing http://www.usbr.gov/pmts/sediment and following the links on the web page. Requests may be sent directly to the Bureau of Reclamation's Sedimentation and River Hydraulics Group (Attention: SRH Support, U.S. Bureau of Reclamation, Sedimentation and River Hydraulics Group, P.O. Box 25007 (86-68540), Denver, CO 80225).

SRH-1D is under continuous development and improvement. A user is encouraged to check the SRH-1D web page regularly for updates.

1.5 Disclaimer

The program SRH-1D and information in this manual are developed for use at Reclamation. Reclamation does not guarantee the performance of the program, nor help external users solve their problems. Reclamation assumes no responsibility for the correct use of SRH-1D and makes no warranties concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the software or the information contained in this manual. SRH-1D is a program that requires engineering expertise to be used correctly. Like other computer programs, SRH-1D is potentially fallible. All results obtained from the use of the program should be carefully examined by an experienced engineer to determine if they are reasonable and accurate. Reclamation will not be liable for any special, collateral, incidental, or consequential damages in connection with the use of the software.

2 Flow Routing Theory

This chapter describes the theoretical basis for the one-dimensional flow solutions used in SRH-1D. SRH-1D has the capability to solve either the steady or unsteady flow equations. The governing equations for steady flow are presented first, followed by the steady flow numerical methods for a single channel, as well as a channel network. The governing equations of unsteady flows are given next with the numerical solution method for simple and complex river networks. The available boundary conditions are described last.

2.1 Steady Flow Solution

SRH-1D uses the standard step method to solve the energy equation for steady gradually varied flows. Presently, only subcritical and critical flow profiles are calculated when the steady flow option is used.

2.1.1 Governing Equations for a Single River

The energy equation for steady gradually varied flow between downstream cross section 1 and upstream cross section 2 is expressed as:

$$Z_2 + \beta_2 \frac{V_2^2}{2g} - Z_1 - \beta_1 \frac{V_1^2}{2g} = h_f + h_c \tag{2.1}$$

where: Z_1, Z_2 = water surface elevations at cross sections 1 and 2, respectively;

V_1, V_2 = average velocities at cross sections 1 and 2, respectively;

β_1, β_2 = velocity distribution coefficients at cross sections 1 and 2, respectively;

g = gravitational acceleration;

h_f = friction loss between cross sections 1 and 2, and

h_c = contraction or expansion losses between cross sections 1 and 2.

The equation for friction loss is calculated in two ways:

$$h_{fa} = \sqrt{S_{f_1} S_{f_2}} L_{eff} \tag{2.2}$$

$$h_{fb} = \left[\frac{2Q}{(K_1 + K_2)} \right]^2 L_{eff} \tag{2.3}$$

where: S_{f_1}, S_{f_2} = friction slopes at cross sections 1 and 2, respectively;

L_{eff} = effective distance between cross sections;

Q = total flow rate at cross section; and

K_1, K_2 = conveyance at cross sections 1 and 2, respectively.

The actual friction loss used is the minimum of the two:

$$h_f = \min\left(h_{fa}, h_{fb}\right) \tag{2.4}$$

The effective distance between cross sections is:

$$L_{eff} = \sum_{i=1}^{3} \Delta s_i Q_i \Big/ Q \tag{2.5}$$

where the sum is performed over three sub-channels: left overbank, main channel and the right overbank. The other variables are:

Q_i = flow in sub-channel i; and

Δs_i = distance between cross sections along flow path in sub-channel *i.*

For a specific discharge, the conveyance, *K,* is used to determine the friction slope in Eq. (2.3):

$$S_f = \left(\frac{Q}{K}\right)^2 \tag{2.6}$$

where *K* is computed from the Manning's equation:

$$Q = KS_f^{1/2} = \frac{C_m}{n} AR^{2/3} S_f^{1/2} \tag{2.7}$$

where: n = Manning's coefficient;

A = cross-sectional area;

R = hydraulic radius (A/P);

P = wetted perimeter; and

C_m = 1.486 for English units or 1.0 for SI units.

The equation for contraction or expansion losses is expressed as:

$$h_c = C_c \left| \frac{\beta_1 V_1^2}{2g} - \frac{\beta_2 V_2^2}{2g} \right| \tag{2.8}$$

where: C_c = a user defined contraction or expansion coefficient

The expansion coefficient is used when the velocity head at the downstream section 1 is less than that at the upstream section 2. Conversely, the contraction coefficient is used when the velocity head at the downstream section 1 is greater than that at the upstream section 2. This is similar to the way HEC-RAS treats energy loss.

2.1.2 Numerical Method for a Single River

Standard step method is used to solve Eq. (2.1), which can be expressed as:

$$f(Z_2) = Z_2 + \beta_2 \frac{V_2^2}{2g} - Z_1 - \beta_1 \frac{V_1^2}{2g} - h_f - h_c = 0 \tag{2.9}$$

This nonlinear algebraic equation can be solved by the Newton-Raphson iterative method (Jain, 2000). Let Z_2^* be an estimate of Z_2, the Newton-Raphson method gives a better estimate of Z_2 using the following:

$$Z_2' = Z_2^* - \frac{f(Z_2^*)}{f^{'}(Z_2^*)} \tag{2.10}$$

where:

$$f^{'}(Z_2^*) = 1 - \beta_2 \frac{V_2^2}{gR} - \frac{\partial h_f}{\partial Z_2} \tag{2.11}$$

After the first 2 iterations, the derivative in Eq (2.10) is computed by using the previous 2 values of $f(Z_2)$. After the updated Z_2' is found, it is checked to see if the flow at that cross section is supercritical. If it is, then the depth is set to either critical depth or normal depth, depending upon the input given by the user (see Data Group 1 in Chapter 5). The iteration continues until a preset accuracy is obtained. The model automatically switches to a bisection method if the method described above does not reach a convergent solution.

2.1.3 Governing Equations In River Networks

SRH-1D provides solutions to both dendritic networks and looped networks. The method used by SRH-1D for such networks is similar to that found in Chaudhry (1993). However, some modifications were made to handle large numbers of connections within a river network.

The following strategy is used to record the network connection information. River numbering is in ascending order from upstream to downstream. The boundary condition for each river entering a junction is the ID numbers of the other rivers entering that junction. If the flow is into the junction, the ID number is positive and if the flow is out of the junction the ID number is negative. In a looped network where the flow direction is unknown before the numerical simulation, the input flow direction can be assumed by the user. A calculated positive discharge means that the assumed flow direction is correct. A negative discharge indicates a flow direction opposite of that initially assumed.

A numerical solution of flow in a network requires the calculation of both the energy equation and the continuity equation. At each cross section, the flow depth and flow discharge are initially unknown. The energy equation and the continuity equation are written for each cross section as:

$$\begin{aligned} F_i &= Z_{i+1} - Z_i + \frac{1}{2g}\left(\frac{\beta_{i+1}Q_{i+1}\left|Q_{i+1}\right|}{A_{i+1}^2} - \frac{\beta_i Q_i \left|Q_i\right|}{A_i^2}\right) \\ &\quad + h_f + \frac{C_c}{4g}\left(\frac{Q_{i+1}\left|Q_{i+1}\right|}{A_{i+1}^2} + \frac{Q_i\left|Q_i\right|}{A_i^2}\right) = 0 \end{aligned} \tag{2.12}$$

$$G_i = Q_{i+1} - Q_i - Q_{Lat_i} = 0 \tag{2.13}$$

where Q_{Lat_i} = the lateral inflow at the reach between cross sections *i* and *i*+1.

Since *A* and *R* are functions of only water surface elevation Z, the unknowns are water surface elevation and discharge. For a river with *N*+1 cross-sections, there are 2(*N*+1) unknowns, but only 2*N* equations for *N* river reaches. Therefore, two boundary conditions are required for a unique solution of the system and these can be written in a general form as:

$$BU = f(Q_1, Z_1) = 0 \tag{2.14}$$

$$BD = f^{'}(Q_{N+1}, Z_{N+1}) = 0 \tag{2.15}$$

where *f* and *f'* are functions defined by the boundary conditions and *BU* and *BD* signify the upstream and downstream boundary conditions, respectively.

2.1.4 Numerical Method for a Network

2.1.4.1 *Internal sections*

By expanding Eqs. (2.11) to (2.14) in Taylor series, the system of equations become:

$$\begin{bmatrix} \frac{\partial BU}{\partial Z_1} & \frac{\partial BU}{\partial Q_1} & & & & & & & \\ \frac{\partial F_1}{\partial Z_1} & \frac{\partial F_1}{\partial Q_1} & \frac{\partial F_1}{\partial Z_2} & \frac{\partial F_1}{\partial Q_2} & & & & & \\ \frac{\partial G_1}{\partial Z_1} & \frac{\partial G_1}{\partial Q_1} & \frac{\partial G_1}{\partial Z_2} & \frac{\partial G_1}{\partial Q_2} & & & & & \\ & & \vdots & \vdots & \ddots & \vdots & \vdots & & \\ & & & & & \frac{\partial G_N}{\partial Z_N} & \frac{\partial G_N}{\partial Q_N} & \frac{\partial G_N}{\partial Z_{N+1}} & \frac{\partial G_N}{\partial Q_{N+1}} \\ & & & & & \frac{\partial G_N}{\partial Z_N} & \frac{\partial G_N}{\partial Q_N} & \frac{\partial G_N}{\partial Z_{N+1}} & \frac{\partial G_N}{\partial Q_{N+1}} \\ & & & & & & & \frac{\partial BD}{\partial Z_{N+1}} & \frac{\partial BD}{\partial Q_{N+1}} \end{bmatrix} \begin{bmatrix} \Delta Z_1 \\ \Delta Q_1 \\ \Delta Z_2 \\ \vdots \\ \Delta Q_N \\ \Delta Z_{N+1} \\ \Delta Q_{N+1} \end{bmatrix} = - \begin{bmatrix} BU \\ F_1 \\ G_1 \\ \vdots \\ F_N \\ G_N \\ BD \end{bmatrix} \tag{2.16}$$

For a river network, one can add equations to the matrix in Eq. (2.15) for each individual cross section. However, the boundary conditions may contain the river depth or discharge in the connected sections of adjoined rivers. For the energy equation F_i, the four non-zero partial derivatives at the nodes joining rivers are written as:

$$\frac{\partial F_i}{\partial Z_i} = -1 + Q_i^2 \left(\frac{2\beta_i + C_{ci}}{2g} \frac{B_i}{A_i^3} \right) + \frac{\partial h_f}{\partial Z_i} \tag{2.17}$$

$$\frac{\partial F_i}{\partial Q_i} = -2Q_i \frac{2\beta_i + C_{ci}}{4gA_i^2} + \frac{\partial h_f}{\partial Q_i} \tag{2.18}$$

$$\frac{\partial F_i}{\partial Z_{i+1}} = 1 - Q_{i+1}^2 \left(\frac{2\beta_{i+1} - C_{ci}}{2g} \frac{B_{i+1}}{A_{i+1}^3} \right) + \frac{\partial h_f}{\partial Z_{i+1}} \tag{2.19}$$

$$\frac{\partial F_i}{\partial Q_{i+1}} = 2Q \left(\frac{2\beta_{i+1} - C_{ci}}{4gA_{i+1}^2}_{\;i} \right) + \frac{\partial h_f}{\partial Q_{i+1}} \tag{2.20}$$

For the continuity equation G_i, the two non-zero partial derivatives are written as:

$$\frac{\partial G_i}{\partial Q_i} = -1 \tag{2.21}$$

$$\frac{\partial G_i}{\partial Q_{i+1}} = 1 \tag{2.22}$$

2.1.4.2 ***Upstream Boundary Conditions***

For each individual river in a network, one upstream and one downstream boundary condition are required. If the upstream or downstream boundary is a junction, then the ID numbers of the other rivers comprising that junction are entered into the input file. Figure 2.1 illustrates a simple network where one river splits into two.

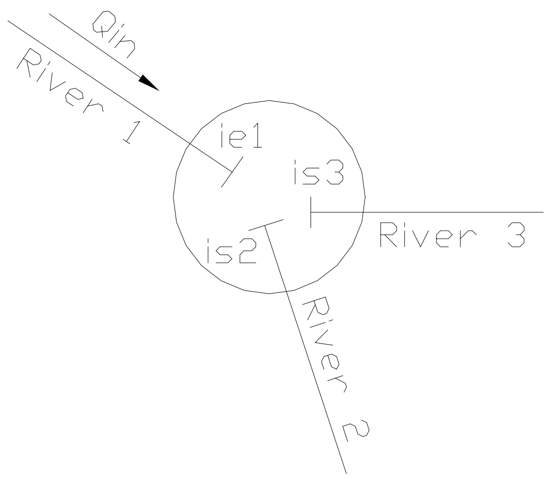

Figure 2.1 Upstream boundaries of River 2 and River 3

River 1 enters into the junction and *ie*1 is the last cross section of River 1. The first cross sections of rivers 2 and 3 are *is*2 and *is*3, respectively. Two equations are necessary to define the flow rates and water surface elevations at the junction. The equations used are the continuity equation and the energy equation, assuming no energy loss. They can be written as:

$$BU_2 = Q_{is2} + Q_{is3} - Q_{in} = 0 \tag{2.23}$$

$$BU_3 = Z_{is3} + \frac{\beta_{is3} Q_{is3}^2}{2gA_{is3}^2} - Z_{is2} - \frac{\beta_{is2} Q_{is2}^2}{2gA_{is2}^2} = 0 \tag{2.24}$$

The non-zero partial derivatives in the matrix are:

$$\frac{\partial BU_2}{\partial Q_{is2}} = \frac{\partial BU_2}{\partial Q_{is3}} = 1 \tag{2.25}$$

$$\frac{\partial BU_3}{\partial Z_{is2}} = -1 + \frac{\beta_{is2} Q_{is2}^2 B_{is2}}{gA_{is2}^3} \tag{2.26}$$

$$\frac{\partial BU_3}{\partial Q_{is2}} = -\frac{\beta_{is2} Q_{is2}}{gA_{is2}^2} \tag{2.27}$$

$$\frac{\partial BU_3}{\partial Z_{is3}} = 1 - \frac{\beta_{is3} Q_{is3}^2 B_{is3}}{g A_{is3}^3} \tag{2.28}$$

$$\frac{\partial BU_3}{\partial Q_{is3}} = \frac{\beta_{is3} Q_{is3}}{g A_{is3}^2} \tag{2.29}$$

If there are other rivers in the network, each river has an additional energy equation for the upstream boundary. For a complex network where the upstream incoming discharge is unknown, the partial derivative of the continuity equation is also a function of the discharge of the upstream river.

2.1.4.3 ***Downstream Boundary Conditions***

For each river in the network, the energy equation is used as the downstream boundary condition:

$$BD = Z_{ie} + \frac{\beta_{ie} Q_{ie}^2}{2 g A_{ie}^2} - Z_{is} - \frac{\beta_{is} Q_{is}^2}{2 g A_{is}^2} = 0 \tag{2.30}$$

where *ie* and *is* denote the cross-sections of the upstream and downstream rivers, respectively, that comprise the junction.

The non-zero partial derivatives in the matrix are:

$$\frac{\partial BD}{\partial Z_{ie}} = 1 - \frac{\beta_{ie} Q_{ie}^2 B_{ie}}{g A_{ie}^3} \tag{2.31}$$

$$\frac{\partial BD}{\partial Q_{ie}} = -\frac{\beta_{ie} Q_{ie}}{g A_{ie}^2} \tag{2.32}$$

$$\frac{\partial BD}{\partial Z_{is}} = -1 + \frac{\beta_{is} Q_{is}^2 B_{is}}{g A_{is}^3} \tag{2.33}$$

$$\frac{\partial BD}{\partial Q_{is}} = -\frac{\beta_{is} Q_{is}}{g A_{is}^2} \tag{2.34}$$

2.2 Unsteady Flow Solution

SRH-1D also has the capability to simulate unsteady flow. The theoretical basis for the unsteady flow solution is described below.

2.2.1 Governing Equations

One-dimensional river flows are described by the conservation of mass equation,

$$\frac{\partial (A + A_d)}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{2.35}$$

and the momentum equation written in divergent form,

$$\frac{\partial Q}{\partial t} + \frac{\partial (\beta Q^2 / A)}{\partial x} + gA\frac{\partial Z}{\partial x} = -gAS_f \tag{2.36}$$

where: Q = discharge (m^3/s),

A = cross section area (m^2),

A_d = ineffective cross section area (m^2),

q_{lat} = lateral inflow per unit length of channel (m^2/s),

t = time independent variable (s),

x = spatial independent variable (m),

g = gravity acceleration (m/s^2),

β = velocity distribution coefficients,

Z = water surface elevation (m),

S_f = energy slope ($=\frac{Q|Q|}{K^2}$), and

K = conveyance (m^3/s).

2.2.2 Numerical Scheme

The numerical scheme used in SRH-1D scheme uses a staggered grid, meaning that the computational points for the flow and area are not coincident, but alternate. The scheme also uses a non-conservative form of the momentum equation. To model transcritical flow, the conservative form of the momentum equations are usually solved (see discussion by Meselhe et al. 2004). However, the advantage of using the non-conservative form of the momentum equations is that mass conservation of flow can easily be ensured. In addition, for complicated natural channels it is analytically and computational difficult to discretize the source terms of the conservative form of the momentum equations to ensure that the scheme preserves a stationary solution (Sanders et al., 2003). That is, it is difficult to discretize the pressure forces of the non-conservative form without inducing artificial flow for cases where the water surface elevation is constant.

The scheme in SRH-1D uses a staggered grid, where the computational points for area, A, are located at the cross section and Q points are located halfway between the cross sections. Figure 2.2 shows a staggered grid with A points placed at the beginning and the end of the domain and known cross sections shown as solid lines.

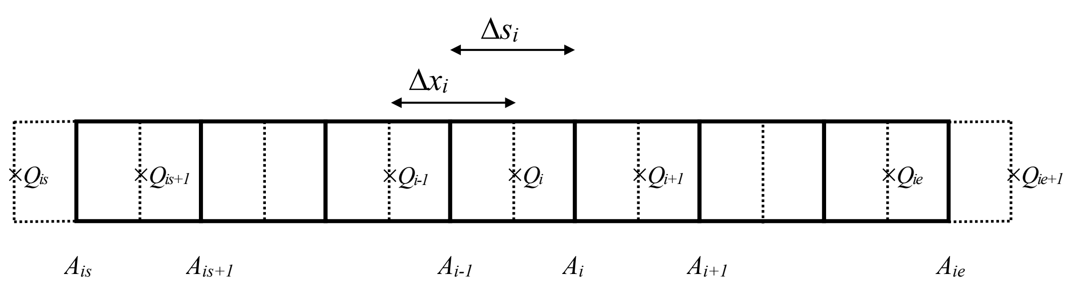

Figure 2.2 Numerical grid used for unsteady flow simulation.

The discretization of the continuity equation is made with one *A*-point and two *Q*-points giving the difference equation:

$$A_i^n + A_{d\,i}^{\;n} - A_i^{n-1} - A_{d\,i}^{\;n-1} = -\frac{\Delta t}{\Delta x_i}(\overline{Q}_{i+1} - \overline{Q}_i) \tag{2.37}$$

where the overbar signifies a time weighted average value with a weighting factor θ in the time dimension. The time weighted discharge, $\overline{Q}_i$, can be written as:

$$\overline{Q}_i = \theta Q_i^n + (1-\theta)Q_i^{n-1} \tag{2.38}$$

and Eq. (2.36) can be written in an iteration form, with *m* signifying the iteration number;

$$\Delta A_i^m = \alpha_i \Delta Q_i^m + \delta_i \Delta Q_{i+1}^m + \gamma_i \tag{2.39}$$

where the coefficients are:

$$\alpha_i = \frac{\theta \Delta t}{\Delta x_i} \tag{2.40}$$

$$\delta_i = -\frac{\theta \Delta t}{\Delta x_i} \tag{2.41}$$

$$\gamma_i = -A_i^n - A_{d\,i}^{\;n} + A_i^{n-1} + A_{d\,i}^{\;n-1} + (\overline{Q}_i - \overline{Q}_{i+1})\frac{\Delta t}{\Delta x_i} \tag{2.42}$$

The discrete form of the momentum equation is made with two *A*-points and three *Q*-points with a weighting factor θ in the time dimension giving the difference equation:

$$Q_i^n - Q_i^{n-1} + \frac{\Delta t}{\Delta s_i}(\overline{F}_{e,i} - \overline{F}_{w,i}) = \Delta t\, g \frac{\overline{A}_i + \overline{A}_{i-1}}{2}\left(\frac{\overline{Z}_i - \overline{Z}_{i-1}}{\Delta s_i} - \overline{S}_{fi}\right) \tag{2.43}$$

The flux term is upwinded using the Froude number as suggested in Catella et al. (2008). The Froude number is computed at the cross section locations using an average of the flow upstream and downstream of the cross section. The momentum flux across the east (*e*) face of the cell is computed as:

$$\overline{F}_{e,i} = \begin{cases} 0.5\beta \dfrac{\left[(1+w_i)\overline{Q}_i + (1-w_i)\overline{Q}_{i+1}\right]^2}{(1-w_i)\overline{A}_i + w_i \overline{A}_{i-1}}, & \overline{Q}_i + \overline{Q}_{i+1} \geq 0 \\ 0.5\beta \dfrac{\left[(1+w_i)\overline{Q}_{i+1} + (1-w_i)\overline{Q}_i\right]^2}{(1-w_i)\overline{A}_i + w_i \overline{A}_{i+1}}, & \overline{Q}_i + \overline{Q}_{i+1} < 0 \end{cases}, \tag{2.44}$$

The weighting factor is computed as:

$$w_i = \min\left(1, F_{r,i}^{\;2}\right) \tag{2.45}$$

where F_r is the Froude number. The west (*w*) face of the cell is simply:

$$\overline{F}_{w,i} = \overline{F}_{e,i-1} \tag{2.46}$$

The friction slope is computed as:

$$S_{fi} = \frac{4\overline{Q}_i \left|\overline{Q}_i\right|}{(\overline{K}_i + \overline{K}_{i-1})^2}$$

Using a weighting factor θ in the time dimension, Eq. (2.39) can be written in iteration form as:

$$\begin{aligned}
&\Delta Q_i^m + \theta \frac{\Delta t}{\Delta x_i} \left(\begin{array}{l} \frac{\partial \overline{F}_e}{\partial Q_i^n} \Delta Q_i^m + \frac{\partial \overline{F}_e}{\partial Q_{i+1}^n} \Delta Q_{i+1}^m + \frac{\partial \overline{F}_e}{\partial A_i^n} \Delta A_i^m \\ - \frac{\partial \overline{F}_w}{\partial Q_i^n} \Delta Q_i^m - \frac{\partial \overline{F}_w}{\partial Q_{i-1}^n} \Delta Q_{i-1}^m - \frac{\partial \overline{F}_w}{\partial A_{i-1}^n} \Delta A_{i-1}^m \end{array} \right) \\
&\quad - \theta \Delta t\, g \frac{\Delta A_i^m + \Delta A_{i-1}^m}{2} \left(\frac{Z_{i-1}^{n+1} - Z_i^{n+1}}{\Delta s_i} - S_{fi}^{n+1} \right) \\
&\quad - \theta \Delta t\, g \frac{\overline{A}_i + \overline{A}_{i-1}}{2} \left(\begin{array}{l} \frac{\Delta A_{i-1}^m}{T_{i-1}^{n+1} \Delta s_i} - \frac{\Delta A_i^m}{T_i^{n+1} \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n} \Delta A_i^m \\ - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n} \Delta A_{i-1}^m - \frac{\partial \overline{S}_{fi}}{\partial Q_i^n} \Delta Q_i^m \end{array} \right) \\
&\quad = -Q_i^n + Q_i^{n-1} - \frac{\Delta t}{\Delta x_i} (\overline{F}_e - \overline{F}_w) + \Delta t\, g \frac{\overline{A}_i + \overline{A}_{i-1}}{2} \left(\frac{\overline{Z}_{i-1} - \overline{Z}_i}{\Delta s_i} - \overline{S}_{fi} \right)
\end{aligned} \tag{2.47}$$

Substituting Eq. (2.38) into Eq. (2.40), results in:

$$a_i \Delta Q_{i-1}^m + b_i \Delta Q_i^m + c_i \Delta Q_{i+1}^m = d_i \tag{2.48}$$

where the coefficients are:

$$\begin{aligned}
a_i &= \theta \frac{\Delta t}{\Delta s_i} \left(- \frac{\partial \overline{F}_w}{\partial Q_{i-1}^n} - \frac{\partial \overline{F}_w}{\partial A_{i-1}^n} \alpha_{i-1} \right) \\
&\quad - \frac{\theta \alpha_{i-1} \Delta t\, g}{2} \left[\frac{Z_{i-1}^{n+1} - Z_i^{n+1}}{\Delta s_i} - S_{fi} + \left(\frac{\overline{A}_i + \overline{A}_{i-1}}{2} \right) \left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n} \right) \right]
\end{aligned} \tag{2.41a}$$

$$\begin{aligned}
b_i &= 1 + \theta \frac{\Delta t}{\Delta s_i} \left(\frac{\partial \overline{F}_e}{\partial Q_i^n} + \frac{\partial \overline{F}_e}{\partial A_i^n} \alpha_i - \frac{\partial \overline{F}_w}{\partial Q_i^n} - \frac{\partial \overline{F}_w}{\partial A_{i-1}^n} \delta_{i-1} \right) \\
&\quad - \theta \frac{\Delta t\, g}{2} (\alpha_i + \delta_{i-1}) \left(\frac{Z_{i-1}^n - Z_i^n}{\Delta s_i} - S_{fi} \right) \\
&\quad - \theta \frac{\Delta t\, g}{2} (\overline{A}_i + \overline{A}_{i-1}) \left[\begin{array}{l} \delta_{i-1} \left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n} \right) + \\ \alpha_i \left(\frac{-1}{T_i^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n} \right) - \frac{\partial \overline{S}_{fi}}{\partial Q_i^n} \end{array} \right]
\end{aligned} \tag{2.41b}$$

$$\begin{aligned}
c_i &= \theta \frac{\Delta t}{\Delta s_i} \left(\frac{\partial \overline{F}_e}{\partial Q_{i+1}^n} + \frac{\partial \overline{F}_e}{\partial A_i^n} \delta_i \right) \\
&\quad - \frac{\theta \delta_i \Delta t\, g}{2} \left[\left(\frac{Z_{i-1}^n - Z_i^n}{\Delta s_i} - S_{fi} \right) + \frac{\overline{A}_i + \overline{A}_{i-1}}{2} \left(\frac{-1}{T_i \Delta s_i} - \frac{\partial S_{fi}}{\partial A_i} \right) \right]
\end{aligned} \tag{2.41c}$$

$$
\begin{aligned}
d_i &= Q_i^{n-1} - Q_i^n \\
&+ \frac{\Delta t}{\Delta s_i}\left(\overline{F}_w - \overline{F}_e - \theta\gamma_i \frac{\partial \overline{F}_e}{\partial A_i^n} + \theta\gamma_{i-1} \frac{\partial \overline{F}_w}{\partial A_{i-1}^n} \right) \\
&+ \frac{\Delta t\, g}{2}\left(\overline{A}_i + \overline{A}_{i-1} + \theta\gamma_i + \theta\gamma_{i-1} \right)\left(\frac{\overline{Z}_{i-1}^n - \overline{Z}_i^n}{\Delta s_i} - \overline{S}_{fi} \right) \\
&+ \frac{\theta\Delta t\, g}{2}\left(\overline{A}_i + \overline{A}_{i-1} \right)\left[\gamma_{i-1}\left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n} \right) + \gamma_i \left(\frac{-1}{T_i^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n} \right) \right]
\end{aligned}
\qquad (2.41d)
$$

where T is the flow top width. For a single channel with $N+1$ cross sections, there are $N+2$ unknowns and N Eqs. (2.41). One upstream and one downstream boundary condition are therefore required.

SRH-1D assumes that subcritical flow occurs at the boundaries of a river and the user must therefore supply both upstream and downstream boundary conditions. Therefore, supercritical flow should not occur at the upstream or downstream boundaries of any river.

A test case was simulated that consisted of an 8 ft wide rectangular channel with 20 ft^3/s of flow and a Manning's roughness coefficient of 0.015. There were 3 reaches. One subcritical reach, followed by a super critical reaches, terminating in a subcritical reach. An analytical water surface was computed using the steady flow energy equation and a momentum balance at the hydraulic jump. SRH-1D simulated the case and the results are shown in Figure 2.3. The hydraulic jump location and height is simulated correctly and there is no mass error introduced by the method (Figure 2.4).

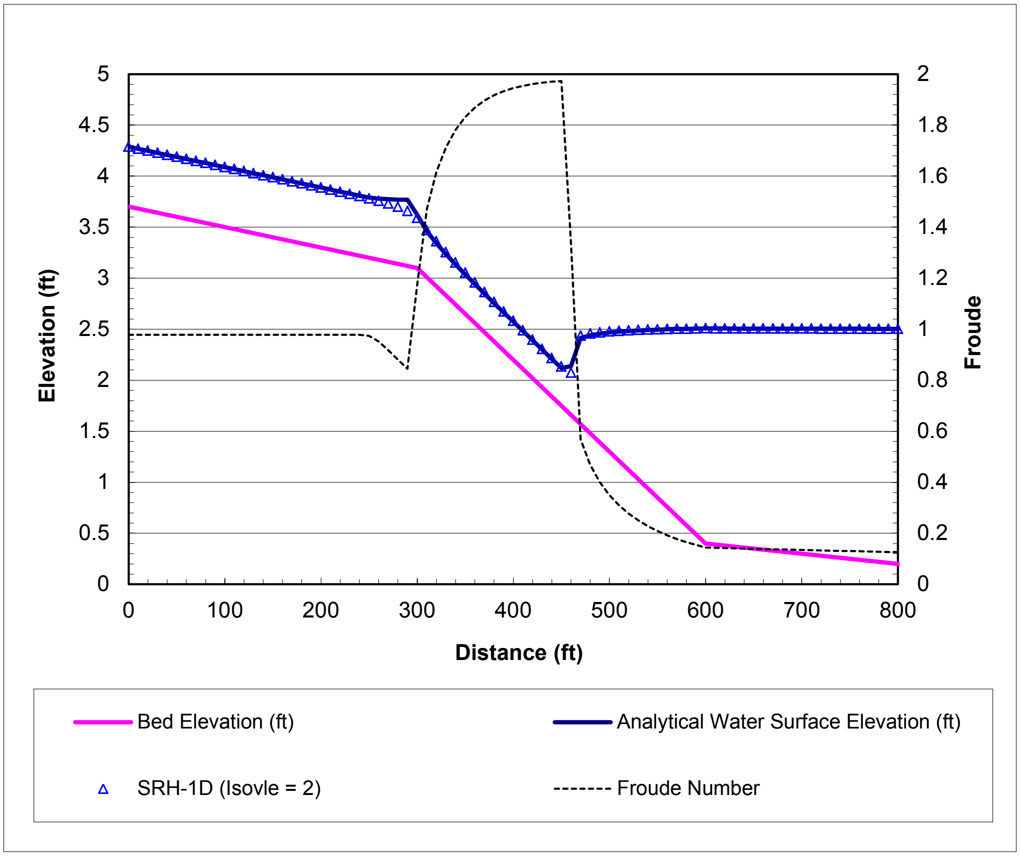

Figure 2.3. Comparison between water surface elevations for unsteady flow solutions in SRH-1D.

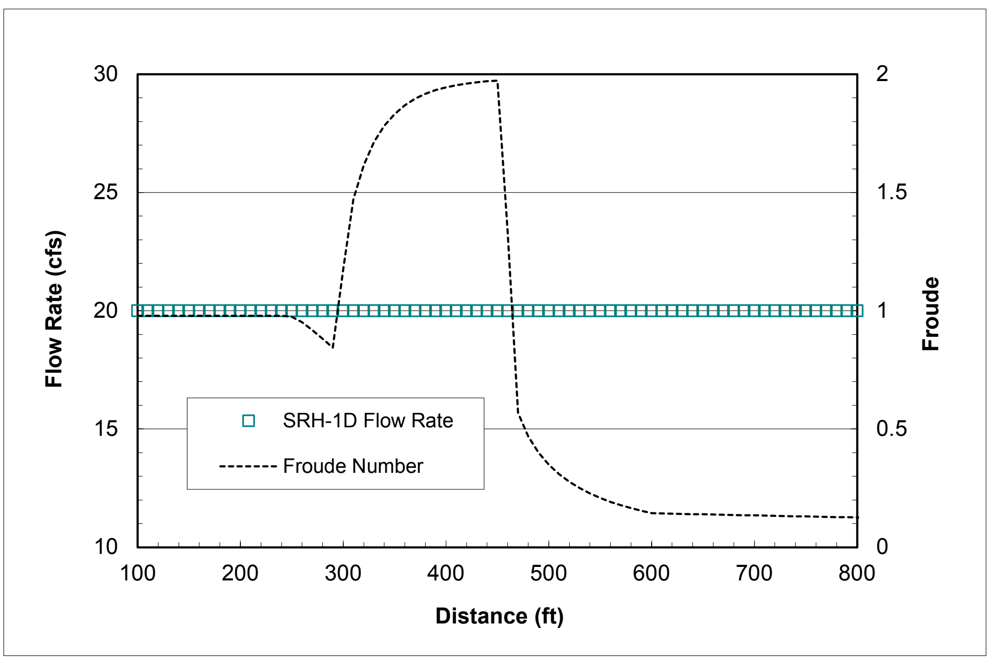

Figure 2.4. Computed flow rate for steady flow supercritical test case.

2.2.3 Upstream Boundary Conditions

Two upstream boundary conditions are available: 1. known water discharge; 2. known water surface elevation

2.2.3.1 *Water Discharge*

The known water discharge boundary condition is summarized as:

$$Q_{is} = f(t) \tag{2.49}$$

where Q_{is} = the discharge at the center of the left fictitious cell (Figure 2.2), i = 1, outside of the model domain. The discretization of the upstream boundary condition written in an iteration form as:

$$\Delta Q_{is} = -Q_{is}^{n} + f(t_{n+1}) \tag{2.50}$$

The above equation can be written in the following form:

$$a_{is}\Delta Q_{is-1}^{m} + b_{is}\Delta Q_{is}^{m} + c_{is}\Delta Q_{is+1}^{m} = d_{is} \tag{2.51}$$

where the coefficients are:

$$a_{is} = 0$$

$$b_{is} = 1$$

$$c_{is} = 0$$

$$d_{is} = f(t) - Q_{is}^{n}$$

These coefficients are used to replace the coefficients defined in Eqs. (2.41a) to (2.41d) at the upstream boundary.

2.2.3.2 *River Stage*

The river stage boundary condition can be written as:

$$H_{is} = f(t) \quad \text{or} \quad A_{is} = f(t) \tag{2.52}$$

The discretized continuity equation (Eq. 2.38) is used to implement this boundary condition:

$$\alpha_{is}\Delta Q_{is}^{m} + \delta_{is}\Delta Q_{is+1}^{m} + \gamma_{is} = \Delta A_{is}^{m} \tag{2.53}$$

where:

$\Delta A_{is}^{m} = A_{is}^{n} - A_{is}^{m-1}$;

A_{is} = the given cross section area defined in Eq. (2.47); and

A_{is}^{m-1} = the estimated cross section area of last iteration.

The above equation can be written in the following form:

$$a_{is}\Delta Q_{is-1}^{m} + b_{is}\Delta Q_{is}^{m} + c_{is}\Delta Q_{is+1}^{m} = d_{is} \tag{2.54}$$

where the coefficients are:

$$a_{is} = 0$$

$$b_{is} = \alpha_{is}$$

$$c_{is} = \delta_{is}$$

$$d_{is} = \Delta A_{is}^{m} - \gamma_{is}$$

These coefficients are used to replace the coefficients defined in Eqs. (2.41a) to (2.41d).

2.2.4 Downstream Boundary Conditions

The downstream boundary conditions can also be grouped into two general types: 1. rating curve (the discharge is a function of the river stage); 2. known water surface elevation.

2.2.4.1 *Rating Curve*

The rating curve boundary conditions can be expressed as:

$$Q_{ie+1} = f(A_{ie}) \tag{2.55}$$

where Q_{ie+1} is the discharge at the center of the right fictitious cell, Q_{ie+1} in Figure 2.2, and A_{ie} is the exit cross section area as defined in Figure 2.2. The discretization of the downstream boundary condition in iteration form is:

$$\Delta Q_{ie+1} = -Q_{ie+1}^{n} + f(A_{ie}^{n}) + \frac{\partial f}{\partial A_{ie}} \Delta A_{ie} \tag{2.56}$$

Expression (2.38) can be used to eliminate the unknown ΔA_{ie} in Eq. (2.51), resulting in the following form:

$$a_{ie+1}\Delta Q_{ie}^{m} + b_{ie+1}\Delta Q_{ie+1}^{m} + c_{ie+1}\Delta Q_{ie+2}^{m} = d_{ie+1} \tag{2.57}$$

where the coefficients are:

$$a_{ie+1} = -\frac{\partial f}{\partial A_{ie}} \alpha_{ie}$$

$$b_{ie+1} = 1 - \frac{\partial f}{\partial A_{ie}} \delta_{ie}$$

$$c_{ie+1} = 0$$

$$d_{ie+1} = f(A_{ie}^{n}) - Q_{ie+1}^{n} + \frac{\partial f}{\partial A_{ie}} \gamma_{ie}$$

These coefficients are used to replace the coefficients defined in Eqs. (2.41a) to (2.41d) for the downstream boundary.

2.2.4.2 ***River Stage***

The given river stage boundary condition can be written as:

$$H_{ie} = f(t) \quad \text{or} \quad A_{ie} = f(t) \tag{2.58}$$

where ie = last cross section. The discretized continuity equation (Eq. 2.38) is used to implement the boundary condition.

$$\alpha_{ie}\Delta Q_{ie}^{m} + \delta_{ie}\Delta Q_{ie+1}^{m} + \gamma_{ie} = \Delta A_{ie}^{m} \tag{2.59}$$

where $\Delta A_{ie}^{m} = A_{ie} - A_{ie}^{m-1}$ and A_{ie} is the given cross section area defined in Eq. (2.53).

The above equation can be written in the following form:

$$a_{ie+1}\Delta Q_{ie}^{m} + b_{ie+1}\Delta Q_{ie+1}^{m} + c_{ie+1}\Delta Q_{ie+2}^{m} = d_{ie+1} \tag{2.60}$$

where the coefficients are:

$$a_{ie+1} = \alpha_{ie}$$

$$b_{ie+1} = \delta_{ie}$$

$$c_{ie+1} = 0$$

$$d_{ie+1} = \Delta A_{ie}^{m} - \gamma_{ie}$$

These coefficients are used to replace the coefficients defined in Eqs. (2.41a) to (2.41d) for the downstream boundary.

2.2.5 Network Boundary Condition

For each river with N cross sections, there are N+1 unknowns of discharge and N-1 equations (Eq. 2.41). Closing the solution system requires equations from boundary conditions. In addition to the upstream and downstream boundary conditions, the junction of the rivers provides the constraints required to solve the continuity and momentum equations.

A general case is discussed here with s rivers entering the junction and t rivers exiting the junction. A total of s+t boundary conditions exist including one continuity equation and s+t-1 momentum equations. No storage is allowed in the junction. The continuity equation is written as:

$$\sum_{l=1}^{s} Q_{l,ie+1}^{m} - \sum_{l=1}^{t} Q_{l,is}^{m} = 0 \tag{2.61}$$

where $Q_{l,ie+1}^{m}$ is the estimated outlet discharge of river l, $Q_{l,is}^{m}$ is the estimated entrance discharge of river l. The correction form of the discharge is written as:

$$\sum_{l=1}^{s} \Delta Q_{l,ie+1}^{m} - \sum_{l=1}^{t} \Delta Q_{l,is}^{m} = 0 \tag{2.62}$$

A simplified momentum equation is introduced at the junction, requiring that all cross sections associated with the junction share the same water level correction.

Assuming river t is the maximum river index of the rivers that exit the junction, the boundary condition for the river l entering the junction is written as:

$$\Delta H^m_{l,ie+1} = \Delta H^m_{t,is} \text{ or } \Delta A^m_{l,ie+1} / T_{l,ie+1} = \Delta A^m_{t,is} / T_{t,is} \quad (2.63)$$

The area correction can be replaced by Eq. (2.49), and Eq. (2.58) can be written as:

$$(\alpha_{l,ie}\Delta Q^m_{l,ie} + \delta_{l,ie}\Delta Q^m_{l,ie+1} + \gamma_{l,ie}) / T_{l,ie} = (\alpha_{t,is}\Delta Q^m_{t,is} + \delta_{t,is}\Delta Q^m_{t,is+1} + \gamma_{t,is}) / T_{t,is} \quad (2.64)$$

The same boundary condition for the river l exiting the junction is written as:

$$(\alpha_{l,is}\Delta Q^m_{l,is} + \delta_{l,is}\Delta Q^m_{l,is+1} + \gamma_{l,is}) / T_{l,is} = (\alpha_{t,is}\Delta Q^m_{t,is} + \delta_{t,is}\Delta Q^m_{t,is+1} + \gamma_{t,is}) / T_{t,is} \quad (2.65)$$

2.3 Structures within the model domain

Hydraulic structures such as dams, bridges, weirs, and gates may exist along a natural river and special treatments are required in the numerical model. For each internal cross sectional structure, two more unknowns are introduced: the discharge Q_i and water surface elevation Z_i at that structure. The conservation of mass serves as one of the equations necessary to solve for the unknowns. The other equation depends upon the particular structure. Structures currently supported by SRH-1D are listed in the following sections. Steady and unsteady flow conditions use the same equations, but the interpolation in time of time series data is handled differently. Internal boundary conditions are interpolated using a step function for steady flow simulations and linearly in time for unsteady flow simulations. Internal structures are assumed to occur between cross sections and are identified by the cross section that occurs immediately upstream.

2.3.1 Governing Equations for Internal Boundaries

2.3.1.1 *Time Stage Table*

For this boundary condition, the user enters a known water surface elevation versus time at a cross section. For example, this boundary condition could represent a pool that is controlled based upon daily operations:

$$H = H(t) \quad (2.66)$$

2.3.1.2 *Elevation versus discharge table*

For this boundary condition, a user inputs a table of water surface elevation versus flow rate. The water surface elevation for each discharge is linearly interpolated between user-entered points. No extrapolation is performed. This boundary condition could represent many different structures that have a unique relationship between flow rate and water surface elevation:

$$H = H(Q) \quad (2.67)$$

2.3.1.3 *Weir*

To simulate weirs in SRH-1D the user enters the spillway crest elevation, the weir width, and the weir coefficient. If the downstream water surface elevation does not affect the upstream water surface elevation, the flow over the weir is considered non-submerged. The submergence parameter, *R*, can be computed as:

$$R = \frac{Z_D - Z_{SP}}{Z_U - Z_{SP}} \tag{2.68}$$

For non-submerged flow past a weir, discharge is expressed as a function of the water surface elevation, *Z*, written as:

$$Q = CB(Z_U - Z_{SP})^{\frac{3}{2}} \quad \text{if} \quad R < 0.67 \tag{2.69}$$

where: C = weir coefficient;

Z_{SP} = elevation of weir crest;

Z_U is the elevation upstream;

Z_D is the elevation downstream; and

B = width of weir crest.

For submerged flow the flow over the weir is computed as:

$$Q = CBF(Z_D - Z_{SP})(Z_U - Z_D)^{\frac{1}{2}} \quad \text{if} \quad R \geq 0.67 \tag{2.70}$$

where *F* is the discharge reduction factor, computed similar to that presented in U.S. Army Corps of Engineers HEC-RAS 4.0 (USACOE, 2008):

$$F = 1 - \left(\frac{R - R_c}{1 - R_c}\right)^5 \tag{2.71}$$

where R_c is equal to 0.67. The function in 2.71 ensures that the submerged and non-submerged results are equivalent at $R = R_c$ and that $F = 0$ at $R = 1$.

2.3.1.4 ***Bridge***

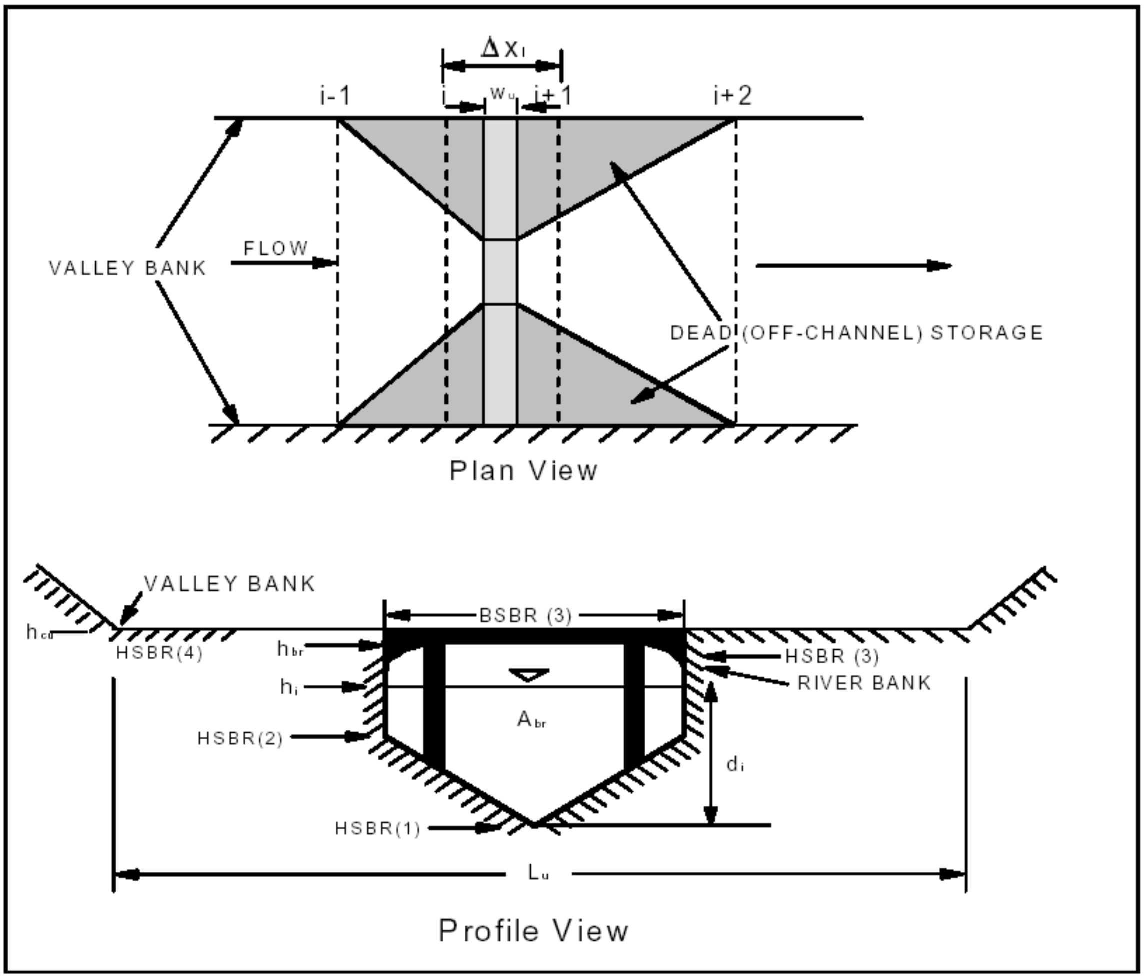

Figure 2.5 Schematic of bridge (Source: Fread and Lewis, 1998)

The present model uses the equations presented in FLDWAV1.0 (Fread and Lewis, 1998) for highway/railway bridges and their associated earthen embankments (as shown in Figure 2.3). The discharge can be expressed as:

$$Q = \sqrt{2\mathrm{g}}CA_{br}(Z_i - Z_{i+1} + V_i^2/2g - \Delta h_f)^{1/2} + cc_u L_u k_u (Z_i - h_{cu})^{3/2} + cc_l L_l k_l (Z_i - h_{cl})^{3/2} \quad (2.72)$$

where:

$$k_u = 1.0 \qquad \text{if} \qquad h_{ru} \le 0.76 \quad (2.73)$$

$$k_u = 1.0 - c_u(h_{ru} - 0.76)^3 \qquad \text{if} \qquad h_{ru} > 0.76 \quad (2.74)$$

$$c_u = 133(h_{ru} - 0.78) + 10 \qquad \text{if} \qquad 0.76 < h_{ru} \le 0.96 \quad (2.75)$$

$$c_u = 400(h_{ru} - 0.96) + 34 \qquad \text{if} \qquad h_{ru} > 0.96 \quad (2.76)$$

$$h_{ru} = (Z_{i+1} - h_{cu})/(Z_i - h_{cu}) \quad (2.77)$$

$$cc_u = 3.02(Z_i - h_{cu})^{0.015} \qquad \text{if} \qquad 0 < h_u \le 0.15 \quad (2.78)$$

$$cc_u = 3.06 + 0.27(h_u - 0.15) \qquad \text{if} \qquad h_u > 0.15 \quad (2.79)$$

$$h_u = (Z_i - h_{cu}) / w_u \quad (2.80)$$

$$\Delta h_f = \Delta x_i (Q_{br} / K_i)^2 \quad (2.81)$$

$$Q_{br} = \sqrt{2g} C A_{br} (Z_i - Z_{i+1} + V_i^2 / 2g)^{1/2} \quad (2.82)$$

$$V = Q_i / A_i \quad (2.83)$$

where: C = bridge coefficient,

A_{br} = cross-section flow area of the downstream end of bridge opening which is user-specified via a tabular relation of wetted top width versus elevation,

h_{cu} = elevation of the upper embankment crest,

Z_i = water surface elevation at section i (slightly upstream of bridge),

Z_{i+1} = water surface elevation at section i+1 (slightly downstream of bridge),

V = velocity of flow within the bridge opening,

L_u = length of the upper embankment crest perpendicular to the flow direction including the length of bridge at elevation h_{cu},

k_u = computed submergence correction factor for flow over the upper embankment crest,

w_u = width (parallel to flow direction) of the crest of the upper embankment, and

d_i = maximum depth of flow under the bridge.

When the bridge opening is submerged, the coefficient C in Eqs. (2.67) and (2.77) is replaced by C' for orifice flow:

$$C' = c_0 C \quad (2.84)$$

where:

$$c_0 = \begin{cases} 1.0 - (r - 0.09) & \text{if } 0.09 \le r \le 0.31 \\ 1.0 & \text{otherwise} \end{cases} \quad (2.85)$$

and:

$$r = (Z_i - h_{br}) / d_i \quad (2.86)$$

2.3.1.5 ***Radial Gate***

For radial gates, SRH-1D uses equations similar to those in HEC-RAS 4.0 (USACOE, 2008). The schematic of radial gate is shown in Figure 2.4. According to the upstream and downstream water surface elevations, the flow can be categorized into three types: free flow, partially submerged flow, and fully submerged flow.

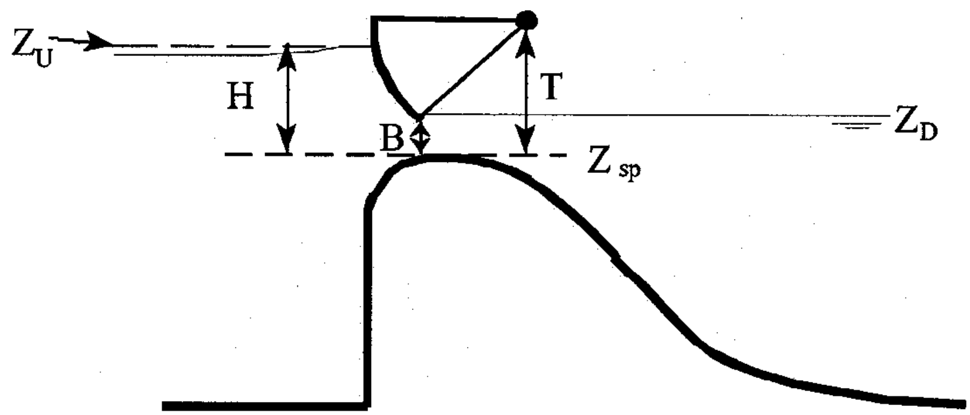

Figure 2.6 Schematic of radial gate (Source: Brunner, 2001).

When the downstream tailwater elevation (Z_D) is not high enough to cause an increase in the upstream headwater elevation, the flow is considered to be "free" flow. The discharge can be expressed as

$$Q = C\sqrt{2g}WT^{TE}B^{BE}H^{HE} \qquad \text{if } \frac{Z_D - Z_{SP}}{Z_U - Z_{SP}} \le 0.67 \tag{2.87}$$

where Q = flow rate (cfs); C = discharge coefficient (typically ranges from 0.6 – 0.8); W = width of the gate (ft); T = trunnion height (ft, from spillway crest to trunnion pivot point); TE = trunnion height exponent (typically about 0.16); B = height of gate opening (ft); BE = gate opening exponent (typically about 0.72); H = upstream energy head above the spillway crest (Z_U-Z_{SP}); HE = head exponent (typically about 0.62); Z_U = elevation of the upstream energy grade line (ft); Z_D = elevation of the downstream water surface (ft); Z_{SP} = elevation of the spillway crest through the gate (ft).

When the downstream tailwater elevation (Z_D) is high enough to cause an increase in the upstream headwater elevation, the flow is considered to be "partially submerged" flow. The discharge can be expressed as

$$Q = C\sqrt{2g}WT^{TE}B^{BE}(3H)^{HE} \quad \text{if } \frac{Z_D - Z_{SP}}{Z_U - Z_{SP}} > 0.67 \tag{2.88}$$

where H = upstream energy head (ft) above the downstream water surface (Z_U-Z_D).

When the discharge is further increased, the gate is "fully submerged" and the discharge can be expressed as

$$Q = CA\sqrt{2gH} \qquad \text{if } \frac{Z_D - Z_{SP}}{Z_U - Z_{SP}} > 0.80 \tag{2.89}$$

where A = area of the gate opening (ft^2); H = upstream energy head (ft) above the downstream water surface (Z_U-Z_D), and C = discharge coefficient (typically 0.8).

2.3.1.6 ***Dam Breach***

Three methods to compute the rate of dam breaching are implemented into SRH-1D: 1. User-specified breaching flow, 2. User specified breaching geometry, and 3. Shear stress methodology. The follow section details the conceptual model and equations that are implemented in SRH-1D.

<u>User-specified breaching flow</u>

In this method, the user enters the time of the initiation of the breach process and the breaching flow. The computation of the time of the breach, the breaching rate, breach geometry, and breaching flow must be done outside of SRH-1D. The reservoir elevation and volume are computed by a mass balance computation. The cross sections through the reservoir area used to compute the reservoir elevation versus volume curve.

<u>User-specified breaching geometry</u>

This method is similar to that implemented into HEC-RAS and is useful for when the breach parameters are computed outside of SRH-1D. For overtopping failure, the flow in the breach is computed as:

$$Q_b = C_d\sqrt{2g}\left[\tfrac{2}{3}b_s(H_t - h_b) + \tfrac{8}{15}z(H_t - h_b)^{2.5}\right] \tag{2.90}$$

where Q_b is the breach outflow, b_s is the base width of the breach opening, H_t = total hydraulic energy head at point upstream of breach, h_b is the base elevation of the breach opening, and z is the side slope of the breach. The coefficient C_d is the discharge coefficient and its value is input by the user. The variables are defined in Figure 2-7. The constants 2/3 and 8/15 are used because those are the coefficients that appear from the integration of the velocity over the depth of flow. The time of breach initiation, the time required for full breach formation (t_b), and the final breach width are entered by the user (B_{final}).

The equation for flow through the piping failure is:

$$Q_b = C_d\sqrt{2g}\left[2b_s(h_p - h_b) + 4z(h_p - h_b)^2\right]\sqrt{H_i - \max(h_b, H_{i+1})} \tag{2.91}$$

where h_p is the elevation at the middle of the piping failure. If a piping failure model is specified, the equation for piping is used as long as the following criterion is met:

$$\frac{h_i - h_p}{h_p - h_b} > 2 \tag{2.92}$$

When the left hand side is less than 2, the breach flow equations are then used. At the transition between piping and breach flow, the flow is interpolated between the piping and breaching algorithms.

It is suggested that the relationship from Froehlich (2016) be used to compute the final breach width (B_{final}), the breach side slope (z), and time required for full breach formation (t_b). Froehlich estimated the final average breach width (b_{ave}), rather than the final breach base width (b_s). The relationship between b_{ave} and b_s is:

$$b_s = 2(b_{ave} - zh_d) \tag{2.93}$$

where h_d is the height of the dam relative to the final bottom of the breach. Other than the relatively simple expressions for breach width and timing, another advantage for using this approach is that uncertainty bounds of the model parameters has been computed in Froehlich (2016). The prediction intervals of each parameter are given in Froehlich (2016).

The rate of breach formation can be assumed to be constant in time or vary according to a sinusoidal function with the breach width defined by:

$$b_s = b_{s,final} \sin\left(\frac{\pi t}{2t_b}\right) \tag{2.94}$$

where t is the time since the start of the breach.

The flow over the dam is computed using a broad crested weir equation as:

$$Q_b = C_d\sqrt{2g}\frac{2}{3}A_b^{\ 1.5}T_b^{\ -0.5} \tag{2.95}$$

where A_b is the area of the breach and T_b is the top width of the breach.

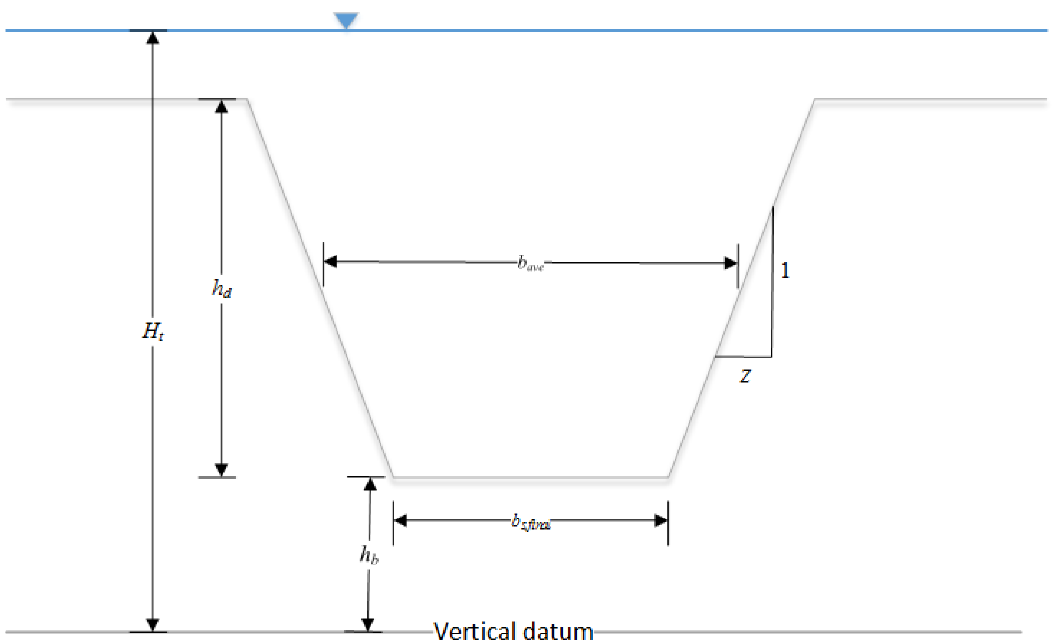

Figure 2-7. Definition of model variables in dam breaching simulation.

<u>Shear Stress Based Methodology</u>

A modified version of the WinDAM methodology is also implemented into SRH-1D. The dam is assumed to be between an upstream and downstream section and will be idealized as being comprised of a spillway section and dam section. In this implementation, only the dam section can be breached and the current methodology only simulates overtopping failure modes, not piping.

In the proposed methodology, the program relies upon the user input to determine the moment the breach will begin. The user can set the breach to begin at a specific time, or set the breach to begin when a specific water surface or discharge per unit with over the dam is exceeded. This is because the specific calculation of the onset of breach would be more simply computed outside the SRH-1D then within the model.

The idealized dam section is given in Figure 2-8, with the associated variables that will be used in the description of the methodology.

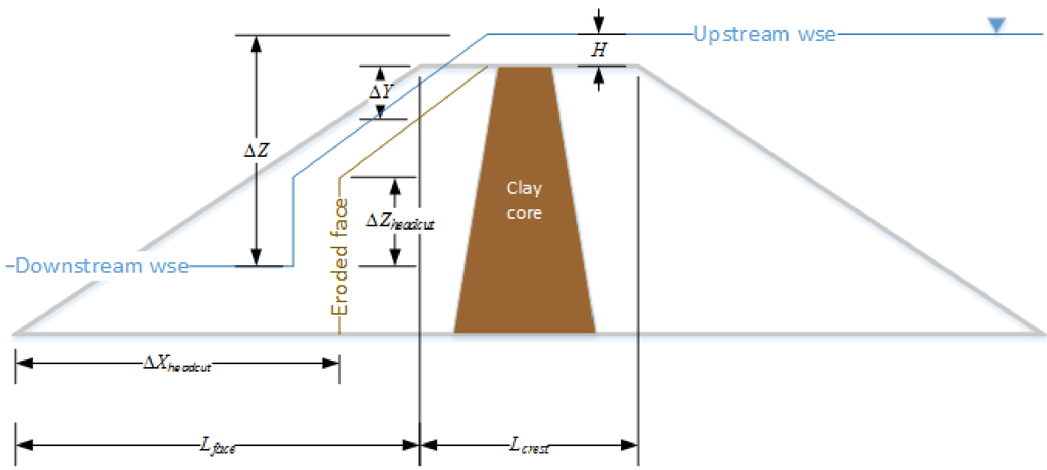

Figure 2-8. Idealized dam section used in dam breach computations.

Two basic modes of erosion are simulated: vertical erosion through the dam face that occurs uniformly along the dam face, and headcut erosion that begins on the downstream end of the dam and progresses upstream through the dam.

The vertical erosion (ΔY) is assumed to occur within a user defined initial channel along the dam face. The user enters an over topping width versus elevation table that is used to represent the initial incisional channel over the dam. The detachment rate (ε_r) is taken as representing the rate of downward erosion of this channel (dY/dt) and is computed by:

$$\frac{dY}{dt} = \varepsilon_r = k_d(\tau_e - \tau_c) \tag{2.96}$$

where ε_r = soil detachment rate in volume per unit area per time (ft/s or m/s)

k_d = a detachment rate coefficient (ft^3/lb/s or m^3/N/s)

τ_e = applied shear stress (lb/ft^2 or N/m^2)

τ_c = critical applied shear stress (lb/ft^2 or N/m^2)

The rate of progression due to vertical erosion is assumed to be uniform across the downstream face of the dam. In recognition of the fact that the actual geometry in the area of the base is complex, no additional adjustment in rate is made for the embankment slope. The average applied shear stress, τ_e, is computed from:

$$\tau_e = \gamma R S_f \tag{2.97}$$

where S_f is the average friction slope across the dam, $S_f = \Delta Z / (L_{face} + L_{crest})$. The hydraulic radius is computed from the Manning's equation. The rate of horizontal retreat can be estimated from the vertical erosion rate multiplied by the downstream face slope. Notice that once the eroded face reaches the upstream side of the dam, the breach area will increase rapidly.

If the embankment is non-cohesive, the median diameter is entered and the Meyer-Peter-Muller formula (Meyer-Peter and Müller, 1947) as modified by Wong and Parker (2006) is used to compute the sediment transport rate.

A headcut process is implemented into the breach model, by assuming that the rate of horizontal progression of the headcut through the embankment is:

$$\frac{\mathrm{dX}_{headcut}}{dt} = C[qh - (qh)_{crit}]^{1/3} \tag{2.98}$$

with C ($s^{-2/3}$) and $(qh)_{crit}$ being user defined coefficients. However, simulations to-date do not indicate that this mechanism is important in the accurate prediction of breach outflow and this will be discussed in the comparison with experiments.

If a zoned embankment is simulated, then the properties for the embankment are entered separately from the clay core. Once the horizontal erosion of the embankment approaches the clay or impervious core, then the erosive properties of the clay core are used instead of the embankment material.

The rate of breach widening is assumed proportional to the rate of incision.

$$\frac{\mathrm{dW}}{dt} = C_w \frac{\mathrm{dY}}{dt} = C_w \varepsilon_r \tag{2.99}$$

where C_w = user input coefficient, which is assumed to be 1.4 in the WinDAM program.

The current model is applicable to zoned embankments with a single impervious core, represented by a cross-section having a fore-slope, level crest section, and a back-slope. The cross section is assumed to be constant from one end of the dam to the other. For purposes of the model computations, the elevation of the base of the dam is assumed constant and level implying an approximation of a rectangular valley cross section. The boundaries of this rectangular section are treated as non-erodible.

2.3.2 Internal Structure Implementation for Steady Flows

For an internal boundary, the mass conservation equation is the same as equation (2.12) and the energy equation (2.11) is replaced by the appropriate internal boundary condition. The water surface elevation upstream of the internal boundary is solved using the flow rate computed from the mass conservation equation.

The equation for an internal boundary can be written as:

$$F_i(Y_i, Q_i, Y_{i+1}, Q_{i+1}) = 0 \tag{2.100}$$

This equation is used to replace the energy equation (Eq. 2.11). The derivatives $\frac{\partial F_i}{\partial Z_i}$, $\frac{\partial F_i}{\partial Q_i}$, $\frac{\partial F_i}{\partial Z_{i+1}}$, and $\frac{\partial F_i}{\partial Q_{i+1}}$ are calculated and substituted into Eq. (2.15).

2.3.3 Internal Structure Implementation for Unsteady Flows

All internal boundary conditions can be summarized as:

$$Q_i = f(A_{i-1}, A_i) \tag{2.101}$$

where A_{i-1} and A_i are the cross section areas before and after the internal boundary, respectively. The discretized form of the internal boundary condition written in iteration form is:

$$\Delta Q_i = -Q_i^n + f(A_{i-1}^n, A_i^n) + \frac{\partial f}{\partial A_{i-1}} \Delta A_{i-1} + \frac{\partial f}{\partial A_i} \Delta A_i \tag{2.102}$$

Expression (2.38) can be used to eliminate unknowns ΔA_{i-1} and ΔA_i in Eq. (2.87), which results in the following form:

$$a_i \Delta Q_{i-1}^m + b_i \Delta Q_i^m + c_i \Delta Q_{i+1}^m = d_i \tag{2.103}$$

where the coefficients are:

$$a_i = -\frac{\partial f}{\partial A_{i-1}} \alpha_{i-1}$$

$$b_i = 1 - \frac{\partial f}{\partial A_{i-1}} \delta_{i-1} - \frac{\partial f}{\partial A_i} \alpha_i$$

$$c_i = -\frac{\partial f}{\partial A_i} \delta_i$$

$$d_i = f(A_{i-1}^n, A_i^n) - Q_i^n + \frac{\partial f}{\partial A_{i-1}} \gamma_{i-1} + \frac{\partial f}{\partial A_i} \gamma_i$$

These coefficients are used to replace the coefficients defined in Eqs. (2.41a) to (2.41d).

3 Sediment Transport

This chapter describes the methods used to perform the sediment transport calculations. SRH-1D simulates the physical processes important to both cohesive and non-cohesive sediment transport. There are three major components of sediment transport within SRH-1D:

1. Sediment Routing
2. Bed Material Mixing
3. Cohesive Sediment Consolidation

Sediment routing is the simulation of the downstream movement of sediment in the river flow. Bed material mixing processes include bed material sorting and armoring. Consolidation is compaction of cohesive sediment over time. The modeling of each of these components is described in the following sections.

3.1 Sediment Routing

There are two sediment routing methods available in SRH-1D: unsteady sediment routing and Exner equation routing. The unsteady sediment routing computes the changes to the suspended sediment concentration with time. The Exner equation routing ignores changes to the suspended sediment concentration over time. Unsteady sediment routing can be used when unsteady flow is being simulated and suspended concentrations change rapidly. In most other cases, Exner equation routing can be used.

3.1.1 Exner Equation Routing

The Exner equation (Exner, 1920; 1925) was derived assuming that changes to the volume of sediment in suspension are much smaller than the changes to the volume of sediment in the bed, which is generally true for long-term simulations where steady flow is being simulated. The mass conservation equation for sediment reduces to,

$$\frac{\partial Q_s}{\partial x} + \varepsilon \frac{\partial A_d}{\partial t} - q_s = 0 \tag{3.1}$$

where ε = volume of sediment in a unit bed layer volume (one minus porosity); A_d = volume of bed sediment per unit length; Q_s = volumetric sediment discharge; and q_s = lateral sediment inflow per unit length. Integrating (3.1) over a control volume centered on each cross section gives an equation for the deposition depth (ΔZ_b) for a single sediment size fraction at a particular cross section, i:

$$\varepsilon_i W_i \Delta x_i \Delta Z_{b,i} = q_{s,i} \Delta x_i \Delta t + \left(Q_{s,i-1} - Q_{s,i}\right)\Delta t \tag{3.2}$$

where W is the width of the cross section subject to erosion or deposition. The erosion volumes for each size fraction are summed to compute the total erosion or deposition for a particular cross section. The lateral inflows are user defined and the erosion width is computed based upon the hydraulic calculations. The only unknowns remaining are the sediment transport rates. The sediment transport rate (Q_s) can also be written as QC, where C is the computed discharge weighted average sediment concentration. The following sections describe the numerical solution for sediment concentration for the cases of non-cohesive sediment, floodplain routing, and cohesive sediment.

3.1.1.1 ***Non-Cohesive Sediment Routing***

If the cross sections are far apart relative to the change in sediment transport capacity, it is acceptable to assume that the bed-material load discharge equals the sediment transport capacity of the flow; i.e., the bed-material load is transported in an equilibrium mode ($Q_s = Q_{cap}$, where Q_{cap} is the transport capacity). In other words, the exchange of sediment between the bed and the fractions in transport is instantaneous. However, the spatial-delay and/or time-delay effects are important in circumstances where there are rapid hydraulic changes in short reaches. For example, reservoir sedimentation processes are non-equilibrium processes. In addition, some laboratory studies have shown that it may take a significant distance for clear water inflow to reach saturation sediment concentrations. To take these effects into consideration, SRH-1D starts with the analytical solution to the following equation:

$$\frac{dQ_s}{dx} = Q\frac{dC}{dx} = \left(V_e - V_d C\right)W \tag{3.3}$$

where Q_s = sediment transport rate, C = flow weighted concentration = Q_s/Q, V_e = erosion velocity, and V_d = deposition velocity. The analytical solution to the above equation between two cross sections, say i and i-1, is:

$$C_i = C_i^* + (C_{i-1} - C_i^*)\exp\left\{-\frac{V_{di}W_i\Delta x}{Q_i}\right\} \tag{3.4}$$

where $C_i^* = V_{ei}/V_{di}$ and is the computed sediment transport capacity concentration; Δx = reach length; and i = cross-section index (increasing from upstream to downstream). Eq. (3.4) is employed for each of the particle size fractions in the non-cohesive range. The erosion and deposition velocity for non-cohesive sediment are given as:

$$V_e = Q_{tot}^*/\left(WL_{tot}\right) \quad \text{and} \quad V_d = Q/\left(WL_{tot}\right) \tag{3.5}$$

where L_{tot} is the adaptation length for total load, and Q_{tot}^* = total sediment transport capacity. The adaptation length for total load is computed as (Greimann et al. 2008):

$$L_{tot} = f_s L_b + \left(1 - f_s\right)\frac{Q}{\alpha W w_f} \tag{3.6}$$

where L_b is the adaptation length for bed load, and α is a suspended sediment recovery factor and the parameter f_s is the fraction of suspended load relative to the total load.

The concept of the adaptation length for bed load, L_b, is taken from Holly and Rahuel (1990). It is a dimensional value that is usually on the order of large bed features, such as bars or channel width. It is assumed proportional to the average depth of water at the cross section; a user enters the constant of proportionality as:

$$L_b = b_L h \tag{3.7}$$

where b_L is a user defined non-dimensional coefficient and h is the average depth at the cross section.

The fraction of suspended load, f_s, was found to be primarily a function of the suspension parameter, Z. Greimann et al. (2008) derived the following empirical function for f_s:

$$f_s = \min\left(1, 2.5e^{-z}\right) \tag{3.8}$$

The parameters α and L_b control the rate at which the sediment concentration approaches the sediment carrying capacity. Higher values of α or lower values of L_b indicate that the concentration reaches the carrying capacity more quickly. While some have used constants for α (Han and He, 1990), Galappatti and Vreugdenhil (1985) and Armanini and Di Silvio (1988) suggest that α is dependent upon the ratio of fall velocity to shear velocity and the relative roughness height. SRH-1D assumes that α is a constant but separate values for α are used for deposition versus erosion and the program automatically chooses the correct one. Han and He (1990) recommend a value of 0.25 for deposition and 1.0 for erosion. The asymptotic behavior of Eq. (3.4) with increasing particle size is shown in Figure 3.1. One can see that as d (or ω_f) becomes larger $C_i \rightarrow C_i^*$.

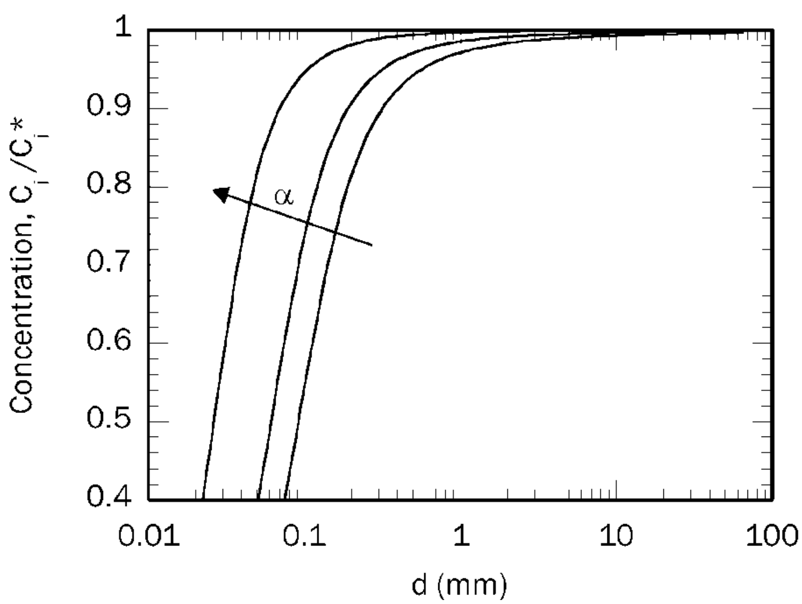

Figure 3.1 Ratio between non-equilibrium concentration and carrying capacity as a function of sediment particle size (from Yang and Simões, 2002).

The influence of the recovery parameter α is illustrated in Figure 3.2. The depositional case represents a situation in which there is a sudden loss of carrying capacity ($C_i^* = 0$) from an upstream equilibrium condition ($C_{i-1} = C_{i-1}^*$). The plot shows the actual normalized concentration for two sizes of the sediment particles. It is clear that the non-equilibrium effect is stronger on the finer particles, and that it diminishes as α increases. The erosional case represents a sudden increase in carrying capacity, such as when clear water enters a channel with an erodible bed. In this case, $C_{i-1} = C_{i-1}^* = 0$ and $C_i^* > 0$. The same trend occurs as before, i.e., the non-equilibrium effects tend to diminish with increasing particle sizes and recovery factor.

The distance between computational cross sections, Δx, is another important factor in non-equilibrium calculations. Figure 3.3 shows how the non-equilibrium effects vary with distance for the same situations and particle sizes in Figure 3.2. In practice, the values of α vary widely. If data are available, α may be a calibration parameter.

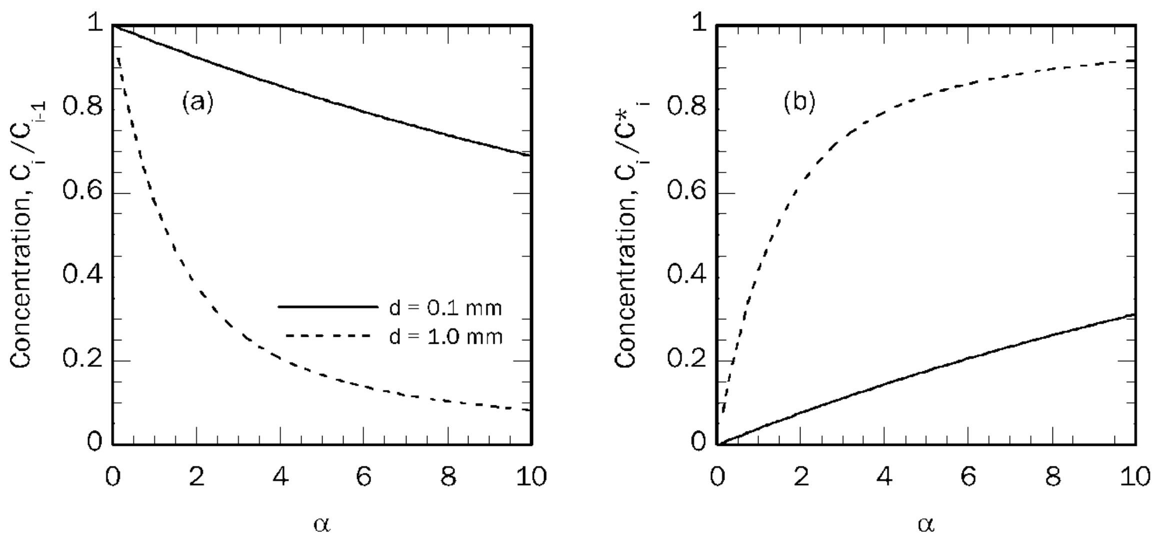

Figure 3.2 Effect of the recovery parameter α on the computation of non-equilibrium sediment concentrations for two sediment particle sizes. (a) deposition and (b) erosion (from Yang and Simões, 2002).

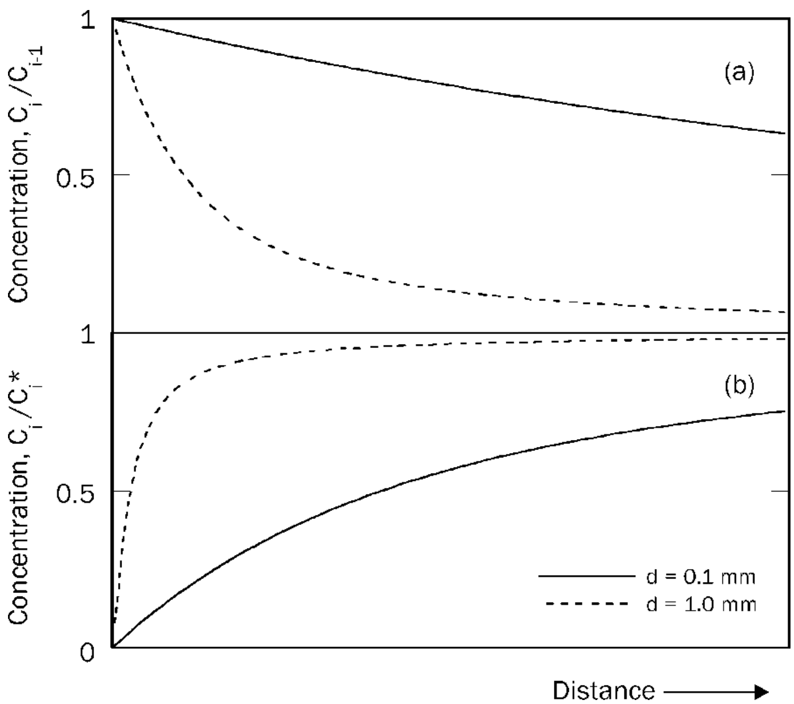

Figure 3.3 Variation of non-equilibrium effects as a function of distance between cross sections for deposition (a) and for erosion (b) (from Yang and Simões, 2002).

3.1.1.2 ***Cohesive Sediment***

SRH-1D defines cohesive sediment as sediment with a diameter smaller than 0.0625 mm (this value can also be modified by the user if necessary). For cohesive sediment, the capacity concentration, C^*, is not needed because the capacity concentration is controlled by the erosion or deposition rate occurring in the river. In SRH-1D, the erosion of fine cohesive sediment is prevented if the volumetric concentration in the stream exceeds a user specified "saturated" volumetric fraction (the default value is 0.15).

The steady sediment transport equation for cohesive sediment is written as

$$\frac{dQ_s}{dx} = (V_e - V_d C)W + \frac{dQ}{dx}\tilde{C} \tag{3.9}$$

where V_e and V_d = cohesive sediment erosion and deposition velocities, respectively; C = cohesive sediment volumetric concentration. The computation of the erosional and depositional velocities is given in Sections 3.1.5 to 3.1.7. If the erosion velocity is zero, and the deposition velocity is greater than zero, the solution to (3.18) is given as:

$$C_i = C_{i-1} \exp\left(-\frac{V_d W \Delta x}{Q}\right) + \frac{\Delta Q}{Q}\tilde{C} \tag{3.10}$$

If the deposition velocity is zero and the erosion velocity is greater than zero, the solution to (3.18) is given as:

$$C_i = C_{i-1} + \frac{V_e W \Delta x}{Q} + \frac{\Delta Q}{Q}\widetilde{C} \tag{3.11}$$

3.1.2 Unsteady Sediment Transport

When simulating unsteady flow or sediment transport, the changes in suspended concentration with time may be important. To compute the changes in suspended sediment concentration, the convection-diffusion equation with a source term for sediment erosion/deposition is used. The 1D depth-averaged convection-diffusion equation for a particular sediment size class is:

$$\frac{\partial Ac}{\partial t} + \frac{\partial \xi Qc}{\partial x} = \frac{\partial}{\partial x}\left(fD_x A \frac{\partial c}{\partial x}\right) + \Omega \tag{3.12}$$

where c = cross section averaged concentration; A = cross section area, Q = flow rate; and D_x = streamwise diffusion coefficient. The parameter, ξ, is the velocity of sediment relative to the water. The source term, Ω, is the erosion or deposition for one sediment constituent and can be written as:

$$\Omega = \left(V_e - \xi V_d c\right)W \tag{3.13}$$

where V_e, V_d = erosion and deposition velocities, respectively. The erosion and deposition velocities have already been defined in previous sections.

SRH-1D uses the expressions developed in Greimann et al. (2008) for ξ. The expression for bed load is:

$$\xi_{bed} = \frac{u_*}{U}\frac{1.1\phi^{0.17}\left[1-\exp(-5\phi)\right]}{\sqrt{\theta_r}} \tag{3.14}$$

where u_* is shear velocity; U is cross-sectional velocity; and $\phi = \min\left(20, \theta/\theta_r\right)$; θ and θ_r are Shields parameter and reference Shields parameter (assumed to be 0.035, or taken from user input), respectively. The expression for suspended load is:

$$\xi_{sus} = 1 + \frac{u_*}{2\kappa U}\left[1-\exp\left(2.7Z\right)\right] \tag{3.15}$$

where $Z = \min\left(1, w_f/(\kappa u_*)\right)$ is the suspension parameter; w_f is the sediment fall velocity; and κ =Von Karman constant (= 0.4). The limit of $Z < 1.0$ is imposed because the Rouse profile is not valid near the bed due to particle inertia effects (Greimann et al., 1999). It should be noted there is a discontinuity in sediment velocity between bedload and suspended load using Eq (3.14) and (3.15). To remedy this situation, the total relative velocity is computed as,

$$\xi = \max\left(\xi_{sus}, \xi_{bed}\right) \tag{3.16}$$

This ensures that the sediment velocity is a continuous function as it transitions from bed load to suspended load.

The diffusion coefficient is computed as in Fischer et al. (1979),

$$D = K_x \frac{W^2 U^2}{H u_*} \tag{3.17}$$

where H is the average cross sectional depth, W is channel top width, U is cross-sectional velocity, u_* is shear velocity, and K_x is a user specified value. Fischer et al. recommends 0.011.

The differential equation is transformed to an integral equation to explicitly conserve mass.

$$\frac{\partial}{\partial t}\int_x cAdx + \sum_f (\xi Qc) = \sum_f (fDA\nabla c) + \int_x \Omega dx \tag{3.18}$$

where the Σ_f indicates a sum over cell boundaries, where flows or gradients out of the control volume are defined as positive and into the control volume are defined as negative.

The stream is discretized into cells centered on the cross sections. The integral equation (3.18) is solved for each cell by calculating the coefficients for the general discrete approximation of the integral equation:

$$A_P C_P + \sum A_L C_L = R_P \tag{3.19}$$

where the sum is over the surrounding cells. The following sections discuss the discretization of the terms in Eq. (3.18).

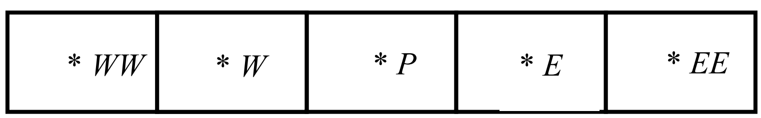

Figure 3.4 Grid Definition for Unsteady Sediment Simulation.

3.1.2.1 ***Unsteady Term***

The unsteady term requires integration over the CS area. The implicit Euler method is applied for time marching. The unsteady term is approximated by the product of CS area and the c value at the CS center,

$$\frac{\partial}{\partial t}\int_x cAdx = \frac{\Delta c_P}{\Delta t} A_P \Delta x_P \tag{3.20}$$

where $\Delta c_P = c_P^n - c_P^{n-1}$, and Δx_P is the length of the grid cell P. the superscripts n-1 and n denote the previous and current time steps, respectively. The unsteady term contributions to the coefficients in Eq. (3.19) and can be written as:

$$A_P \,|_U = \frac{A_P \Delta x_P}{\Delta t} \tag{3.21}$$

where the subscript U indicates the contribution of the unsteady term to the A_p coefficient; Δt = time step.

3.1.2.2 *Convective Term*

The Lax-Wendroff TVD (Total Variation Diminishing) Method is used to discretize the convective term. The original Lax-Wendroff Method is a second-order accuracy scheme. However, numerical results oscillate on discontinuities. The Lax-Wendroff TVD Method suppresses the correction term in Lax-Wendroff Method when discontinuities appear. The TVD scheme remains second-order accurate for smooth regions but becomes a first order scheme near discontinuities to avoid oscillations. Details of Lax-Wendroff TVD Method are discussed in Tannehill et al. (1997).

Approximations of the convective term involve values of variables at the CL centers:

$$\sum_f (\xi Qc) = (\xi Qc)_e - (\xi Qc)_w \tag{3.22}$$

where e denotes the face between P and E. Using the Lax-Wendroff TVD method, F_e^* can be expressed as

$$(\xi Qc)_e = \frac{1}{2}\left[(\xi Q)_e (c_P + c_E) - W_e (c_E - c_P)\right] \tag{3.23}$$

where

$$W_e = \left|(\xi Q)_e\right| \left[(1-\psi) + \psi c_r \left|(\xi Q)_e\right|\right]$$

where $c_r = \dfrac{(\xi Q)_e \Delta t}{A_P \Delta x_P}$ and ψ is the flux limiter computed as,

$$\psi = \max\left[0, \min\left(2, 2r, (1+r)/2\right)\right], \; r = \frac{c_E - c_P}{c_{i1} - c_{i2}} \tag{3.24}$$

with $i_1 = P$ and $i_2 = W$ if Q_e is positive and $i_1 = EE$ and $i_2 = E$ if Q_e is negative. Eq. (3.29) is van Leer's MUSCL flux limiter (van Leer, 1979). If $\psi = 1$ then the 2nd order accurate Lax-Wendroff scheme is obtained. If $\psi = 0$ then the scheme is a first order accurate upwind scheme. The Crank-Nicolson method is applied to get second-order accuracy in time, but it is conditionally stable. With this scheme, $(\xi Qc)_e$ can be expressed as

$$(\xi Qc)_e = \frac{1}{2}(Q_e + W_e)\left(c_P^{n-1} + \theta \Delta c_p\right) + \frac{1}{2}(Q_e - W_e)\left(c_E^{n-1} + \theta \Delta c_E\right) \tag{3.25}$$

where θ = implicit factor ($0 < \theta < 1$). If unconditional stability is to be guaranteed, then θ should be greater than 0.5. Similar expressions can be written for the other term in Eq (3.22). The final contributions of the convective term to the coefficients in Eq. (3.19) can be written as:

$$
\begin{aligned}
A_E\,|_C &= \tfrac{1}{2}\theta\left(Q_e - W_e\right) \\
A_W\,|_C &= \tfrac{1}{2}\theta\left(-Q_w - W_w\right) \\
A_P\,|_C &= \tfrac{1}{2}\theta\left(Q_e + W\right)_e + \theta\left(-Q_w + W_w\right) \\
&\quad + \tfrac{1}{2}\theta\left(Q_n + W_n\right) + \theta\left(-Q_s + W_s\right) \\
R\,|_C &= -\frac{1}{\theta}\left(A_P\,|_C\; c_P^{n-1} + A_E\,|_C\; c_E^{n-1} + A_W\,|_C\; c_W^{n-1}\right)
\end{aligned}
\tag{3.26}
$$

where the subscript C indicates the contribution of the convective term to the coefficients of Eq. (3.19).

3.1.2.3 ***Diffusion Term***

The approximation of the diffusion term in Eq. (3.18) also involves the values of variables at the CL. First, the central differential scheme (CDS) is applied in space, and then the Crank-Nicolson method is applied in time. The discretization of the diffusion term is second-order accurate in both space and time.

$$
\begin{aligned}
-\int_l Dh(\nabla c \cdot \vec{n})dl &= -D_e a_e \frac{c_E - c_P}{\Delta x_e} + D_w a_w \frac{c_P - c_W}{\Delta x_w} \\
&= -D_e a_e \frac{c_E^{n-1} + \theta\Delta c_E - c_P^{n-1} - \theta\Delta c_P}{\Delta x_e} + D_w a_w \frac{C_P^{n-1} + \theta\Delta C_P - C_W^{n-1} - \theta\Delta C_W}{\Delta x_w}
\end{aligned}
\tag{3.27}
$$

where Δx_e, Δx_w, Δx_s, and Δx_n are distances between the CS center P and neighborhood CS centers E, W, N, and S, respectively. The coefficients from the diffusion term can now be summarized as:

$$
\begin{aligned}
A_E\,|_D &= -\theta D_e a_e / \Delta x_e \\
A_W\,|_D &= -\theta D_w a_w / \Delta x_w \\
A_P\,|_D &= -(A_E\,|_D + A_W\,|_D) \\
R\,|_D &= -\frac{1}{\theta}\left(A_P\,|_D\; c_P^{n-1} + A_E\,|_D\; c_E^{n-1} + A_W\,|_D\; c_W^{n-1}\right)
\end{aligned}
\tag{3.28}
$$

where the subscript D indicates the contribution of the diffusion term to the coefficients of Eq. (3.19).

3.1.2.4 ***Source Term***

The only term remaining in the sediment transport is the source term from net sediment erosion and deposition in the streamwise direction.

$$
\begin{aligned}
A_E\,|_D &= -\theta D_e a_e / \Delta x_e \\
A_W\,|_D &= -\theta D_w a_w / \Delta x_w \\
A_P\,|_D &= -(A_E\,|_D + A_W\,|_D) \\
R\,|_D &= -\frac{1}{\theta}\left(A_P\,|_D\; c_P^{n-1} + A_E\,|_D\; c_E^{n-1} + A_W\,|_D\; c_W^{n-1}\right)
\end{aligned}
$$

3.1.2.5 ***Discretized Sediment Transport Equation***

Adding all the convective and diffusive terms gives:

$$A_P c_P + \sum A_L c_L = R \tag{3.29}$$

where P = CS center; L = neighborhood CS centers W or E; and:

$$\begin{aligned} A_P &= A_P|_U + A_P|_C + A_P|_D \\ A_L &= A_L|_C + A_L|_D \\ R &= R|_C + R|_D \end{aligned} \tag{3.30}$$

The matrix equation 3.29 can be solved by a tri-diagonal matrix solver using the Thompson Algorithm.

3.1.3 Non-Cohesive Particle Fall Velocity

Computation of particle fall velocity is necessary for several non-cohesive sediment transport capacity calculations. The fall velocity is computed using values recommended by the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957) (Figure 3.5). SRH-1D assumes the Corey shape factor of $SF = 0.7$, which is defined as

$$SF = \frac{c}{\sqrt{ab}} \tag{3.31}$$

where a, b, and c = the length of the longest, the intermediate, and the shortest mutually perpendicular axes of the particle, respectively. For particles with diameters above the range given in Figure 3.5, i.e. greater than 10 mm, the following formula is used:

$$w_f = 1.1\sqrt{(G-1)gd} \tag{3.32}$$

where w_f is the fall velocity, g = acceleration due to gravity, G = specific gravity of sediments, and d = particle diameter. In some cases, it is also necessary to compute the kinematic viscosity, for which the following formula is used:

$$\nu = \frac{1.792 \times 10^{-6}}{1.0 + 0.0337T + 0.000221T^2} \tag{3.33}$$

where T is the water temperature in degrees Centigrade and ν in m^2/s.

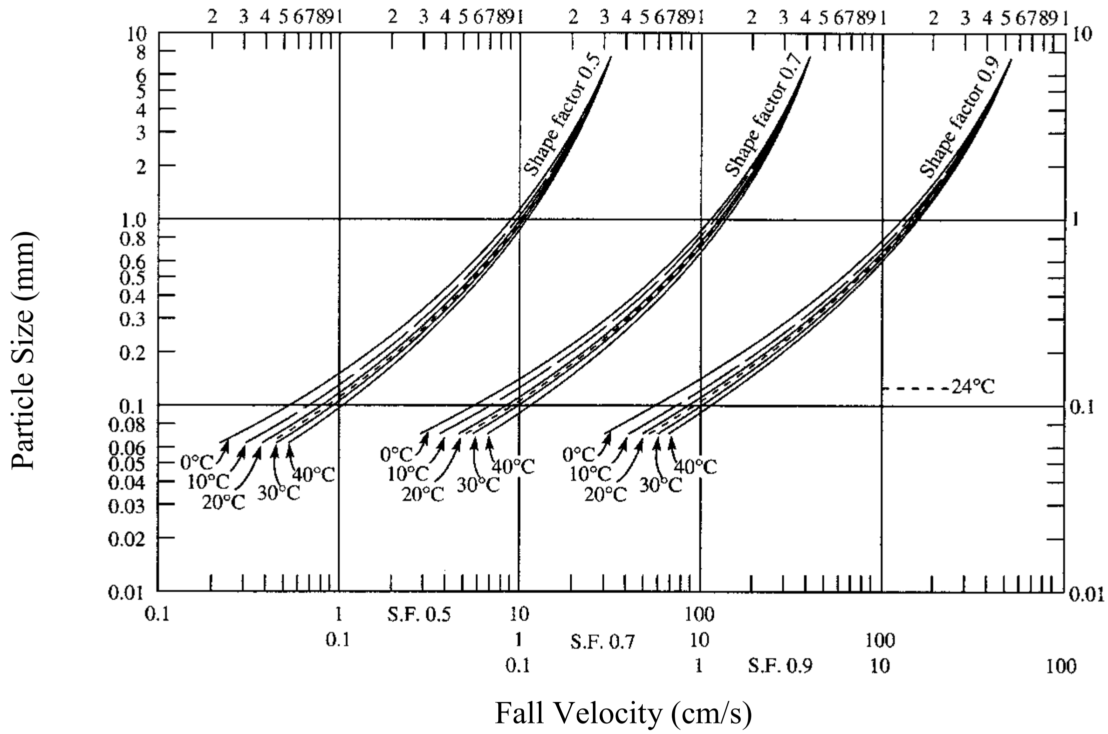

Figure 3.5 Relation between particle sieve diameter and its fall velocity according to the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957)

3.1.4 Non-Cohesive Sediment Transport Capacity

The literature contains many sediment transport capacity functions. Usually, each transport function was developed for a certain range of sediment size and flow conditions. Computed results based on different transport functions can differ significantly from each other and from measurements. No universal function exists which can be applied with accuracy to all sediment and flow conditions. SRH-1D employs a number of transport functions for non-cohesive material, presented in Table 3.1. Yang (1996) published a more detailed description of some of these functions including comprehensive comparisons and evaluations. New transport formulas are often added to the code as they are developed. It is recommended that user's frequently check for the most recent version of the code on the Reclamation web site.

Many transport capacity formula were developed assuming uniform size gradations. In these cases, the transport capacity is modified by the fraction of the size class in the active layer according to the following equation,

$$Q_i^* = p_i Q_i^T \tag{3.34}$$

where p_i is the mass fraction of that size class in the active layer and Q_i^T is the transport capacity predicted by the formula assuming uniform size.

Table 3.1 Sediment transport functions available in SRH-1D and its type (B = bed load; BM = bed-material total load).

Equation	Type
Meyer-Peter and Müller (1948) and Wong and Parker (2006)	B
Laursen (1958)	BM
Modified Laursen's Formula (Madden, 1993)	BM
Engelund and Hansen (1972)	BM
Ackers and White (1973)	BM
Ackers and White (HR Wallingford, 1990)	BM
Yang (1973) + Yang (1984)	BM
Yang (1979) + Yang (1984)	BM
Brownlie (1981)	BM
Yang et al. (1996)	BM
Parker (1990)	B
Wilcock and Crowe (2003)	B
Wu (2000)	BM

3.1.4.1 *Meyer-Peter and Müller's Formula (1948) modified by Wong and Parker (2006)*

In non-dimension form, the Meyer-Peter and Müller's bedload formula (1948) is:

$$\frac{q_{bi}}{\sqrt{g(s-1)d^3}} = 8\left(\frac{(K_s/K_r)^{1.5}RS}{(s-1)d} - 0.047\right)^{1.5} \tag{3.35}$$

where γ and γ_s = specific weights of water and sediment, respectively; R = hydraulic radius; S = energy slope; d = mean particle diameter; s = specific gravity of sediment; q_b = volume bed load transport per unit width; and $(K_s/K_r)S$ = the adjusted energy slope that is responsible for bed-load motion. The value of K_s and K_r can be computed from:

$$K_s = \frac{V}{C_m R^{2/3} S^{1/2}} \tag{3.36}$$

and

$$K_r = \frac{26}{d_{90}^{1/6}} \tag{3.37}$$

where d_{90} = the size of sediment for which 90 percent of the material is finer and is in meters.

Wong and Parker (2006) reanalyzed the data used by Meyer-Peter and Müller and found that the energy slope correction in the equation is unnecessary. The modified formula suggested by them is:

$$\frac{q_{bi}}{\sqrt{g(s-1)d^3}} = 3.97\left(\frac{RS}{(s-1)d} - 0.0495\right)^{1.5} \tag{3.38}$$

This is the formula used in SRH-1D.

3.1.4.2 ***Laursen's Formula (1958) and Modified Version (Madden, 1993)***

Laursen's formula (1958) was expressed in dimensionally homogeneous forms by an American Society of Civil Engineers Task Committee (1971) as,

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{D}\right)^{7/6} (\phi_i - 1) f\left(\frac{U^*}{w_{fi}}\right) \tag{3.39}$$

where C_t = sediment concentration by weight per unit volume, $U^* = \sqrt{gDS}$; p_i = percentage of materials available in size fraction *i,* w_{fi} = fall velocity of particles of mean size d_i in water, and D = average water depth. The parameter ϕ_i is a measure of the shear stress relative to the reference shear stress:

$$\phi_i = \theta_i / (\xi_i \theta_c) \tag{3.40}$$

where θ_c is the reference Shield's number; and θ_i = Shield's parameter of the sediment size class *i* computed as:

$$\theta_i = \tau_g / (\gamma (s-1) d_i) \tag{3.41}$$

where τ_g is the grain shear stress. The parameter ξ_i is the exposure factor, which accounts for the reduction in the critical shear stress for relatively large particles and the increase in the critical shear stress for relatively small particles:

$$\xi_i = (d_i / d_{50})^{-\alpha} \tag{3.42}$$

where α = a constant. Laursen assumed that θ_c = 0.039 and that α = 0, meaning that there is no hiding and exposure. SRH-1D adds the ability to compute the effect of mixtures by allowing the user to specify different values of θ_c and α.

Laursen's grain shear, τ_g, was computed as,

$$\tau_g = \frac{\rho V^2}{58} \left(\frac{d_{50}}{D}\right)^{1/3} \tag{3.43}$$

In Eq. 3.39, ϕ_i is important in determining bed load, and the parameter U_* / w_{fi} relates to suspended load. The functional relation $f(U_* / w_{fi})$ is given by Laursen (1958) in a graphical form and SRH-1D uses the following functions to approximate the curve:

$$\begin{aligned} \ln[f(\eta)] = {} & 2.25 + 0.25\lambda + 6.9[1 - \exp(-0.085\eta)] \\ & - 0.37 \exp\left[-(\lambda - 3.8)^2\right] \end{aligned} \tag{3.44}$$

where $\eta = U_* / w_{fi}$ and $\lambda = \ln(\eta)$.

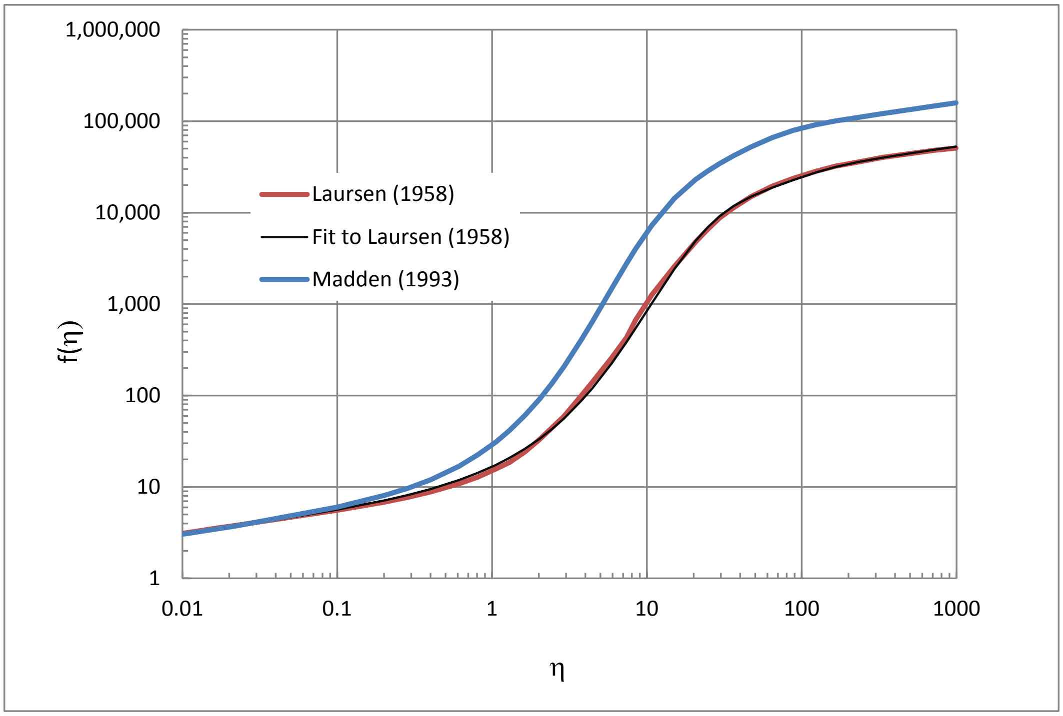

Figure 3.6. Comparison between Laursen's (1958) function and Eq. 3.44.

Madden (1993) revised the Laursen relation to fit the sediment load discharge rating curves in the lower Arkansas River. The result was a curve similar in shape to Laursen, but one that predicts significantly higher transport rates as η increases. Both the original Laursen equation and the revised equation by Madden are implemented in SRH-1D. The fit equation for the Madden (1993) equation is:

$$\ln[f(\eta)] = 2.25 + 0.25\lambda + 8[1 - \exp(-0.15\eta)] - 0.6\exp\left[-(\lambda - 3.1)^2\right] \tag{3.45}$$

3.1.4.3 ***Engelund and Hansen's Method (1972)***

Engelund and Hansen (1972) proposed the following transport function for use in primarily sand bed rivers:

$$f'\phi = 0.1\theta^{5/2} \tag{3.46}$$

where:

$$f' = \frac{\tau}{\frac{1}{2}\rho V^2} \tag{3.47}$$

$$\phi = q_t \Big/ \sqrt{(s-1)gd^3} \tag{3.48}$$

$$\theta = \frac{\tau}{(\gamma_s - \gamma)d} \tag{3.49}$$

where f' = friction coefficient, g = gravitational acceleration; V = average flow velocity; q_t = total sediment discharge by volume per unit width; s = specific gravity of sediment; γ_s and γ = specific weights of sediment and water, respectively; d = median particle diameter; and τ = total shear stress along the bed.

3.1.4.4 ***Ackers and White's Method (1973) and (HR Wallingford, 1990)***

Ackers and White (1973) applied dimensional analysis to express the mobility and transport rate of sediment in terms of dimensionless parameters. Their mobility number for sediment is

$$F_{gr} = \frac{U_*^{\ n}}{\sqrt{gd(s-1)}}\left[\frac{V}{\sqrt{32}\log(10D/d)}\right]^{1-n} \tag{3.50}$$

where U_* = shear velocity; n = transition exponent, depending on sediment size; d = sediment particle size; and D = average water depth. They also expressed the sediment size by a dimensionless grain diameter

$$d_{gr} = d\left[\frac{g}{\nu^2}(s-1)\right]^{1/3} \tag{3.51}$$

where ν = kinematic viscosity of water. A dimensionless sediment transport function can then be expressed as

$$G_{gr} = f(F_{gr}, d_{gr}) \tag{3.52}$$

with

$$G_{gr} = \frac{CD}{d}(\frac{U^*}{V})^n \tag{3.53}$$

where C = volumetric concentration of sediment. They postulated the generalized dimensionless sediment transport function as

$$G_{gr} = C_w\left(\frac{F_{gr}}{A} - 1\right)^m \tag{3.54}$$

The values of A, C_w, m, and n were determined by Ackers and White (1973) based on best-fit curves of laboratory data with sediment sizes greater than 0.04 mm and Froude numbers less than 0.8. To model mixtures, SRH-1D implements the following equation to revise the computation of the A parameter, which is effectively a critical shear stress

$$A = A_0\left(d_i / d_m\right)^{-\alpha} \tag{3.55}$$

where α is a user-defined hiding/exposure coefficient and A_0 is the original coefficient as defined by Ackers and White.

The original Ackers and White formula is known to over-predict transport rates for fine sediments (smaller than 0.2 mm). To correct that tendency, a revised form of the coefficients was published (HR Wallingford, 1990). Both versions of the coefficients are implemented in SRH-1D. Table 3.2 compares the original and the revised coefficients. Within SRH-1D, the value of m is limited to a value of 5 or less. Greater exponents than 5 lead to instability and over-prediction of fine sediment transport rates.

Table 3.2 Coefficients for the 1973 and 1990 versions of the Ackers and White formula.

	1973	1990
$1 < d_{gr} \le 60$	$A_0 = 0.23 d_{gr}^{-1/2} + 0.14$ $\log C_w = -3.53 + 2.86 \log d_{gr} - (\log d_{gr})^2$ $m = 9.66 d_{gr}^{-1} + 1.34$ $n = 1.00 - 0.56 \log d_{gr}$	$A_0 = 0.23 d_{gr}^{-1/2} + 0.14$ $\log C_w = -3.46 + 2.79 \log d_{gr} - 0.98(\log d_{gr})^2$ $m = 6.83 d_{gr}^{-1} + 1.67$ $n = 1.00 - 0.56 \log d_{gr}$
$d_{gr} > 60$	$A_0 = 0.17$ $C_w = 0.025$ $m = 1.50$ $n = 0$	$A_0 = 0.17$ $C_w = 0.025$ $m = 1.78$ $n = 0$

3.1.4.5 *Yang's Sand (1973) and Gravel (1984) Transport Formulas*

Yang's 1973 dimensionless unit stream power formula for sand transport is,

$$\begin{aligned}\log C_{ts} &= 5.435 - 0.286 \log \frac{w_f d}{\nu} - 0.457 \log \frac{u_*}{w_f} \\ &+ \left(1.799 - 0.409 \log \frac{w_f d}{\nu} - 0.314 \log \frac{u_*}{w_f}\right) \log\left(\frac{VS}{w_f} - \frac{V_{cr} S}{w_f}\right)\end{aligned} \tag{3.56}$$

where C_{ts} = total sand concentration in parts per million by weight; w_f = sediment fall velocity; d = sediment particle diameter; ν = kinematic viscosity of water; u_* = shear velocity; VS = unit stream power; V = average flow velocity; S = water surface or energy slope; and V_{cr} = critical average flow velocity at incipient motion. The coefficients in Eq. (3.56) were determined from 463 sets of laboratory flume data and this equation applies to sand transport with particle diameters less than 2 mm.

The critical velocity, V_{cr}, is computed from,

$$\frac{V_{cr}}{\omega} = \begin{cases} \dfrac{2.5}{\log(u_* d/\nu) - 0.06} + 0.66 & \text{if } 1.2 < \dfrac{u_* d}{\nu} < 70 \\ 2.05 & \text{if } 70 \le \dfrac{u_* d}{\nu} \end{cases} \tag{3.57}$$

Yang's 1984 dimensionless unit stream power formula for gravel transport with particle diameters equal to or greater than 2 mm is

$$\log C_{tg} = 6.681 - 0.633\log\frac{w_f d}{\nu} - 4.816\log\frac{u_*}{w_f}$$

$$+\left(2.784 - 0.305\log\frac{w_f d}{\nu} - 0.282\log\frac{u_*}{w_f}\right)\cdot \log\left(\frac{VS}{w_f} - \frac{V_{cr}S}{w_f}\right) \quad (3.58)$$

where C_{tg} = total gravel concentration in parts per million by weight. The coefficients in Eq. (3.58) were determined from 167 sets of laboratory flume data.

The incipient motion criteria given in Eq. (3.57) should be used for Eqs. (3.56) and (3.58). Because of the range of data used for the determination of the coefficients in Eq. (3.58), the equation should be applied to gravel with median particle size between 2 and 10 mm and therefore may not be applicable for large gravel or cobbles. Eqs. (3.56) and (3.58) were originally derived for uniform materials. For natural rivers, the bed-material size may vary from sand to gravel. In this case, SRH-1D uses Eqs. (3.56) for the sand sized sediment and (3.58) for the gravel sized sediment.

3.1.4.6 *Yang's Sand (1979) Transport Formulas*

Yang (1979) proposed a sand transport formula for flow conditions well exceeding those required for incipient motion. In this case, the dimensionless critical unit stream power required at incipient motion can be neglected. Yang's 1979 sand transport formula for sediment concentration greater than 100 parts per million by weight is

$$\log C_{ts} = 5.165 - 0.153\log\frac{w_f d}{\nu} - 0.297\log\frac{u_*}{w_f} + \left(1.78 - 0.36\log\frac{w_f d}{\nu} - 0.48\log\frac{u_*}{w_f}\right)\log\frac{VS}{w_f} \quad (3.59)$$

The coefficients in Eq. (3.59) were determined from 452 sets of laboratory flume data. Eqs. (3.56) and (3.59) give about the same degree of accuracy when the bed-material concentration is greater than about 100 parts per million by weight.

3.1.4.7 *Yang et al. 's Modified Formula for Sand Transport with High Concentration of Wash Load (1996)*

Up to this point, all transport functions were developed for equilibrium sediment transport where the effects of wash load can be neglected. The existence of high concentration of wash load can significantly affect the flow viscosity, sediment fall velocity, and the relative density or relative specific weight of sediment. For a given set of hydraulic conditions, non-equilibrium sediment transport of varying rates may occur because of a varying rate of high concentration of wash load. Yang et al. (1996) rewrote Yang's 1979 formula in the following form for sediment-laden flow with high concentration of wash load:

$$\log C_{ts} = 5.165 - 0.153\log\frac{w_{fm}d}{\nu_m} - 0.297\log\frac{U^*}{w_{fm}} + \left(1.78 - 0.36\log\frac{w_{fm}d}{\nu_m} - 0.48\log\frac{U^*}{w_{fm}}\right)\log\left(\frac{\gamma_m}{\gamma_s - \gamma_m}\frac{VS}{w_{fm}}\right) \quad (3.60)$$

where w_{fm}= particle fall velocity in a sediment-laden flow; ν_m = kinematic viscosity of sediment laden flow; and γ_s, γ_m = specific weights of sediment and sediment-laden flow, respectively.

It should be noted that the coefficients in Eq. (3.60) are similar to those in Eq. (3.59). However, the values of fall velocity, kinematic viscosity, and relative specific weight are modified for sediment transport in sediment-laden flows with high concentrations of fine suspended materials. The modifications made by Yang et al. (1996) were based on sediments from the Yellow River in China, which is noted for its high concentration of wash load and bed-material load.

3.1.4.8 ***Brownlie's Method***

Brownlie (1981) developed a sediment transport equation based solely on dimensional analysis. The equation is best used for sand transport and yields parts per million by weight as

$$C = 7115C_F(F_g - F_{g0})^{1.978} S_f^{0.6601} (\frac{R}{d_i})^{-0.3301} \quad (3.61)$$

where C_F = Brownlie's coefficient for field application (=1.268); F_g, F_{go} = the grain Froude number and critical grain Froude number, respectively, calculated as:

$$F_g = \frac{V}{\sqrt{\left(\frac{\rho_s - \rho}{\rho}\right) g\, d_{50}}} \quad (3.62)$$

$$F_{go} = \frac{4.596\, \tau_{*c}^{0.5293}}{S_f^{0.1405}\, \sigma_g^{0.1606}} \quad (3.63)$$

where σ_g = the geometric standard deviation of bed-particle sizes $= \sqrt{d_{84}/d_{16}}$; and τ_{*c} = the critical shear stress calculated as:

$$\tau_{*c} = 0.22Y + \frac{0.06}{(10)^{7.7Y}} \quad (3.64)$$

$$Y = \left(\sqrt{\frac{\rho_s - \rho}{\rho}}\, R_g\right)^{-0.6} \quad (3.65)$$

$$R_g = \frac{\sqrt{g\, d_{50}^3}}{\nu} \quad (3.66)$$

where R_g = the grain Reynolds number, and Y = temporary variable.

3.1.4.9 ***Parker's Method (1990)***

Parker (1990) developed an empirical gravel transport function based on the equal mobility concept and field data:

$$\frac{q_{bi} g(s-1)}{p_i (\tau_g / \rho)^{1.5}} = 11.93 f(\phi_i) \qquad (3.67)$$

where q_{bi} = volumetric sediment transport rate per unit width for size fraction i; τ_g = grain shear stress, d_{50} = the median diameter; g = acceleration of gravity; γ = specific weight of water; and s = relative specific density of sediment (ρ_s / ρ). The parameter ϕ_i is a measure of the shear stress relative to the reference shear stress:

$$\phi_i = \theta_i / (\xi_i \theta_c) \qquad (3.68)$$

where θ_c is the reference Shield's number; and θ_i = Shield's parameter of the sediment size class i computed as:

$$\theta_i = \tau_g / (\gamma (s-1) d_i) \qquad (3.69)$$

where τ_g is the grain shear stress. The grain shear stress is computed based upon the velocity and representative grain diameter:

$$\frac{U}{\sqrt{\tau_g / \rho}} = 2.5 \ln\left(\frac{12.27 R'}{k_s}\right) \qquad (3.70)$$

where U is the cross sectional average velocity, R' is the hydraulic radius due to grain shear stress ($\tau_g = \gamma R' S_f$). The parameter, k_s, is the grain roughness height computed as, $k_s = 2d_{90}$ as suggested by Parker (1990). Because this introduces another empirical parameter, the user also has the option of using the total shear stress in Eq (3.69). The parameter ξ_i is the exposure factor, which accounts for the reduction in the critical shear stress for relatively large particles and the increase in the critical shear stress for relatively small particles:

$$\xi_i = (d_i / d_{50})^{-\alpha} \qquad (3.71)$$

where α = a constant. The function, $f(\phi_i)$, was fit to field data and is:

$$f(\phi) = \begin{cases} (1 - 0.853/\phi)^{4.5} & , \phi > 1.59 \\ 0.000183 \exp\left[14.2(\phi - 1) - 9.28(\phi - 1)^2\right] & , 1 < \phi \le 1.59 \\ 0.000183 \phi^{14.2} & , \phi \le 1 \end{cases} \qquad (3.72)$$

Two parameters can be defined by the user to use Parker's equation: θ_c and α. Ideally, these values should be fit to data of the stream being simulated. However, in the absence of data, several references provide guidance, such as Buffington and Montgomery (1997), Andrews (2000), and Mueller et al. (2005). Default values for θ_c and α are 0.0386 and 0.905 as recommended in Parker (1990).

3.1.4.10 *Wilcock and Crowe (2003)*

The Wilcock and Crowe formula is similar to the Parker (1990) in that it is a bedload formula and written in similar form:

$$\frac{q_{bi} g(s-1)}{p_i(\tau_g/\rho)^{1.5}} = 14 f(\phi_i) \tag{3.73}$$

where the variable definition is the same as in the Parker equation. The roughness height used to compute the grain shear stress is $k_s = 2d_{65}$. The function f is computed as:

$$f(\phi) = \begin{cases} \left(1 - 0.894/\sqrt{\phi}\right)^{4.5} & , \phi \geq 1.35 \\ 0.000143\phi^{7.5} & , \phi < 1.35 \end{cases} \tag{3.74}$$

The function has the behavior that as ϕ_i becomes large, $f(\phi_i)$ approaches 1. The parameter, ϕ, is defined similar to the Parker equation:

$$\phi_i = \theta_i / (\xi_i \theta_c) \tag{3.75}$$

Wilcock and Crowe formulated an expression for the reference shear stress that was dependent upon the fraction of sand within the bed:

$$\theta_c = 0.021 + 0.015[\exp(-20F_s)] \tag{3.76}$$

where F_s is the fraction of bed material in the active layer sand sized or less. The hiding function, ξ, is:

$$\xi = (d_i / d_m)^{-\alpha} \tag{3.77}$$

where d_m is the geometric mean diameter. Notice that the geometric mean diameter is used in the above equation and not the median. The original paper mistakenly stated that the median should be used. The parameter α was specified as:

$$\alpha = 1 - 0.67[1 + \exp(1.5 - d_i / d_m)]^{-1} \tag{3.78}$$

where d_m is the mean particle diameter in the bed. The above equation has the behavior of approaching 0.33 for large d_i/d_m and approaching 0.88 for small d_i/d_m.

In SRH-1D, the following equations are used to compute θ_c and α:

$$\theta_c = \theta_{c0} + 0.015[\exp(-20F_s)]$$

$$\alpha = 1 - (1 - \alpha_0)[1 + \exp(1.5 - d_i / d_m)]^{-1} \tag{3.79}$$

where if $\theta_{c0} = 0.021$ and $\alpha_0 = 0.33$, the Wilcock and Crowe (2003) relation is recovered. The user can specify the value of θ_{c0} and α_0.

3.1.4.11 *Gaeuman et al (2009)*

Gaeuman et al. (2009) modified some of the functions within Wilcock and Crowe (2003) to better fit bedload data from the Trinity River in Northern California. Specifically, the equations for θ_c and α were modified to:

$$\theta_c = 0.03 + 0.022\left[1 + \exp\left(7.1\sigma_{sg} - 11.786\right)\right]^{-1} \quad (3.80)$$

$$\alpha = 1 - 0.7\left[1 + \exp\left(1.9 - \frac{d_i}{3d_m}\right)\right]^{-1} \quad (3.81)$$

Where σ_{sg} is the standard deviation of the particle size distribution. All other relations of the original Wilcock and Crowe (2003) relationship still apply. In SRH-1D, the following equations are used to compute θ_c and α:

$$\theta_c = \theta_{c0} + 0.022\left[1 + \exp\left(7.1\sigma_{sg} - 11.786\right)\right]^{-1}$$

$$\alpha = 1 - \left(1 - \alpha_0\right)\left[1 + \exp\left(1.9 - d_i / \left(3d_m\right)\right)\right]^{-1} \quad (3.82)$$

where if $\theta_c = 0.03$ and $\alpha_0 = 0.3$, the Gaeuman et al. (2009) relation is recovered. The user can specify the value of θ_{c0} and α_0.

3.1.4.12 ***Wu et al. (2000)***

The Wu et al. (2000) formula computes the suspended and bed load separately and adds them together to obtain the total bed material sediment load:

$$q_t = q_b + q_s \quad (3.83)$$

The bed load is computed from:

$$\frac{q_{bi}}{p_i\sqrt{g(s-1)d_i^3}} = 0.0053\left[\left(\frac{n'}{n}\right)^{1.5}\frac{\tau_b}{\tau_{ci}} - 1\right]^{2.2} \quad (3.84)$$

where $n' = 0.05d_{50}^{1/6}$ and n is total Manning's roughness coefficient for the bed. The crictical shear stress is computed as:

$$\tau_{ci} = \theta_c\left(s-1\right)d_i\xi_i \quad (3.85)$$

and the exposure factor, ξ_i, is computed as:

$$\xi_i = \left(\frac{p_{hi}}{p_{ei}}\right)^{\alpha} \quad (3.86)$$

where $\alpha = 0.6$, which can be modified by the user. The probability of hiding and exposure, p_{hi} and p_{ei} respectively, are computed as:

$$p_{hi} = \sum_{j=1}^{N}\frac{p_j d_j}{\left(d_i + d_j\right)}, \quad p_{ei} = \sum_{j=1}^{N}\frac{p_j d_i}{\left(d_i + d_j\right)} \quad (3.87)$$

The critical shear stress, θ_c, recommended is 0.03; however, the user can modify this if necessary. The suspended load is computed as:

$$\frac{q_{si}}{p_i\sqrt{g(s-1)d_i^3}} = 0.0000262\left(\frac{U}{w_{fi}}\left(\frac{\tau_b}{\tau_{ci}} - 1\right)\right)^{1.74} \quad (3.88)$$

3.1.4.13 ***Parker or Wilcock and Crowe combined with Engelund-Hansen***

Bed load equations like Parker and Wilcock and Crowe ignore the suspended load transport and in systems where both suspended and bed load are a concern, they should be paired with an equation that would predict the suspended load. In SRH-1D, three options are given:

1) If the median particle size is sand sized or smaller, use the Engelund-Hansen formula for all particle sizes. If the median particle diameter is gravel or larger, use the bed load equation for all particle sizes.
2) Use Engelund-Hansen equation for sand at all times. For gravel and larger sized sediment, use bedload equation if median particle size is larger than sand, and use Engelund-Hansen equation if median particle size is sand sized or smaller.
3) The Engelund-Hansen formula can be rewritten in the form:

   $$\frac{q_{si}g(s-1)}{(\tau_g/\rho)^{1.5}} = p_i \frac{0.05V^2}{g(s-1)d_i}$$

   which is similar in form to the Parker and Wilcock and Crowe formulas. The similar forms suggest that a transport equation for sand in a gravel system could be obtained by combining the Parker or Wilcock formulas with the Engelund-Hansen formula as follows:

   $$\frac{q_{si}g(s-1)}{(\tau_g/\rho)^{1.5}} = p_i \max\left[C, \frac{0.05V^2}{g(s-1)d_i}\right] f(\phi_i)$$

   with C = 11.93 for the Parker and 14 for the Wilcock and Crowe methods. The function f is (3.72) for Parker's method and (3.74) for Wilcock and Crowe's method. The above method is used to compute the sand load, while the standard methods for Parker, Wilcock and Crowe, and Gaeuman et al. are used for the gravel and larger sizes. There is some caution suggested in the application of this combination because its use has not been extensively applied or tested.
4) Use Engelund-Hansen formula for sand sized material and use bedload formula for sediment larger than sand. This is the recommended method in most situations.

For example, to specify that option 1 should be used with the Parker transport equation, "PARKER1" would be entered in the SEQ record.

3.1.5 Cohesive Sediment Aggregation

Cohesive sediments tend to aggregate to form large, low-density units. This process is strongly dependent on the type of sediment, the type and concentration of ions in the water, and the flow condition (Mehta et al. 1989). Cohesive sediments are primarily composed of clay-sized material, which have strong interparticle forces because of their surface ionic charges. As particle size decreases, the interparticle forces dominate gravitational force, and the settling velocity is no longer a function of only particle size. McAnally and Mehta (2001) provided a new formulation of the collision efficiency and collision diameter function through a non-dimensional analysis of the significant parameters in collision, aggregation, and disaggregation. In engineering models, aggregation is often indirectly considered by the change in settling velocity.

Several researchers investigated the effects of aggregation on the settling velocity. Krone (1962) performed flume studies and found settling velocity increases with sediment concentration. Cole and Miles (1983) used a linear relationship between fall velocity and sediment concentration. Van Leussen (1994) proposed an empirical relationship between settling velocity, concentration and shear stress. Nicholson and O'Connor (1986) developed a relationship for settling velocity that incoroporates high concentrations of cohesive particles. Burban et al. (1990) linked the settling velocity with the median floc diameter from laboratory experiment data.

Thorn (1981) showed settling velocity increases with concentration at low concentrations, attains a maximum value, and then decreases due to hindered settling at intermediate concentrations and structural flocculation at high concentrations. Van Rijn (1993) summarized the influence of sediment concentration on the settling velocity for several types of sediments (Figure 3.7).

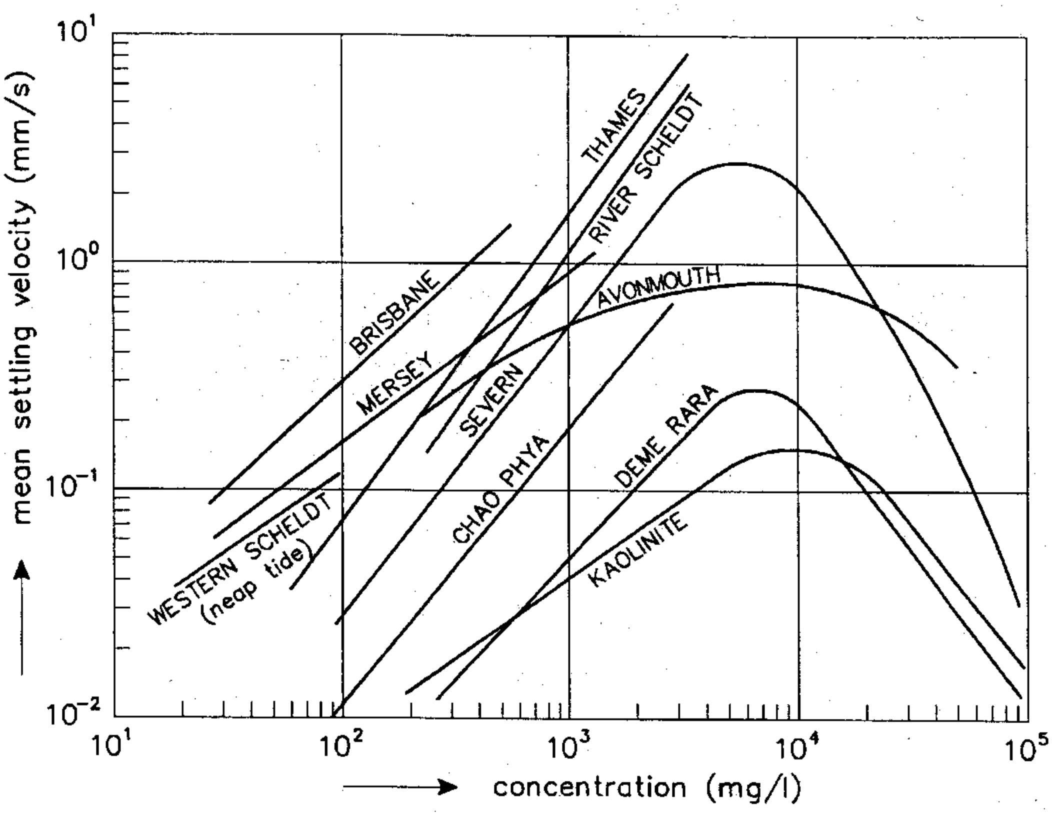

Figure 3.7 The influence of sediment concentration on the settling velocity (source: Van Rijn, 1993, figure 11.4.2)

Settling velocities due to sediment flocculating are usually site-specific and should be determined by experiment. SRH-1D allows the user to enter a set of 4-

point data (C_1, V_1, C_2, V_2, C_3, V_3, C_4, and V_4) as shown in Figure 3.8 that gives the variation of fall velocity with the cohesive concentration

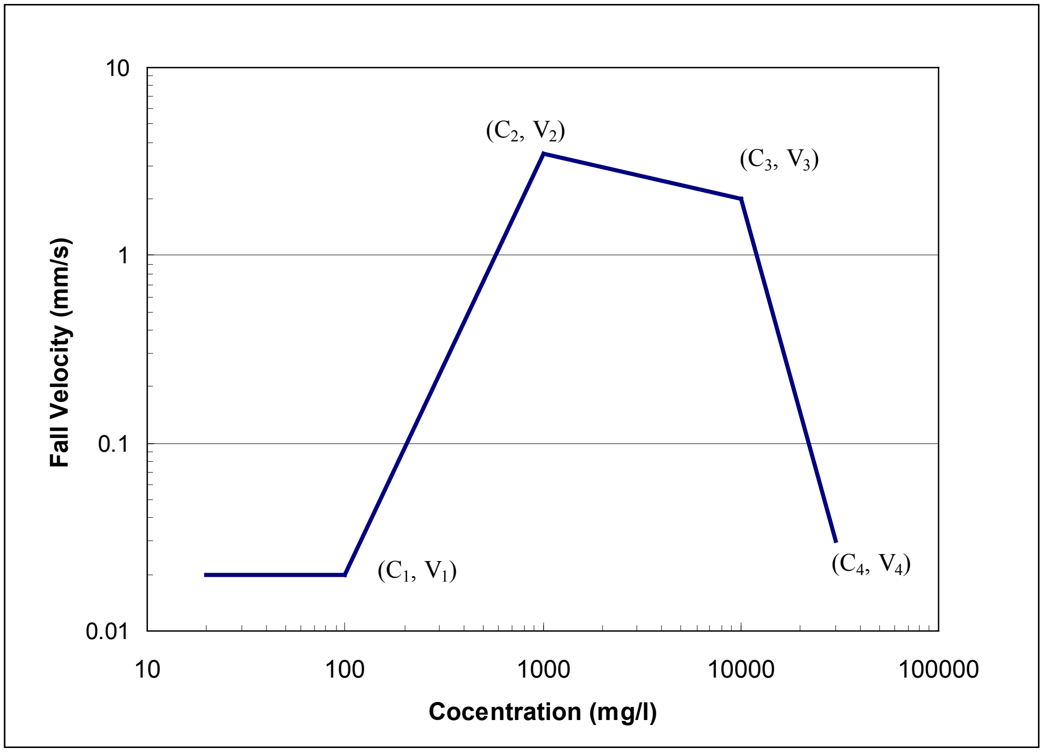

Figure 3.8 Input data illustration for settling velocity

3.1.6 Cohesive Sediment Deposition

Deposition occurs when the bottom shear stress is less than a critical shear stress. Only aggregates with sufficient shear strengths to withstand highly disruptive shear stresses in the near bed region will deposit and adhere to the bed. Mehta and Partheniades (1973) performed laboratory studies on the depositional behavior of cohesive sediment and found that deposition is controlled by the bed shear stress, turbulence processes in the zone near the bed, settling velocity, type of sediment, depth of flow, suspension concentration, and ionic constitution of the suspending fluid (also summarized in Hayter et al., 1999).

Two kinds of sediment deposition are included in SRH-1D, full and partial depositions. Van Rijn (1993) provides more information about the equations used below.

Krone's (1962) deposition formulation governs when the bed shear stress (τ) is smaller than the critical shear stress for full deposition ($\tau_{d,full}$) and all sediment particles and flocs can deposit.

$$V_d = P_d \omega \quad \text{for } \tau \le \tau_{d,full} \tag{3.89}$$

where V_d = deposition velocity, and P_d = the deposition probability. The variable P_d is also the probability of particles sticking to the bed and not being re-entrained by the flow. A fraction of sediments settling to the near bed region cannot withstand the high shear stresses at the sediment-water interface and are broken up and resuspended. The probability of deposition is given by,

$$P_d = 1 - \tau / \tau_{d,full} \quad \text{for} \quad \tau \le \tau_{d,full} \tag{3.90}$$

where τ = bottom shear stress; and $\tau_{d,\,full}$ = critical shear stress for full deposition. Many experiments were performed to determine the values of critical shear stress for full deposition of cohesive sediments. They range between 0.06 and 1.1 N/m^2 depending upon the sediment type and concentration. Krone (1962) conducted a series of flume experiments to determine the critical shear stress for full deposition. For San Francisco Bay sediment, he found that $\tau_{d,\,full}$ = 0.06 N/m^2 when $c < 0.3$ g/l; $\tau_{d,\,full}$ = 0.078 N/m^2 when $0.3 < c < 10$ g/l. Mehta and Partheniades (1975) found that $\tau_{d,\,full}$ = 0.15 N/m^2 for kaolinite in distilled water.

Partial deposition exists when the bed shear stress is greater than the critical shear stress for full deposition but smaller than the critical shear stress for partial deposition (Van Rijn, 1993). At this range of bed shear stress, relatively strong flocs are deposited and relatively weak flocs remain in suspension. The partial deposition formulation is written as,

$$V_d = P_d \omega \left(1 - \frac{C_{eq}}{C} \right) \quad \text{for} \quad \tau_{d,full} < \tau < \tau_{d,part} \tag{3.91}$$

where C_{eq} is the equilibrium cohesive sediment concentration, which is the concentration of relatively weak flocs that are broken apart before reaching the bed or eroded immediately after deposition. The probability of deposition is given by,

$$P_d = 1 - \tau / \tau_{d,part} \quad \text{for} \quad \tau_{d,full} < \tau < \tau_{d,part} \tag{3.92}$$

The deposition rate is zero when the bed shear stress is larger than the critical shear stress for partial deposition,

$$P_d = 0 \quad \text{for} \quad \tau \ge \tau_{d,part} \tag{3.93}$$

At present, the behavior of critical shear stresses for full and partial depositions are not well understood, but the accuracy of the deposition model depends on the use of correct values. When the actual value of $\tau_{d,full}$ and $\tau_{d,part}$ are uncertain, they become primary calibration parameters for determining the deposition rate.

3.1.7 Cohesive Sediment Erosion

Two kinds of erosion modes are simulated: surface and mass erosion. Surface erosion occurs when the bed shear stress is just above a critical value. At higher levels of stress, the bed shear stress exceeds the bulk shear strength of a layer of material and that layer of bed material is susceptible to mass erosion.

The excess bed shear stress, defined as $\tau - \tau_e$, is a measure of erosion force. The critical erosion shear stress depends on a number of factors including sediment composition, bed structure, chemical compositions of the pore and eroding fluids, deposition history, and organic matter and its state of oxidation (Ariathurai and Krone, 1976; Mehta et al., 1989). Usually, both erosion rate constant M and critical erosion shear stress τ_e change with the bed properties in depth and time. Field studies or laboratory measurements should be made to obtain the critical shear stress and erosion rate.

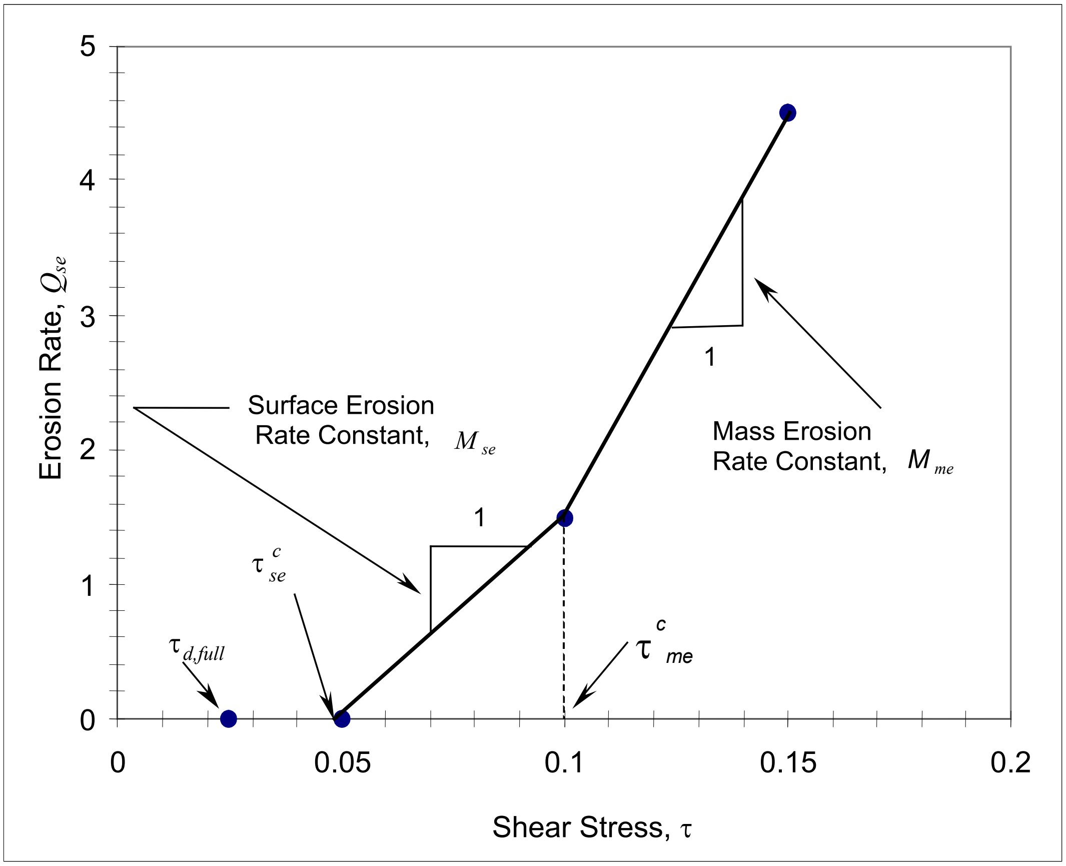

Figure 3.9 The schematic illustrates the erosional characteristics that need to be determined from erosion tests (*after*: Vermeyen, 1995)

Field studies and laboratory flume studies are the most reliable physical methods to determine empirical model parameters. Figure 3.8 illustrates the ideal erosional and depositional characteristics that can be determined from physical tests. In general, a physical test should provide the following information: critical shear stresses for deposition, surface erosion, mass erosion, and the erosion rates for surface and mass erosion. Measured erosion rates often exhibit large amounts of scatter or are not linearly dependent upon shear stress. However, a simple linear model is often the most reasonable approach.

A formula for surface erosion rate was described by Partheniades (1965):

$$Q_{se} = \begin{cases} M_{se} \dfrac{\tau - \tau_{se}^c}{\tau_{se}^c} & \tau \ge \tau_{se}^c \\ 0 & \tau < \tau_{se}^c \end{cases} \tag{3.94}$$

where Q_{se} (lb/ft^2/hr or kg/m^2/hr) = surface erosion rate; τ and τ_{se}^c (lb/ft^2 or kg/m^2) = bed shear stress and critical surface erosion shear stress, respectively; M_{se} = surface erosion constant (lb/ft^2/hr or kg/m^2/hr). The SRH-1D model uses a modified version of Eq. (3.94):

$$Q_{se} = \begin{cases} P_{se}\left(\dfrac{\tau - \tau_{se}^c}{\tau_{me}^c - \tau_{se}^c}\right) & \tau \geq \tau_{se}^c \\ 0 & \tau < \tau_{se}^c \end{cases} \tag{3.95}$$

where τ_{me}^c = critical mass erosion shear stress and P_{se} is the surface erosion constant replacing M_{se}. The modified relationship is more consistent with the mass erosion rate discussed below. The parameters τ_{se}^c and P_{se} are site-specific and have to be determined experimentally.

Mass erosion is usually arbitrarily dependent on the model setup and its time scale. Hwang and Mehta (1989) found a maximum rate of mass erosion is on the order of 0.6 g/s/m^2. The presented model uses a mass erosion equation similar to surface erosion:

$$Q_{me} = M_{me}\left(\frac{\tau - \tau_{me}^c}{\tau_{me}^c}\right) + P_{se} \qquad \tau \geq \tau_{me}^c \tag{3.96}$$

where Q_{me} = mass erosion rate; τ and τ_{me}^c = bed shear stress and critical mass erosion shear stress, respectively; M_{me} = mass erosion constant. The erosion rates in lb/ft^2/hr or kg/m^2/hr are converted to the erosion velocity, V_e, through appropriate unit conversion before calculations proceed in SRH-1D.

3.2 Bed Material Mixing

This section describes the simulation of the bed material mixing processes that occur in natural river systems. Figure 3.10 provides a schematic of the active layer conceptual model, in which the bed is composed of one active layer and N-1 inactive layers. In this figure, h_n = bed thickness of layer n, $P_{n,k}$ = mass fraction of k-th size class in layer n. A user-defined number of size fractions will be used to represent the sediment size distributions. The bed profile is composed of a number of layers of various thicknesses and bulk densities. Each individual layer is assumed to have the same size distribution and bulk density throughout its depth. In each layer, bulk density of the cohesive sediment increases with time due to consolidation. The bulk density of the non-cohesive sediment remains constant. During consolidation, the bed thickness decreases but no mixing occurs between layers.

The active layer is defined as a thin upper zone of constant thickness that is proportional to the geometric mean of the largest size class. The constant of proportionality is user defined. The thickness of the active layer can control the rate at which the bed armors. The active layer methodology assumes that all sediment particles of a given size class inside the active layer are equally exposed to the flow.

Another phenomena simulated in SRH-1D is the reduction in erosion rate of non-cohesive sediment by cohesive sediment. Experimental results demonstrate that the presence of fine cohesive sediment in the bed can increase the bed's resistance to erosion. The model used by SRH-1D assumes that the erosion rates of sand and gravel are limited by the entrainment rate of the silt and clay if the fraction of the silt and clay is above a user specified value.

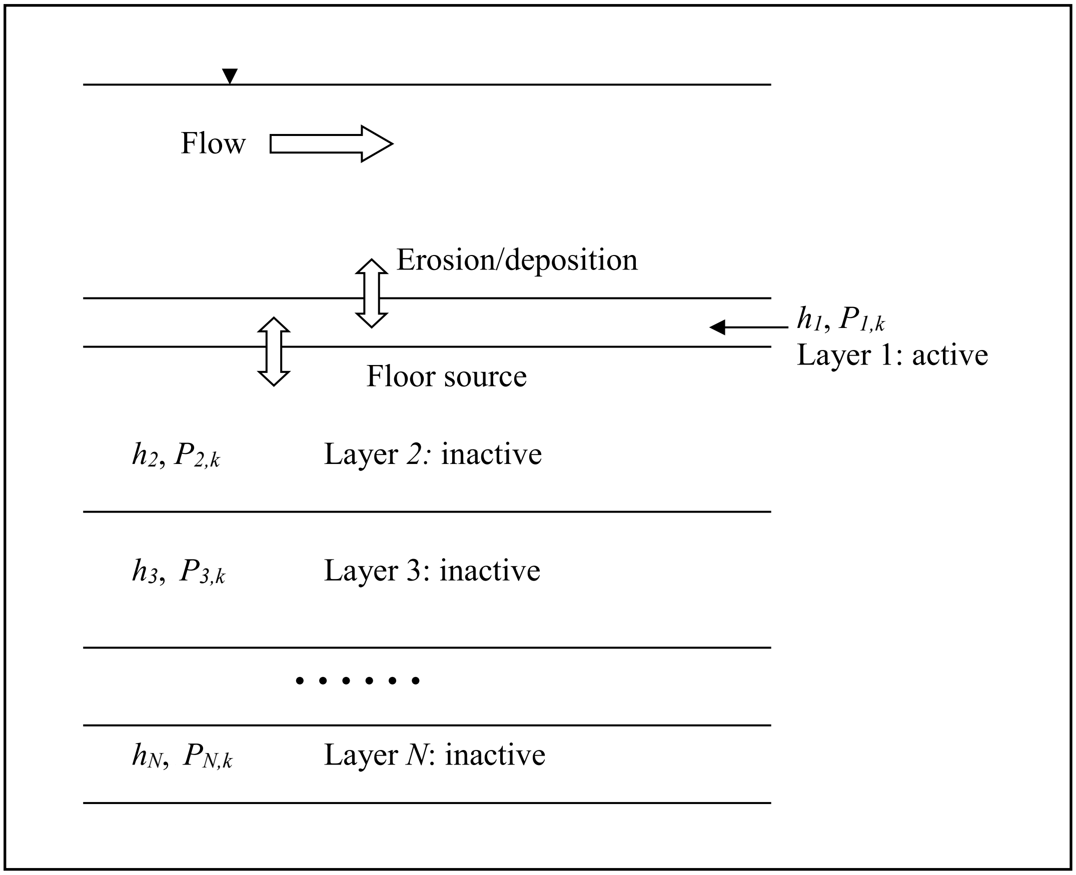

Figure 3.10 Conceptual model of bed mixing.

Armoring effects can be simulated using the active layer concept. If the bed shear stress is larger than the critical shear stress for the finer size classes, but smaller than that for coarser size classes, only the finer size classes are eroded from the active layer. This process of selective erosion will eventually armor the bed surface and prevent further erosion.

The active layer contains the bed material available for transport. During net erosion, the first inactive layer supplies material to the active layer. During net deposition, the additional material is moved to the first inactive layer. A minimum and a maximum thickness are specified for all inactive layers. If the thickness of the first inactive layer is smaller than the minimum thickness, the first inactive layer merges with the next layer. On the other hand, if the layer thickness is larger than the maximum, it is separated into two layers. All other layers are shifted accordingly. The minimum and maximum thicknesses can be specified by the user as a multiple of the active layer thickness.

The notation of the active layer provides a means to model winnowing and armoring. Sediment can only be eroded from or deposited onto the active layer. The active layer thickness is defined by an auxiliary relation proportional to the geometric mean of the largest size class of the bed material at that location.

As the bed elevation descends or ascends during erosion and deposition, the active-layer floor changes its elevation to keep the active-layer thickness constant, as shown in Figure 3.10. The movement of the active-layer floor generates the active-layer floor source $\Omega_{f,k}$ for the size class k. The mass conservation equation of the k-th size fraction in the active layer can be written as:

$$\frac{d\left(h_a \varepsilon_{a,k} P_{a,k}\right)}{dt} = -\Omega_k + \Omega_{f,k} \tag{3.97}$$

where $P_{a,k}$ is the bulk volume fraction of size class k in active layer a; $\varepsilon_{a,k}$ is equal to one minus porosity; Ω_k and $\Omega_{f,k}$ = the active layer source and floor source material volume fluxes, respectively.

Summation of Eq. (3.97) gives the global mass-conservation equation for the active layer:

$$\sum_k \Omega_k = \sum_k \Omega_{f,k} \tag{3.98}$$

which shows that the change of the bed elevation due to erosion (or deposition) is the same as the change of the active-layer floor elevation, and the active-layer thickness remains constant. Substituting this equation into Eq. 3.97 gives:

$$\begin{aligned} \frac{d\left(h_a \varepsilon_{a,k} P_{a,k}\right)}{dt} &= -\Omega_k + \widetilde{P}_k \sum_k \Omega_{f,k} \\ &= -\Omega_k + \widetilde{P}_k \sum_k \Omega_k \end{aligned} \tag{3.99}$$

where $\widetilde{P}_k$ can be expressed as (Hoy and Ferguson, 1994):

$$\widetilde{P}_k = \begin{cases} P_{2,k} & net\ erosion \\ \chi p_k + (1-\chi) P_{a,k} & net\ deposition \end{cases} \tag{3.100}$$

where p_k is the bed load fraction, and χ is the weight given to the bed load during the transfer of material to the sublayer and must be between 0 and 1. Toro-Escobar et al. (1996) use data collected from depositional experiments to calculate a best fit value of 0.7 for χ for a gravel mixture. Hoy and Ferguson (1994) tested various value of χ in numerical simulations of downstream fining. They found little effect on results for values of χ between 0 and 0.5. The downstream fining, however, did significantly increase when the value of χ was increased beyond 0.5. The value of χ is specified by the user in SRH-1D. It should be considered a secondary calibration parameter and because of lack of the practical applicability of the Hoy and Ferguson formulation, its recommended value is 0.

To ensure mass conservation, the active layer source terms (Ω_k, Ω_k), are calculated using the expressions from the sediment routing equations (see Eqs. 3.2 and 3.13).

$$\Omega_k = \frac{\varepsilon_{a,k} \Delta Z_{bk}}{\Delta t}, \text{ and } \Delta Z_T = \sum_k \Delta Z_{bk} \tag{3.101}$$

which gives the update equation for bed fractions in the active layer:

$$P_{a,k}^{n+1} = P_{a,k}^{n} - \left(\Delta Z_{bk} + \Delta Z_T \widetilde{P}_k \right) / h_a \tag{3.102}$$

Once the thickness of the first inactive layer decreases below a minimum value, the content of the layer merges with the underlying layer. The minimum thickness for the first inactive layer is the thickness of the active layer. Though merging of bed layers is not a physical process, it is a requirement of the discrete representation of the sediment bed. During the merging of two layers, a new layer thickness is calculated as the sum of the two layers:

$$h = h_n + h_{n+1} \tag{3.103}$$

and the volume size fraction is

$$P_k = \frac{P_{n,k} h_n + P_{n+1,k} h_{n+1}}{h_n + h_{n+1}} \tag{3.104}$$

The mass conservation equation used to obtain ε_k is:

$$\varepsilon_k = \frac{\varepsilon_{n,k} P_{n,k} h_n + \varepsilon_{n+1,k} P_{n+1,k} h_{n+1}}{P_k h} \tag{3.105}$$

3.3 Consolidation

Consolidation changes the thickness and density of the bed through decreases in porosity. Consolidation processes also affect the tracking of size-fraction distributions within the bed because the size fraction distribution in SRH-1D depends on volume. Due to the slow rate of consolidation, SRH-1D uncouples the simulation of erosion and deposition from the bed consolidation process. Simulation of bed consolidation applies to both the active and inactive layers.

During consolidation, the mass of each size fraction remains constant. The mass-conservation equation for the sediment in each layer is:

$$\frac{d\left(\varepsilon_{n,k} P_{n,k} h_n\right)}{dt} = 0 \tag{3.106}$$

where the subscripts n, k = the layer and size class indexes, respectively; $P_{n,k}$ = volume fraction of sediment size class k in layer n; $\varepsilon_{n,k}$ = volume concentration of sediment size class k in layer n ($\varepsilon = 1 - \eta$); and h_n = thickness of layer n;

Eq. (3.106) can also be written as:

$$P_{n,k}^{t+\Delta t} h_n^{t+\Delta t} = \varepsilon_{n,k}^{t} P_{n,k}^{t} h_n^{t} / \varepsilon_{n,k}^{t+\Delta t} \tag{3.107}$$

where t = time before consolidation, and $t+\Delta t$ = time after consolidation.

Summation of Eq. (3.107) with the constraint of size fractions $\sum_k P_{n,k} = 1$ gives the global mass conservation equation for sediment in layer n, i.e.,

$$h_n^{t+\Delta t} = \sum_k (\varepsilon_{n,k}^t P_{n,k}^t h_n^t / \varepsilon_{n,k}^{t+\Delta t}) \tag{3.108}$$

The expression for the bulk volume size fraction change can now be written as,

$$P_{n,k}^{t+\Delta t} = \frac{\varepsilon_{n,k}^t P_{n,k}^t h_n^t / \varepsilon_{n,k}^{t+\Delta t}}{h_n^{t+\Delta t}} \tag{3.109}$$

Eqs (3.108) and (3.109) are the governing equations for bed consolidation. The change of ε can be written as:

$$\frac{d\varepsilon}{dt} = \beta(\varepsilon_f - \varepsilon) \tag{3.110}$$

where β = the consolidation coefficient, computed from user input for initial density ρ_i, fully consolidated density ρ_f, and density ρ_e at the reference time t_e by ,

$$\beta = \log\left(\frac{\rho_f - \rho_i}{\rho_f - \rho_e}\right)$$

An explicit Euler method is used to calculate the sediment volume concentration after consolidation:

$$\varepsilon_{n,k}^{t+\Delta t} = \varepsilon_{n,k}^t + d\varepsilon = \varepsilon_{n,k}^t + \beta(\varepsilon_f - \varepsilon)\Delta t \tag{3.111}$$

4 Bedrock Erosion

Bedrock is an important control to the channel geometry. In some cases, the bedrock is erodible and one would like to estimate the erosion rates. The erosion of rock material in rivers can be caused by three primary factors: 1. Hydraulic forces on the rock exceed the ability of rock to resist scour. 2. Abrasion of rock material due to the movement of sediment across the rock. 3. Chemical or physical weathering of the rock. SRH-1D includes capability to simulate the first two processes.

4.1 Hydraulic Erosion of Bedrock

Hydraulic forces can cause bedrock scour by instantaneous or progressive failure of closed-end rock joints or by dynamic ejection of single rock blocks (Bollaert and Schleiss, 2005). To estimate the erosion of rock masses due to hydraulic forces, Annandale (1995, 2006) used an index methodology to measure the resistance of material to motion under a range of hydraulic conditions. Annadale related the rock strength erosivity index, k_h, to the critical stream power , P_{crit} (in kW/m^2) applied to the bed:

$$P_{crit}\,(\mathrm{kW/m^2}) = \begin{cases} 0.48 k_h^{\ 0.44} & , k_h \le 0.1 \\ k_h^{\ 0.75} & , k_h > 0.1 \end{cases} \tag{4.1}$$

The data used to derive this expression was mostly unpublished but there is verification of the method published in Annadale et al. (1998) and Wittler et al. (1998). Annadale (2006) does not extend this methodology to compute the erosion rates of the rock material, but only computes the onset of erosion and maximum scour depths.

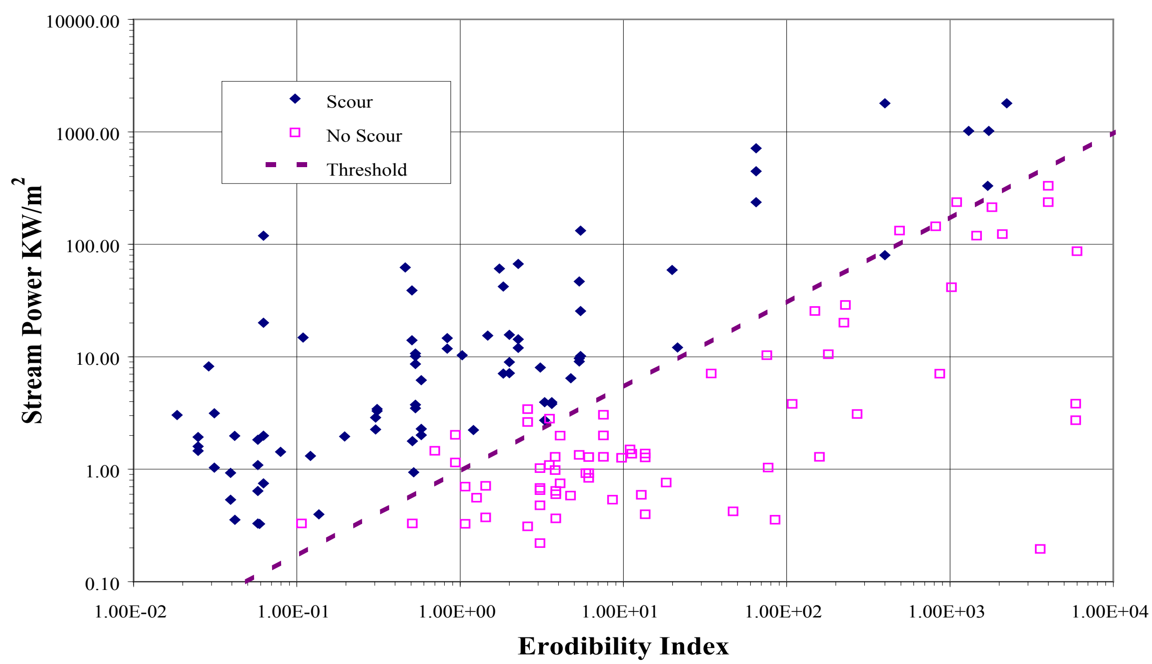

Figure 4.1. Plot of stream power versus erodibility index taken from Annandale (2006).

This index was original developed by Kirsten (1982) to characterize the excavation properties of earth materials. The erosivity index is written as:

$$k_h = M_s k_b k_d J_s \tag{4.2}$$

where,

k_h	= erosivity index;
M_s	= mass strength number;
k_b	= block size number,
k_d	= discontinuity number, and
J_s	= relative ground structure.

Each of the variables in Eq 4.2 can be measured using standard testing procedures or through field observations.

4.2 Bedrock Erosion due to Sediment Abrasion

Sklar and Dietrich (2006) review various methodologies to compute rock scour and classify approaches to compute rock incision based upon the methods include sediment wear and sediment cover into the approach. Coarse sediment moving as bed load over the surface of rock will act to wear the surface of the rock. If the sediment supply becomes too high the sediment will deposit on the rock and protect it from scour. There is an optimum coarse sediment supply that will maximize the erosion of rock. Foley (1980) developed a mechanistic formulation to account for the wear of sediment particles saltating across the bedrock surface. The formulation was further expanded upon by Sklar and Dietrich (2004) to compute the erosion of rock due to bedload abrasion. Lamb et al. (2008) incorporated the effect of suspended load to develop the following equation:

$$E = \frac{A_1 \rho_s w_s^3 Y C_b}{k_v \sigma_T^2} \tag{4.3}$$

where:

E	= erosion rate (m/s);
A_1	= constant factor accounting for lift forces of bed particles (-);
w_s	= effective impact velocity of sediment particles (m/s);
C_b	= sediment concentration in bed load layer (-);
Y	= modulus of elasticity of rock (Pa);
k_v	= rock strength parameter (-); and
σ_T	= tensile strength of rock (Pa).

The parameters σ_T and Y can be measured using laboratory tests of rock cores. Sklar and Dietrich (2004) attempted to measure the value of k_v directly from laboratory abrasion tests using various rock types. A table of values is given in Table 4.1. In field situations, it is likely that k_v will be a calibration parameter, but in general it seems to vary between 10^7 to 10^8 (Sklar and Dietrich, 2012). The parameter A_1 is a constant.

Table 4.1. Table 4b from Sklar and Dietrich (2012) containing values of k_v.

Table 4b. K_v Calibration From Single-Grain Abrasion Mill Experiments

Rock Type	σ_t (MPa)	ρ_s (kg m^{-3})	E (g h^{-1})	E (m s^{-1})[a]	k_v
Artificial (20:1)[b]	0.163	2300	215	8.69×10^{-7}	4.07×10^6
Artificial (6:1)	0.448	2300	71	2.87×10^{-7}	1.63×10^6
Artificial (4:1)	1.12	2300	5.1	2.06×10^{-8}	3.63×10^6
Sandstone	1.583	2450	2.9	1.11×10^{-8}	3.37×10^6
Graywacke	9.1	2500	0.22	8.18×10^{-10}	1.38×10^6
Limestone	9.78	2600	0.21	7.51×10^{-10}	1.30×10^6
Welded Tuff	10.9	2600	0.036	1.26×10^{-10}	6.23×10^6
Quartzite	19	2600	0.008	2.86×10^{-11}	9.09×10^6
Andesite	24.4	2600	0.030	1.06×10^{-10}	1.47×10^6

[a]Erosion rate units conversion made with bedrock disc area of 0.03 m^2.
[b]Numbers in parenthesis indicate sand to Portland cement ratios for artificial sandstone.

Lamb et al (2008) computed the effective impact velocity, w_s, based upon a probability distribution of particle velocities. The computation required a integration of the probability density function of the particle velocity and introduced several new empirical parameters. The two-phase flow analysis of Greimann et al. (1999) implies that the magnitude of particles vertical velocity fluctuations scales with the friction velocity. Because k_v is considered to be a calibration parameter, it is sufficient to allow the downward velocity be equal to the friction velocity:

$$w_s = u_* \tag{4.4}$$

4.3 Estimation of Bedrock Erosion Rates in SRH-1D

In SRH-1D, the erosion rate of exposed bedrock is computed from a general combination of the erosion rate due to hydraulic forces and that due to abrasion of sediment particles:

$$E = K_p U \cdot \max\left(\frac{\tau}{\tau_c} - 1, 0\right) + K_a \frac{\rho_s u_*^3 Y C_b}{\sigma_T^2} \tag{4.5}$$

where K_p is a non-dimensional parameter controlling rate of hydraulic scour and K_a is a non-dimensional parameter controlling the rate of abrasive scour and is approximately equal to A_1/k_V. The above expression has the advantage of being dimensionally consistent as opposed to the dimensional equations used in Tomkin et al. (2003). It is also consistent in form to the cohesive sediment transport relationships used in SRH-1D.

The expression for critical stream power, P_c, in Eq (4.1) could be recast as an expression for critical shear stress by assuming uniform flow. The resulting expression to relate critical shear stress to stream power under uniform flow conditions is:

$$\tau_c = \left[\frac{P_c \sqrt{\rho}}{7.66}\left(\frac{k_s}{R}\right)^{\frac{1}{6}}\right]^{\frac{2}{3}} \tag{4.6}$$

where ρ is the density of water. Because the ratio k_s/R is taken to the 1/9 power, its affect is rather small and the possible value of the term will be between 0.6 and 0.9.

The evaluation of the parameters in (4.5) relies extensively on experimental or field data. The critical shear stress, τ_c, can be approximately evaluated based upon erodibility index, k_h, using 4.1, and the erodiblity index can be determined from field data.

It is possible that both hydraulic forces and abrasion occur at a particular field site and their relative contributions may be difficult to distinguish. If the mechanism of erosion is not clear, it would be possible to assume that only the hydraulic forces are important and calibrate τ_c and K_p to the field data. Then one could assume that only sediment abrasion is important to bedrock scour and calibrate K_a to the field data. In many cases, there may not be sufficient data to recommend one approach over the other. In addition, the hydraulic forces and abrasion rates are correlated and the degree to which one is more directly responsible for bedrock erosion may not affect the ability to predict future bedrock erosion.

4.4 Geometrical Representation of Bedrock

The bedrock geometry is input in the same manner as the cross section geometry. The rock properties are also input, such its critical shear stress at which is begins to erode, and/or other rock properties such as its tensile strength and modulus of elasticity. The model tracks whether or not the bedrock is exposed to the erosive action of water and moving sediment. If the bedrock is covered by a layer of stationary sediment, no erosion would occur. If the protective sediment layer is eroded, the bedrock would be allowed to erode. A schematic of the geometrical representation of a cross section is shown in Figure 4.2.

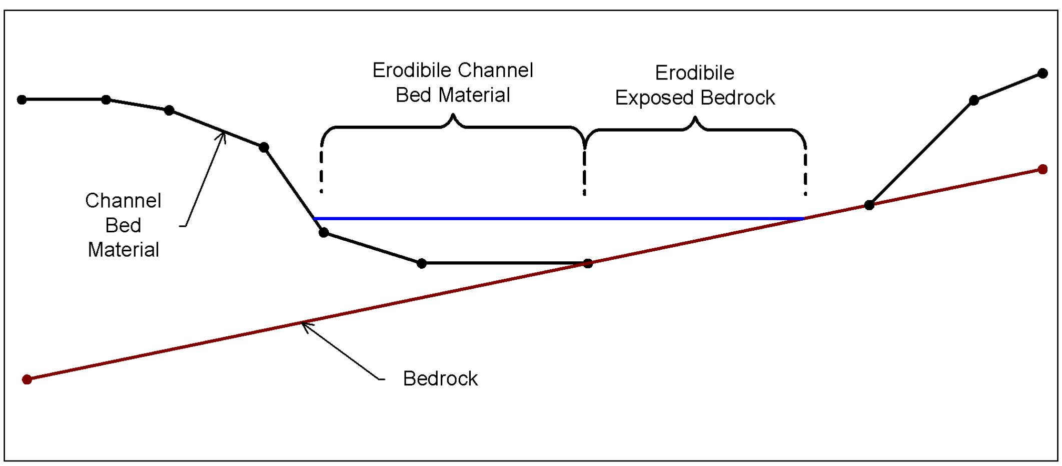

Figure 4.2. Geometrical representation of a cross section and bed rock in SRH-1D.

5 Bed Geometry Solution

5.1 Channel Geometry Adjustment

The volume of erosion or deposition is computed using the mass conservation equations described in Chapter 3. This chapter describes the methods used to apply the computed volume of erosion or deposition to the cross sections. Figure 5.1 shows the two methods SRH-1D uses to adjust channel geometry: vertical adjustment and width adjustment. A vertical adjustment will move all the cross section points below the water surface the same vertical distance as shown in Figure 5.1(a). A width adjustment will move the cross section points below the water surface according to the local water depth as shown in Figure 4.1(b), e.g., $\Delta z_i = ch_i$, where Δz_i is the depth change at point *i*, h_i is the water depth at point *i*, and *c* is a constant. For width adjustments, the maximum bed geometry change occurs near the bank and the thalweg elevation remains unchanged. The user can choose to allow only vertical changes or the user can select the used of energy slope minimization methods for the automatic selection of vertical or width changes by SRH-1D. If floodplains are being simulated, channel adjustment in the floodplains is always assumed to occur in the vertical direction. The width adjustment methods are only applied to the main channel.

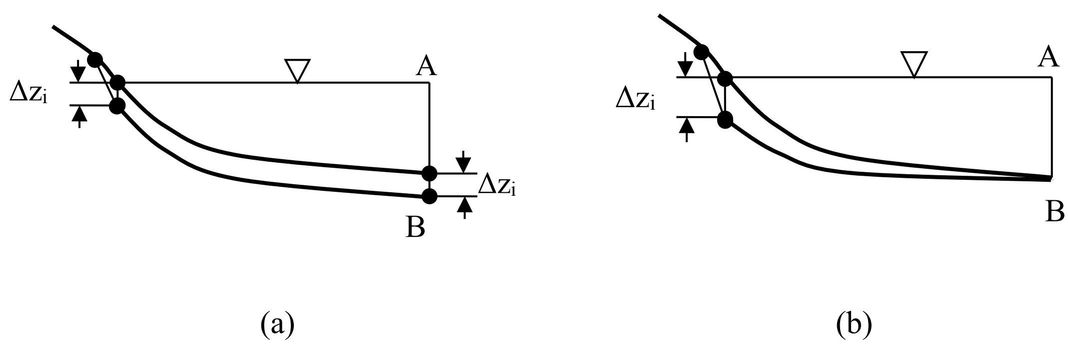

Figure 5.1 Schematic representation of channel changes: (a) vertical adjustment due to scour or deposition; (b) width adjustment due to scour or deposition.

It some cases, erosion does not occur across the entire channel. For example, the sediment delta in a reservoir is much wider than the upstream or downstream river and as the reservoir is drawdown, or the dam is removed, the width of the incising channel is usually similar to the width of the upstream and downstream river. In SRH-1D, the user can specify the erosion width as a function of stream flow. The following equation is used in SRH-1D to determine the erosion width:

$$W_e = aQ^b \tag{5.1}$$

where W_e is the erosion width, Q is the stream flow, and a and b are user defined constants. The boundaries of the erosion width are determined by first finding the centroid, then assuming that W_e is apportioned equally on either side.

5.2 Channel Width Change using Minimization

The user has the option of using the stream power minimization procedure of Chang (1988) to adjust channel geometry. A channel width reduction is usually associated with a decrease in energy gradient at a section, whereas a channel width increase is associated with an increase in energy gradient. To determine the direction of channel geometry change, the energy slope at a section ($S_{f,i}$) is compared with the weighted average of its adjacent sections ($\overline{S}_{f,i}$), which is determined as

$$\overline{S}_{f,i} = \frac{S_{f,i+1} ds_i + S_{f,i-1} ds_{i+1}}{ds_i + ds_{i+1}} \tag{5.2}$$

where ds_{i-1}, ds_i and ds_{i+1} = distances between sections i-1, i, and i+1, respectively. If the energy slope $S_{f,i}$ is greater than $\overline{S}_{f,i}$, the channel width at this section is reduced during deposition or the depth is increased during erosion. If the energy slope $S_{f,i}$ is smaller than $\overline{S}_{f,i}$, the channel depth at this section is decreased during deposition or the width is increased during erosion.

5.3 Angle of Repose Adjustments

As erosion progresses, the steepness of the bank slope will increase. The maximum allowable bank slope depends on the stability of bank materials. When erosion undermines the lower portion of the bank and the slope increases past a critical value, the bank may collapse to a stable slope. The bank slope should not be allowed to increase beyond a certain critical value. The critical angle may vary from case to case, depending on the type of soil and the existence of natural or artificial protection.

SRH-1D checks the angle between points against the critical angle of repose. The user must specify one critical angle above the water surface, and another critical angle below the water surface.

SRH-1D scans each cross section at the end of each time step to determine if vertical or horizontal adjustments have caused the banks to become too steep. If violations occur, the two points adjacent to the segment are adjusted vertically until the slope equals the user-provided critical slope. If the segment is all above or below water, then the appropriate user defined angle of repose is used. If the water surface elevation intersects the segment, then the average of the above and below water angle of repose is used. The material taken from the bank is added as a lateral sediment input at that cross section.

6 Input Data Requirements

The input data necessary to run the SRH-1D model may be separated into 15 data groups as listed below:

1. Model Parameters
2. Upstream Boundary Conditions
3. Downstream Boundary Conditions
4. Internal Boundary Conditions
5. Lateral Inflows
6. Channel Geometry and Flow Characteristics
7. Sediment Model Parameters
8. Upstream Sediment Boundary Conditions
9. Lateral Sediment Discharge
10. Sediment Bed Material
11. Water Temperature
12. Erosion and Deposition Limits
13. Sediment Transport Parameters
14. Cohesive Sediment Transport Parameters
15. Bedrock Geometry and Parameters

The following sections describe each data group.

6.1 Model Parameters

The Model Parameters data group contains the input parameters that control the overall simulation. The Model Parameters contain the title of the simulation and the several parameters that control program execution. A list of records is given in Table 6.1.

There are two basic types of flow and sediment solutions offered: Steady and Unsteady. It is recommended that if the steady flow solution is chosen, then the steady sediment solution is also chosen. The same is true for the unsteady flow and unsteady sediment solutions.

There are two options for unsteady flow: unsteady and shock capturing.

The time step is an important parameter that influences the stability and accuracy of the simulation. In general, smaller time steps will produce more stable and more accurate results. However, the computer time required for simulation is directly proportional to the number of time steps calculated. It is recommended that the time step be decreased until further decreases no longer significant affect the final answer. The time step required for unsteady flow is usually much smaller than for steady flow.

The output file sizes may be unreasonably large if the output time step is too small. In addition, the time required for simulation will also increase. If small file sizes or fast computational time is required, increase the output time step. The hotstart option is not functioning in this current version.

Table 6.1 Input records in Model Parameter data group.

Record	Description
YTT	Title of study
YSL	Solution parameters
YTM	Time of simulation, minimum flow option
YDT	Simulation time step and output time step

6.2 Upstream Flow Boundary Conditions

The upstream flow boundary condition can be specified as a junction to another river, a stage time series or a water discharge time series. When a time series is specified and the simulated time falls between the given values, interpolation is required. The interpolation is linear in time when unsteady flow is specified. If steady flow is specified, no interpolation is performed and the water discharge or stage does not change until the time of the next input water discharge is reached. An example of the steady flow approximation of a water discharge hydrograph is shown in Figure 6.1.

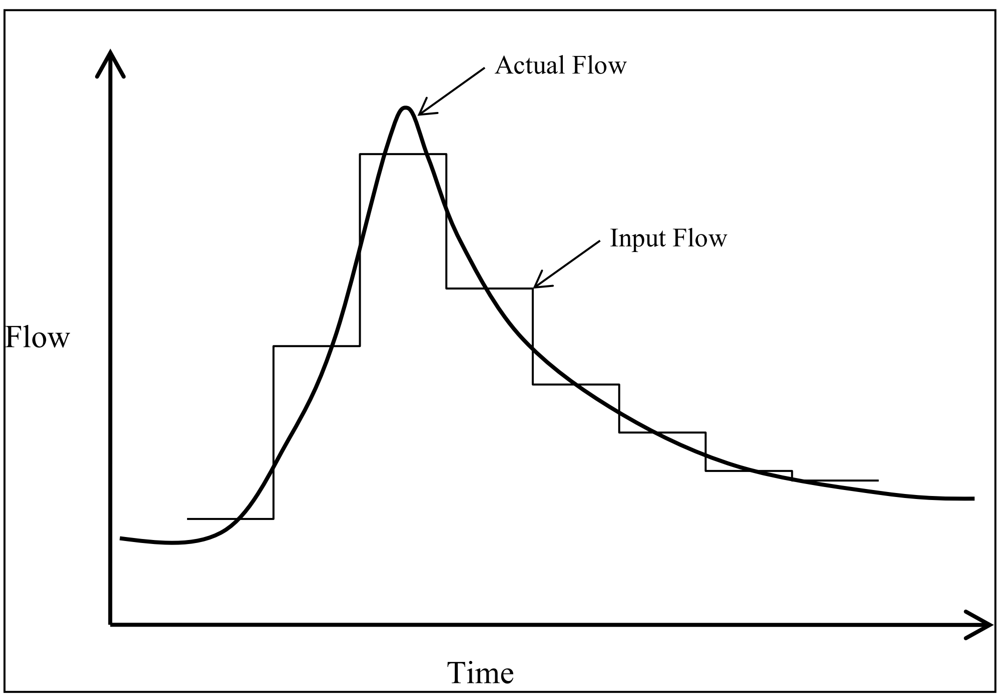

Figure 6.1 Steady Flow Representation of a Water Discharge Hydrograph.

6.3 Downstream Flow Boundary Conditions

Several different types of downstream boundary conditions are possible. A water discharge rating curve specifies the relationship between water discharge and elevation. The downstream boundary condition can also be a times series of water surface elevations or, for unsteady flow, water discharge. For time series data, the interpolation between given values is performed the same as for the upstream flow boundary condition. A weir boundary condition can also be specified where the weir elevation, width, and discharge coefficient are given. The rating curve option is similar to the water discharge versus water surface elevation table, but the user just enters the coefficients in a power relationship between water discharge and water surface elevation.

A combination of specified discharge and downstream rating curve can also be used for unsteady simulations. This boundary condition could be used, for example, when the downstream boundary is a dam and one wants to deliver a certain flow from the dam. However, the downstream delivery would be limited by the outlet capacity.

Table 6.2 Possible downstream boundary conditions.

Record	Description
D00	Junction – this river is linked to another river
D01	Time versus water surface elevation table
D02	Time versus water discharge table (only available for unsteady flow)
D03	Water discharge versus water surface elevation table
D04	Weir
D09	Rating Curve relationship between water discharge and water surface elevation

6.4 Internal Boundary Conditions

Many of the same boundary conditions that can be applied at the downstream end of the modeled reach can also be used at internal cross sections. In addition, bridges and radial gates can be modeled. The types of permissible internal boundary conditions, along with their record identification are given in Table 6.3. A combination of specified discharge and downstream rating curve can also be used for unsteady simulations. This boundary condition could be used, for example, when the downstream boundary is a dam and one wants to deliver a certain flow from the dam. However, the downstream delivery would be limited by the outlet capacity.

Table 6.3 Possible internal boundary conditions.

Record	Description
I01	Time versus water surface elevation table
I02	Time versus water discharge table (only available for unsteady flow)
I03	Water discharge versus water surface elevation table
I04	Weir
I06	Bridge
I08	Radial Gate – inline or side discharge
I09	Rating Curve relationship between water discharge and water surface

	elevation

6.5 Lateral Inflows

Lateral inflows can be specified anywhere along a river reach according to the stream distance where the lateral inflow enters. Each lateral inflow requires a time series table of water discharge.

6.6 Channel Geometry and Flow Characteristics

SRH-1D represents the river in a manner similar to other 1D models. The river is described by discrete cross sections located at specified intervals (Figure 6.2). The cross sections are chosen by the user to represent important hydraulic behaviors of the river and all the controls that may exist on that river. The distance between the cross sections is termed the reach length. The reach length should be appropriate to the problem being solved. Many factors control the choice of cross section location and reach lengths, but some guidelines are given below (modified from Samuels, 1990):

1. Select all sites of key interest.
2. Select cross sections adjacent to major structures and control points.
3. Select cross sections representative of the river geometry.
4. As a first estimate, select cross sections 20 times the channel width apart.
5. Select sections a maximum of $0.2Y/S_0$ apart, where Y is the depth and S_0 is the bed slope.
6. For unsteady flow modeling, select sections a maximum of $L/30$ apart, where L is the length of the physically important flood wave.
7. Cross sections spacing must be greater than the survey horizontal error and greater than the computer's precision for representing distance.
8. The ratio of the area between two adjacent cross sections should be between 2/3 and 3/2.
9. Cross-sectional spacing may have to be reduced for shallow flows where the average of the friction slope between cross sections has a large error.

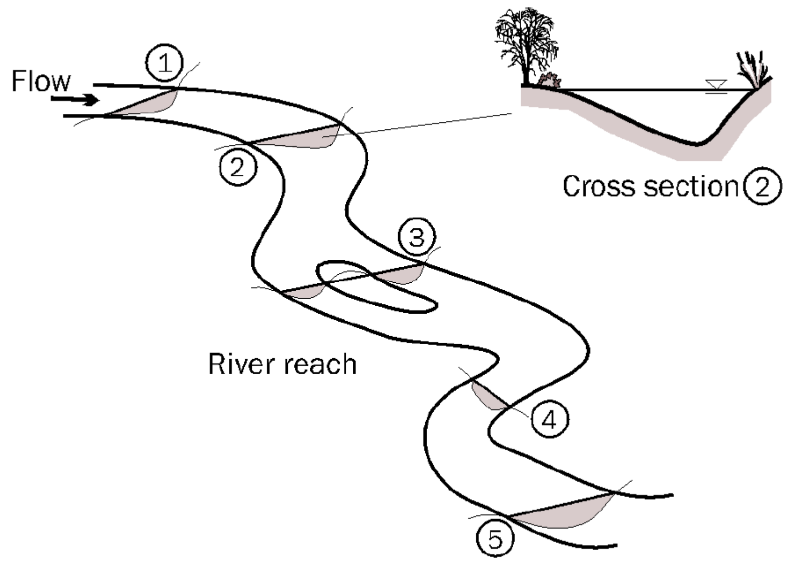

Figure 6.2 Representation of River by Discrete Cross sections. (From Yang and Simoes, 2002).

The SRH-1D cross section geometry representation was developed similar to the HEC-RAS representation. The cross section representation used in HEC-RAS can be found in the Hydraulic Reference Manual of HEC-RAS 4.0 (USACOE, 2008). An example of a cross section is shown in Figure 6.3. Three components are required for every cross section. The cross section points describe the geometry. The over bank points distinguish the main channel from the floodplain. For braided streams, these points should be located on the left most and right most points of the active channels. Roughness coefficients are defined for segments of the cross section. The user may define one to 10 different roughness segments for each cross section. The Manning's equation is used to calculate friction loss. Many references describe the selection of the Manning's roughness coefficients. A pictorial guide of roughness characteristics of streams is found in Barnes (1987). Extensive tables of Manning's roughness coefficient values are found in Chow (1959). Cowan (1956) and Arcement and Schneider (1987) use various factors, such as bed material type, vegetation, channel meandering, etc. and develop a method for computing Manning's roughness coefficients based on individual modifications. There have also been several attempts to develop equations to predict Manning's *n* value based upon water discharge and bed material characteristics. For example, see Einstein and Barbarossa (1952), Engelund and Hansen (1966), Richardson and Simon (1967), Limerinos (1970), White et al. (1979), Griffiths (1981), van Rijn (1982), Brownlie (1983), Jarrett (1984), Karim and Kennedy (1990), and Yang (1996).

Optional flow areas are available to restrict conveyance in a cross section. The options are designed similar to those of HEC-RAS. These options include ineffective flow areas, permanent ineffective flow areas, dry areas, and blocked areas. Ineffective flow is used to define a portion of a cross section where water is not actively conveyed. In an ineffective flow area, water ponds and the velocity of the water is close to zero. Ineffective flow areas become effective once the water surface rises above the defined elevations. Permanent ineffective flow areas are used to define a portion of a cross section where the water is always ineffective below the established elevation, and effective above the elevation. Dry areas are used to define an area protected by levees. No water is allowed in the area until the levee elevation is exceeded. Blocked areas are used to define a portion of a cross section permanently blocked by a hydraulic structure or other feature.

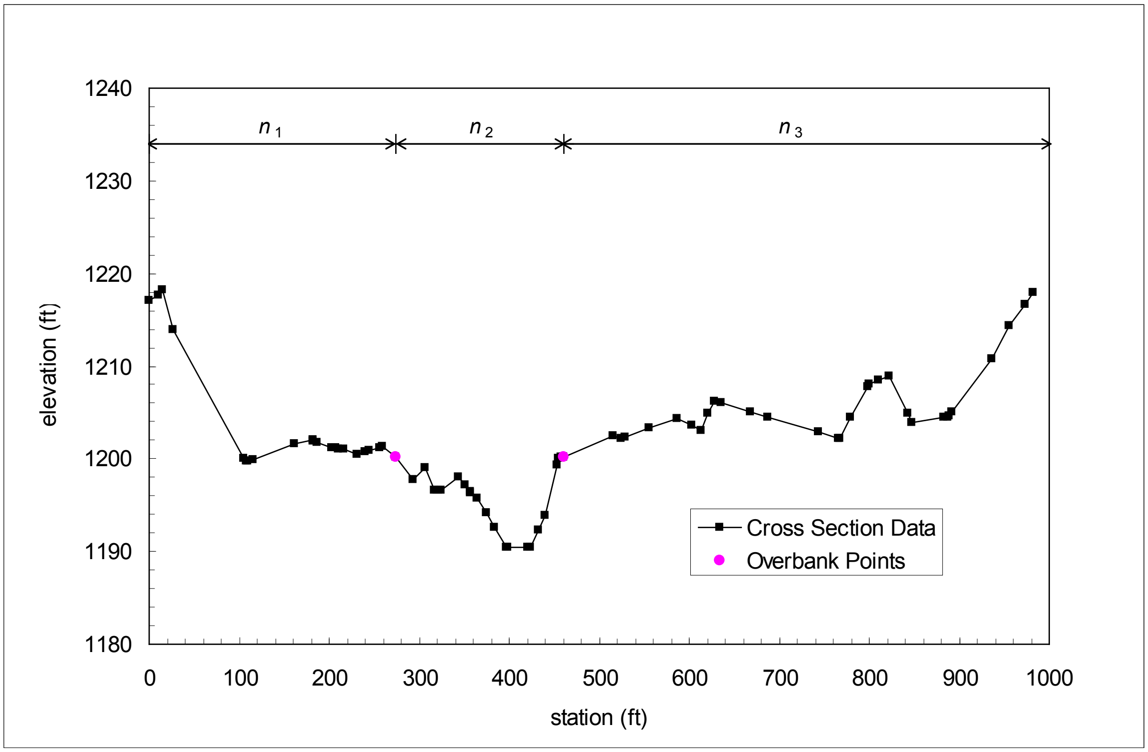

Figure 6.3 Representation of Cross Section by Discrete Points.

6.7 Sediment Model Parameters

Sediment model parameters control the number of bed layers used to represent the river bed, the implicit factor for sediment transport computations and number of sediment time steps performed for each hydraulic time step. The default value for the number of river bed layers is 3. The default for the implicit factor is 1. The number of sediment time steps default value is 1. The frequency the angle of repose condition is checked is set here too. The default is that the angle of repose is checked every time step. The user can also set the minimum and maximum size of the bed layers in this data group. The user enters a constant by which the active layer thickness is multiplied to determine the minimum and maximum thicknesses of each bed layer. The sediment size groups are also given in this data group.

6.8 Sediment Boundary Conditions

Sediment entering a reach at an upstream boundary must be specified for each size fraction. There are several ways to specify incoming sediment loads:

1. An equilibrium sediment load can be assumed. If this option is chosen, then the sediment load coming into the reach is calculated based on the bed material and the sediment transport equation specified in Data Group 13. The hydraulics of the most upstream section are used in the transport equation.
2. A sediment rating curve is used. The sediment rating curve is a power relationship between flow and total sediment discharge. The total sediment discharge is divided into fractional sediment discharge using a table of water discharge and fraction of total sediment load for each size fraction.
3. A total sediment load versus discharge table is specified. This option is similar to the previous option except that a table is used to specify the sediment discharge instead of a power function.
4. The total sediment load is specified as a time series. The user may directly specify the amount of sediment entering the reach as a function of time. The total sediment discharge is divided into the sediment size fractions similar to the previous two options.

Ideally, to determine the amount of sediment entering a reach, there is a sediment measuring station at the most upstream cross section of the model. However, this is rarely the case. It may be necessary to calculate an approximate incoming load based upon bed material and a sediment transport function. The sediment transport function generally should be consistent with the Sediment Transport Parameters Data Group.

6.9 Lateral Sediment Discharge

A lateral sediment discharge can be specified for each lateral inflow specified in Data Group 5. The lateral sediment discharge is specified in the same way as the upstream sediment discharge.

6.10 Sediment Bed Material

The percentage of each sediment size fraction present in the initial river bed is required for each river reach. The information is given at specific locations or select cross sections and interpolated to the rest of the river. Edwards and Glysson (1999) describe bed material sampling methods and equipment appropriate for material finer than medium gravel (less than 8 mm) as well as those appropriate for larger material. Bunte and Abt (2001) provide a comprehensive detailed description of available methods.

6.11 Water Temperature

The water temperature is input for each river as a time series. Presently, a uniform temperature is assumed throughout the river.

6.12 Erosion and Deposition Limits

The erosion and deposition limits control the allowable extents of cross section change. No deposition is allowed above the maximum vertical limit and no erosion is allowed below the minimum vertical limit. The points to the left of the minimum horizontal erosion limit and to the right of the maximum horizontal erosion limit are not allowed to erode. The points to the left of the minimum horizontal deposit limit and to the right of the maximum horizontal deposit limit are not allowed to deposit.

The constants used to determine the erosion width are also set here. These are commonly required when such processes as incision through reservoir deltas are being simulated.

6.13 Sediment Transport Parameters

The Sediment Transport Parameters Data Group contains several parameters used in the computation of sediment transport. These are given in Table 6.4.

The minimization option controls how channel geometry changes. Currently, only the no minimization option or the minimization of energy slope options are recommended.

The model may be sensitive to the sediment transport equation chosen. No one equation can be recommended for all rivers. Ideally, the sediment transport equation should be compared against actual sediment load measurements. Most often, a range of transport formulas is suggested.

The active layer thickness is also set here. The active layer thickness is an important parameter in determining the rate at which the simulated river responds to changes in sediment load. The active layer thickness is the thickness over which mixing of sediment occurs. As the active layer thickness increases, the bed fractions of the active layer thickness will change more slowly. Therefore, armoring occurs more slowly. Conversely, as the active layer thickness decreases, armoring will occur more rapidly. The coefficient that is multiplied by a representative particle diameter to obtain the active layer thickness is often a calibration parameter. However, the developer’s experience is that it is related to the dune height in sand bed streams and related to the largest particle in gravel bed streams.

The angle of repose defines the maximum bank angle within the cross section. This information can be taken from field data of bank angles.

Table 6.4 Records used in Sediment Transport Parameters data group.

Record	Description
SMN	Minimization option – 0 if no minimization performed
SEQ	Sediment transport equation
SE1	The reference or critical shear stress and hiding factor

SA_	Location of sediment transport parameters in SAT
SAT	Sediment transport parameters – angle of repose, active layer thickness, non-equilibrium factors, diffusion coefficients

6.14 Cohesive Sediment Transport Parameters

Sediment particles smaller than 0.0625 mm are assumed cohesive sediment and require several parameters to define their transport characteristics (Table 5.5). The physical significance of the parameters are given in Sections 3.1.5 to 3.1.7. Additional guidance on the parameter values can be found in Reclamation (2008).

Table 6.5 Parameters necessary for cohesive sediment erosion and deposition.

Parameter	**Description**
Fall velocity, ω	Controls the rate at which deposition occurs
Critical shear stress for full deposition, $\tau^c_{d,full}$	Deposition will occur at shear stresses below $\tau^c_{d,full}$.
Critical shear stress for partial deposition, $\tau^c_{d,part}$	Partial deposition will occur at shear stresses below $\tau^c_{d,part}$ and above $\tau^c_{d,full}$.
Equilibrium concentration for partial deposition, c_{eq}	Equilibrium concentration during partial deposition
Critical shear stress for surface erosion, τ^c_{se}	Surface erosion occurs above τ^c_{se} and below τ^c_{me}.
Critical shear stress for mass erosion, τ^c_{me}	Mass erosion occurs above τ^c_{me}.
Rate Constant for Surface Erosion, P_{se}	Slope of surface erosion rate versus shear stress line
Rate Constant for Mass Erosion, M_{me}	Slope of mass erosion rate versus shear stress line
Initial bulk density, ρ_i	Initial bulk density of cohesive sediment
Final bulk density, ρ_f	Final bulk density after full consolidation
Time to reference bulk density, t_e, and reference bulk density, ρ_e	t_e and ρ_e are used to compute, β, which is the consolidation parameter controlling the rate of consolidation

6.15 Bedrock Geometry and Parameters

The user is required to enter the station elevation data of the bedrock for cross sections where it exists. This entire data group is optional and if not significant bedrock control exists in the model reach, it can be skipped. After the bedrock geometry is entered, parameters the determine the bedrock's resistance to scour need to be entered. The parameters that determine the rate of hydraulic scour are the critical shear stress at which bedrock scour starts and a non-dimensional constant the controls the rate of scour. The parameters that determine the rate of scour due to sediment abrasion are 1) the modulus of elasticity of rock, which is proportional to the rate of scour, 2) the tensile strength of rock, which is inversely proportional to the rate of scour, and 3) a non-dimensional rock strength parameter, that is treated as a calibration parameter and is inversely proportional to the rate of scour.

If no bedrock scour is desired, set the K_p and k_v parameters to zero.

7 Running SRH-1D

7.1 Input Data Format

SRH-1D reads a single input file that contains all the necessary information to perform a simulation. An input file is organized in sequential records. The sequence is presented in a flow chart in Appendix A. A record is a line of up to 300 characters in length. A line starting with "*" is a comment line and will be ignored by the model. A record starts with a specific record name containing 3 characters. Each record name is unique and inputs specific data to the program. A comprehensive list of all records names used by SRH-1D is given in Appendix B. A detailed explanation of all the records is given in Appendix C. Not all records are used (for example, some are mutually exclusive) but they have to be in an appropriate sequence.

Data after the record name is in an unformatted form to prevent unnecessary errors. Error checking is provided to prevent some human errors, which include:

- empty lines;
- lines started with space instead of the record name;
- incorrect record names;
- incorrect number of data following the record name;
- incorrect data values.

The data are prepared in ASCII files. For easy data input, sample examples are provided in the Microsoft EXCEL format, users may save the data in type of "Text Formatted (Space delimited) *.prn". It is recommended that the user study the example input files included in the distribution of SRH-1D to become familiar with the input data format. The EXCEL sample input files also contain the explanation of each variable in the comment field.

7.2 Executing SRH-1D

After preparing the input data file, SRH-1D can be executed within windows by double-clicking the filename in Windows Explorer. SRH-1D can also be used from the command line interface. At the prompt, simply type:

C:\> PROGRAM_NAME FILENAME

or

C:\> PROGRAM_NAME –e FILENAME

where PROGRAM_NAME is the name of the SRH-1D executable and FILENAME is the input filename (including the filename extension) that will be run. The argument "-e" in the commend line forces the program to exit all windows when the program is terminated.

Make sure the executables exist in the system PATH variable. If SRH-1D is launched without an input file name, the program prompts the user to enter it. For consistency, the input data file should have an extension .SRH (or .srh), but the program will work with any other extension. The FILENAME argument can also include the drive letter and path information if the entire string is encapsulated by quotes.

SRH-1D displays the current bed profile and user specified cross sections during the simulation. Using this real time display, one can monitor the simulation during a run. This feature is useful in debugging the simulation.

7.3 Output Files

For a given input file named sample.dat, the following files may be generated.

sample_OUT.dat: the *_OUT.dat file first summarizes the dimensions used by the model, such as the river number, the sediment size fractions, the bed layer number, the cross section number, the maximum points in a cross section, etc. Then it echoes the input data. When an error occurs on reading the input files, the users should first check this file for possible warnings.

sample_ERR.dat: the *_ERR.dat file contains errors encountered during run time. If the program stops, please check this file for error messages.

sample_HEC_RAS_GEOMETRY.g01: the *_HEC_RAS_GEOMETRY.g01 is a HEC-RAS geometry file. It is updated each DTPLT time step defined in record YDT. User may use HEC_RAS model to check the initial input geometry and the final geometry.

sample_OUT_Profile.dat: the *_ **OUT_Profile**.dat file is the bed profile file, which contains the cross section number, the original cross section number, the cross section location, the discharge, the lateral water discharge, the original thalweg elevation, the current thalweg elevation, the current water surface elevation, the average bed elevation of the main channel, the friction slope, the channel top width, the hydraulic radius, the sediment sizes d_{16}, d_{35}, d_{50}, d_{86}, and the bed shear stress.

sample_OUT_XC.dat: the ***_OUT_XC.dat** file contains the cross section data. The program will not permit the cross section file to be written more than 20 times.

sample_OUT_MaterialVolume.dat: the ***_OUT_MaterialVolume**.dat file contains the cumulative material volume of deposition in all sub-channels and in each sub-channel.

sample_OUT_Volume.dat: the ***_OUT_Volume**.dat file contains the cumulative volume of deposition material in all size fractions and as calculated in the main channel and left and right floodplains.

sample_OUT_MassBalance.dat: the ***_MassBalance**.dat file is the mass balance file, which contains the mass balance, sediment coming in from upstream entrances, sediment flowing out from downstream exits, sediment coming in from lateral point and not-point sources, and sediment erosion. The sediment mass balance is only valid for a steady sediment transport model.

sample_OUT_Conc.dat: the ***_OUT_Conc.dat** file contains the sediment concentration data of each size fraction in each sub-channel.

sample_OUT_BedLayer.dat: the ***_OUT_BedLayer**.dat file contains the bed thickness data of each bed layer in each sub-channel.

sample_OUT_BedFraction.dat: the ***_OUT_BedFraction**.dat file contains the sediment size fraction data of each bed layer in each sub-channel.

sample_OUT_Porosity.dat: the ***_OUT_Porosity**.dat file contains the sediment porosity data of each bed layer in each sub-channel.

sample_OUT_SedimentLoad.dat: the ***_OUT_SedimentLoad**.dat file contains the sediment load passing each cross section for each size fraction in each sub-channel.

sample_OUT_TimeSeries.dat: the ***_OUT_TimeSeries**.dat file contains time series information at the cross sections being viewed on screen during run time.

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APPENDIX A - Flow Chart of Input Data Records

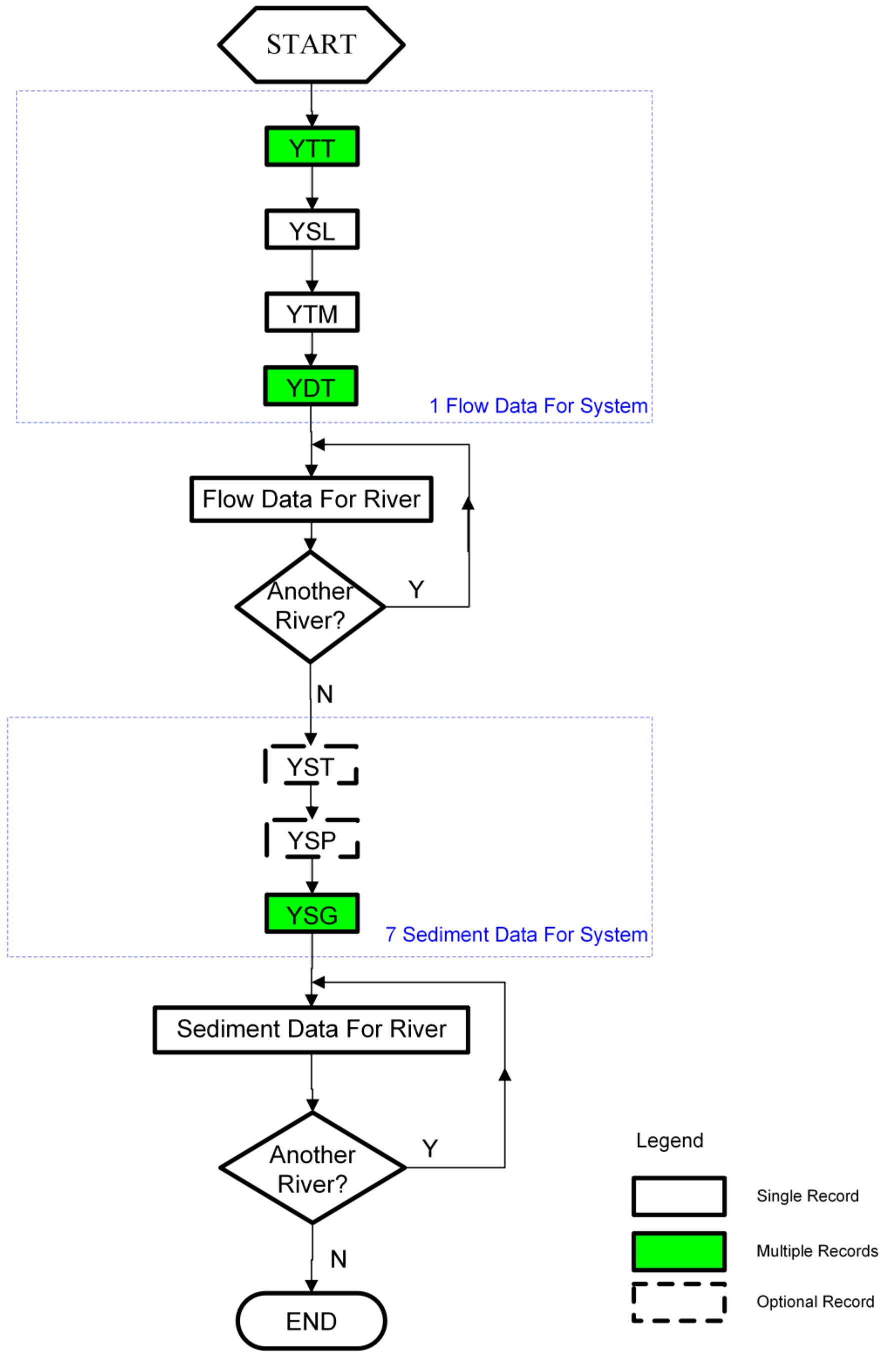

Figure A-1 Flowchart of input data records

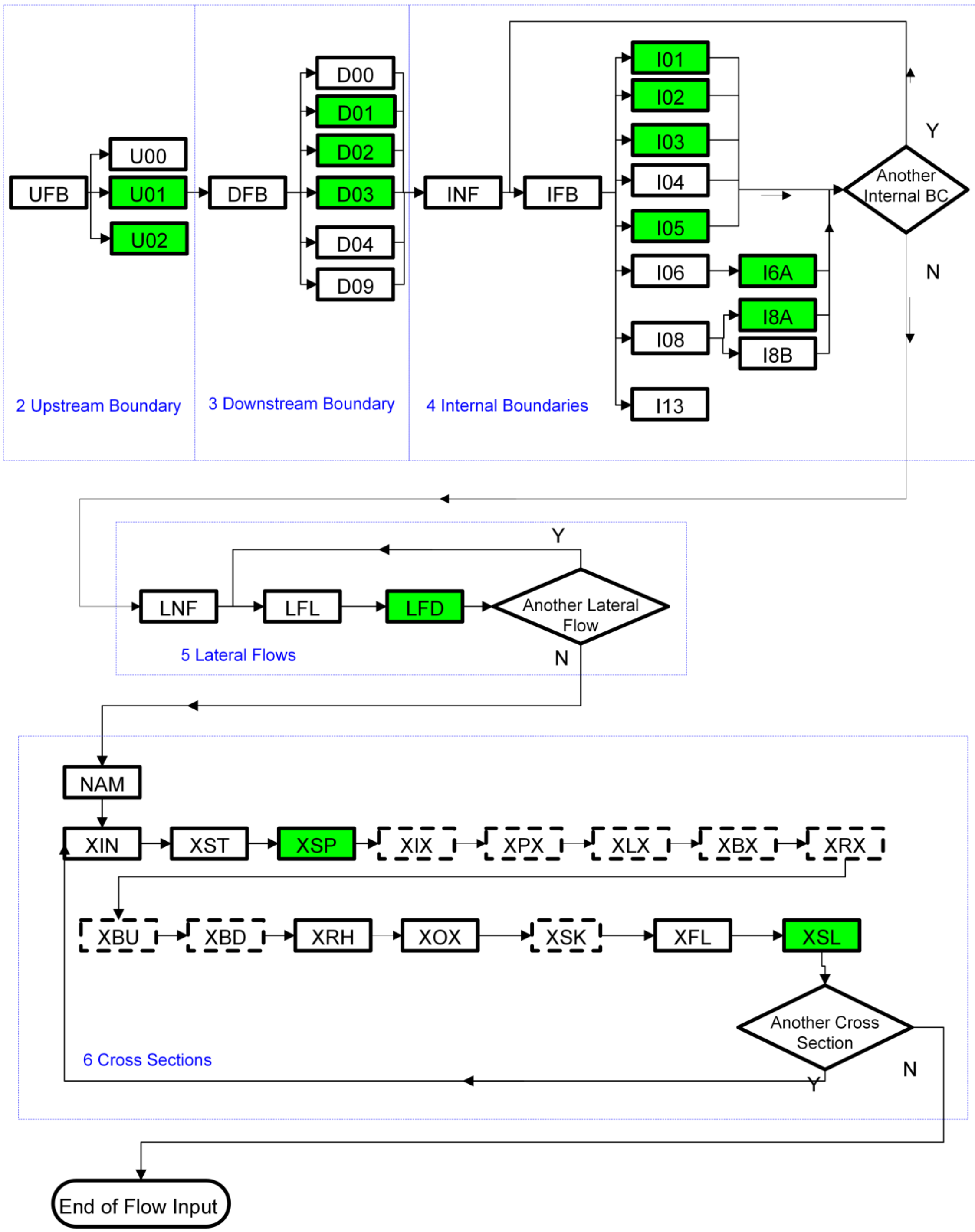

Figure A-2 Flowchart of flow data records for a river

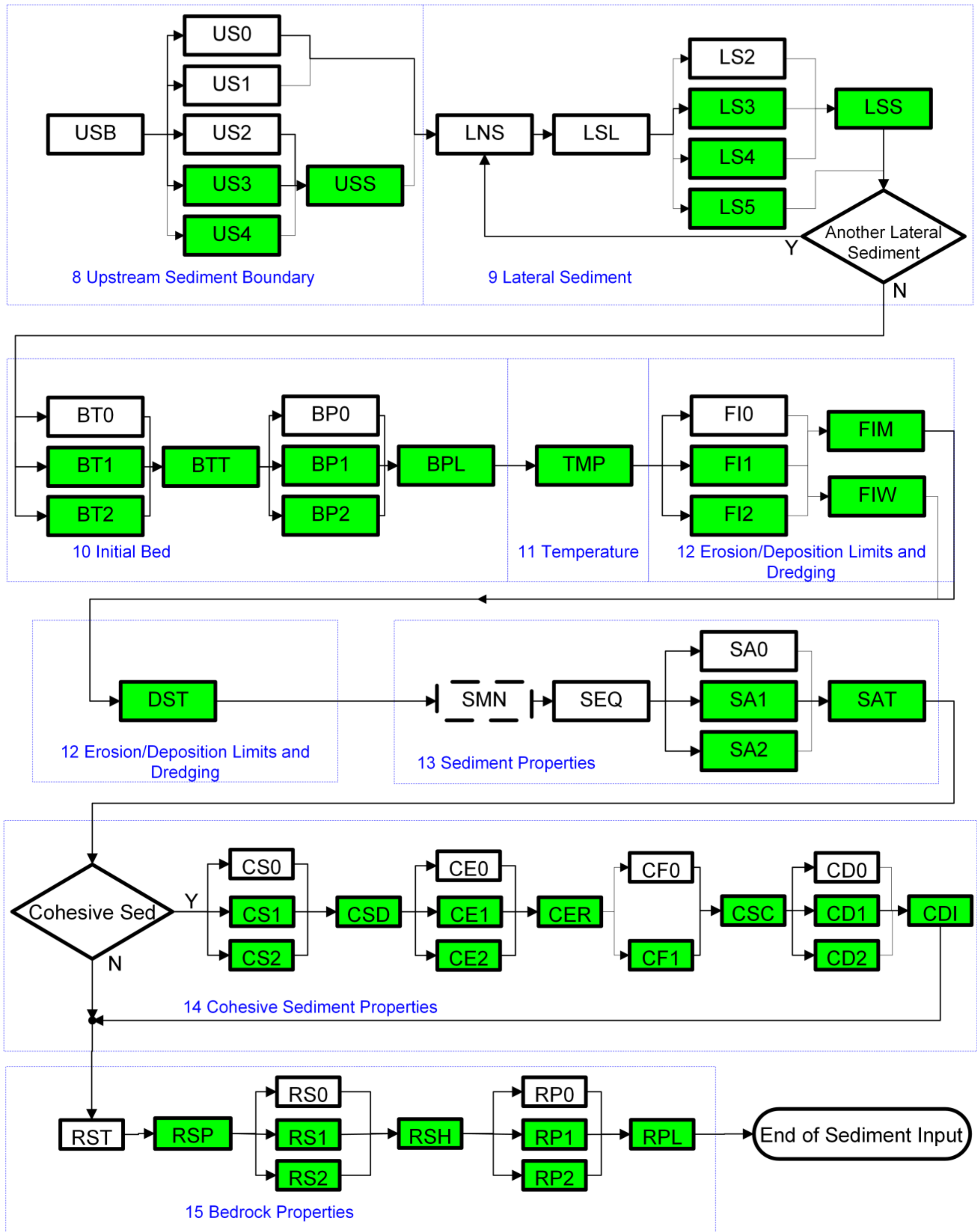

Figure A-3 Flowchart of sediment and bedrock data records for a river.

APPENDIX B – List of the Input Data Records

Data Group Page in Appendix C

Alphabetical List

Record: Explanation Page in Appendix C

Sequential List

Record: Explanation — Page in Appendix C

APPENDIX C - Descriptions of Records

The following sections detail the input data for each of the 14 data groups. Each record is defined by a three letter code followed by variables. Each variable can be one of three types: text, integer, or real number data. Each record may contain several variables. Each variable is described as follows:

Variable: Gives the variable name.

Type: The type can be either text, integer (int), or real (float).

Value: Give the potential ranges for this variable.

Description: Describes the significance of this variable.

Data Group 1. Model Parameters

YTT

YTT: Title of Study

Optional

The YTT record is used to define the title of the simulation. Any number of YTT records can be used. The text will be echoed to the output files generated by SRH-1D.

If a river network is simulated, records YTT to YDT are common data for the entire network. Records UFB to XSL are specified for each river.

YTT TITIL

Variable	Type	Value	Description
TITIL	text		Title of study

YSL

YSL: Solution parameters

Required

The YSL record specifies the solution method used to compute the hydraulics, the solution method used to compute the sediment transport, the calculation tolerance, the implicit factor, the streamwise distance scaling factor, metric option, and the cross section coordinate order.

YSL ISOLVE ISOLVES EPSY F1 XFACT METRIC YZ ISMET

Variable	Type	Value	Description
ISOLVE	int		Type of flow solution
		1	Steady flow, critical depth default
		2	Unsteady flow, central difference
		3	Unsteady flow, shock capturing
ISOLVES	int		Type of sediment solution
		0	No Sediment computations performed
		1	Exner Equation Routing
		2	Unsteady Sediment Transport Routing
EPSY	float	+	Calculating tolerance for flow and sediment
F1	float	+	Implicit factor for unsteady flow, not used for steady flow
XFACT	float	+	Scaling factor, the cross-section streamwise distance will be multiplied by this factor
METRIC	int		Metric units option
		0	English units
		1	Metric units
YZ	int		Coordinate Order
		0	ZY order, bed elevation (Z value) followed by the lateral location (Y value)
		1	YZ order, lateral location (Y value) followed by the bed elevation (Z value)
GISMET	int		Metric units option for GIS cut lines
		0	English units
		1	Metric units

YTM

YTM: Time

Required

YTM record defines the total time of simulation, the hot start condition, and the minimum flow parameter.

The minimum flow discharge defines the discharge below which no hydraulic calculations or sediment transport is simulated. It can be set to zero if the user wants to include all flows in the hydrology record.

YTM THE IHOTST QMIN TSTART XC_OUT

Variable	Type	Value	Description
THE	float	+	Total time of simulation (hr)
IHOTST	int	0	Do not start up from hotstart file, but do produce one during simulation
		1	Start simulation from hotstart file
		2	Do not write or use hotstart file
QMIN	float	0/+	Minimum flow discharge to be calculated Discharges smaller than this value will be ignored.
TSTART	float	0/+	Time at which simulation starts
XC_OUT	int	0	Output cross section at end of simulation
		1	Output cross sections maximum of 20 times
		2	Output cross sections every DTOUT
BED_LAY	int	0	Output only first bed layer
YEAR0	float	0/+	Year at start of simulation
MONTH0	float	0/+	Month at start of simulation
DAY0	float	0/+	Day at start of simulation
HOUR0	float	0/+	Hour at start of simulation (24 hr)

YDT

YDT: Time Step

Required

This record defines the time step for flow simulation and for printing. This record also defines the cross section numbers that will be displayed on the screen during the simulation. More than one YDT record can be used. No interpolation and extrapolation is used. If the time step is smaller than the time TDT at the first record, the time step at the first record is used. If the time step is larger than the time TDT at the last record, the time step at the last record is used. Multiple XCPLT numbers can be specified, with a maximum of 10 suggested.

YDT TDT DT DTOUT DTPLT XCPLT

Variable	Type	Value	Description
TDT	float	+	Time (hr) when time step is defined (increases in each record)
DT	float	+	Time step (hr) at time TDT
DTOUT	float	+	Time interval (hr) at time TDT to write to file
DTPLT	float	+	Time interval (hr) at time TDT to update screen
XCPLT	int	+	Cross section number for on-screen plotting at time TDT

Data Group 2. Upstream Boundary Conditions

UFB

UFB: Upstream Flow Boundary Condition

Required

The UFB record specifies the upstream flow boundary condition type.

If a river network is simulated, records YTT to YDT are common flow data for the entire network. Records UFB to XSL are specified for each river.

UFB KU

Variable	Type	Value	Description
KU	int	0/+	Type of upstream boundary condition
		0	Junction
		1	Table (time, stage)
		2	Table (time, flow rate).

U00

U00: Upstream Flow Boundary Condition ------ Junction

Optional, required only if KU = 0 in record UFB

The U00 record specifies which rivers connect to the upstream end of the river. The record ID is followed by other river indexes at the junction. A positive number is used if the connecting river is entering the junction and negative number is used if the connecting river is exiting the junction. If flow direction is not known before the simulation is run, a flow direction can be assumed and a negative discharge for that river at the junction indicates that flow is in the other direction. The program organizes the rivers in ascending order with river 1 being the most upstream.

U00 URIV(1:nu)

Variable	Type	Value	Description
URIV	int	-/+	River indexes at the junction for, nu is number of rivers connection upstream
		+	Flow enters junction
		-	Flow exits junction

U01

U01: Upstream Flow Boundary Condition ------ Time-Stage Table

Optional, required only if KU = 1 in record UFB

The U01 record defines the upstream flow boundary condition as a time-stage table. The U01 record is repeated until the entire table is input. This record can only be used for unsteady flow simulations.

U01 T1 ST1

Variable	Type	Value	Description
T1	float	+	time (hr)
ST1	float	+	river stage (cfs or cms) at upstream at time T1

U02

U02: Upstream Flow Boundary Condition ------ Time-Discharge Table

Optional, required only if KU = 2 in record UFB

The U02 record defines the upstream flow boundary condition as a time-discharge table. The U02 record is repeated until the entire table is input. One record is used for each time-discharge pair. The U02 record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table. For unsteady flow, the discharges are interpolated in time between the specified $T1$ values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < T1_1$ the discharge for $T1_1$ is used; if $T > T1_n$ the discharge for $T1_n$ is used, where n is the total last row of the table. If there is no discharge before the first value or after the last value, a zero discharge should be added at the beginning or end of the table, respectively.

U02 T1 ST1

Variable	Type	Value	Description
T1	float	+	time (hr)
ST1	float	+	river discharge (cfs or cms) at upstream at time T1

Data Group 3. Downstream Boundary Condition

DFB

DFB: Downstream Flow Boundary Condition

Required

The DFB record specifies the downstream flow boundary condition type.

DFB KD

Variable	Type	Value	Description
KD	int	0/+	Type of downstream boundary condition
		0	Junction
		1	Table (time, stage)
		2	Table (time, discharge)
		3	Table (discharge, stage)
		4	Weir flow
		9	Rating curve with coefficients
		11	Combination of Time-discharge table and Discharge-stage table (I02 and I03), only available for unsteady flow simulations

D00

D00: Downstream Flow Boundary Condition ------ Junction

Optional, required only if KD = 0 in record DFB

The D00 record specifies which rivers connect to the downstream end of the river. The record ID is followed by other river indexes at the junction. A positive number is used if the connecting river is entering the junction and negative number is used if the connecting river is exiting the junction. If flow direction is not known before the simulation is run, a flow direction can be assumed and a negative discharge for that river at the junction indicates that flow is in the other direction. The program organizes the rivers in ascending order with river 1 upstream.

D00 DRIV(1:nd)

Variable	Type	Value	Description
DRIV	int	-/+	River index at the junction, nd = Number of rivers connected with the river at downstream
		+	Flow enters junction
		-	Flow exits junction

D01

D01: Downstream Flow Boundary Condition ------ Time-Stage Table

Optional, required only if KD = 1 in record DFB

The D01 record defines the downstream flow boundary condition as a time-stage table. The record ID is followed by one pair of time and stage data. The D01 record is repeated until the entire table is input.

D01 TN STN

Variable	Type	Value	Description
TN	float	+	Time (hr)
STN	float	+	River stage (ft or m) at downstream at time TN

D02

D02: Downstream Flow Boundary Condition ------ Time-Discharge Table

Optional, required only if KD = 2 or 11 in record DFB

The D02 record defines the downstream flow boundary condition as a time-discharge table. The record ID is followed by one pair of time and discharge data. The D02 record is repeated until the entire table is input. For unsteady flow, the discharges are interpolated in time between the specified T1 values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < TN_1$ the discharge for TN_1 is used; if $T > TN_n$ the discharge for TN_n is used, where n is the total last row of the table. For steady flow, this record should not be used.

D02 TN STN

Variable	Type	Value	Description
TN	float	+	Time (hr)
STN	float	+	Discharge (cfs or cms) at downstream boundary at time TN

D03

D03: Downstream Flow Boundary Condition ------ Discharge-Stage Table

Optional, required only if KD = 3or 11 in record DFB

The D03 record defines the downstream flow boundary condition as a discharge-stage table. The record ID is followed by one pair of discharge and stage data. The D03 record is repeated until the entire table is input.

D03 TN STN

Variable	Type	Value	Description
TN	float	+	Discharge (cfs or cms)
STN	float	+	Stage (ft or m) at downstream at time TN

D04

D04: Downstream Flow Boundary Condition ------ Weir

Optional, required only if KD = 4 in record DFB

The D04 record defines the weir downstream flow boundary condition. The record ID is followed by three weir parameters: weir height H_0, weir width B, and weir constant C. For free flowing weirs, the discharge is calculated as $Q = CB(H - H_0)^{3/2}$, where H is the elevation of the total energy head upstream of the weir.

D04 WEIR_HEIGHT WEIR_WIDTH WEIR_CONST

Variable	Type	Value	Description
WEIR_HEIGHT	float	+	Weir elevation, H_0 (ft or m)
WEIR_WIDTH	float	+	Weir width, B (ft or m)
WEIR_CONST	float	+	Weir constant, C ($ft^{1/2}/s$ or $m^{1/2}/s$)

D09

D09: Downstream Flow Boundary Condition ------ Rating Curve

Optional, required only if KD = 9 in record DFB

The D09 record defines the rating curve downstream flow boundary condition. The record ID is followed by three rating curve parameters: *a*, *b*, and *c*. The river stage is calculated as, $H = aQ^b + c$, where Q is the flow discharge and H is the river stage.

D09 RC_A RC_B RC_C

Variable	Type	Value	Description
RC_A	float	0/+	Parameter a
RC_B	float	0/+	Parameter b
RC_C	float	-/0/+	Parameter c

Data Group 4. Internal Boundary Conditions

INF

INF: Internal Flow Boundary Condition ------ Number

Required

The INF record specifies the number of internal flow boundary conditions.

INF NKI

Variable	Type	Value	Description
NKI	int	0/+	Number of internal flow boundary conditions
		0	No internal flow boundary conditions. Skip records IFB to I8B
		n	n internal flow boundary conditions, repeat records IFB to I8B for n times

IFB

IFB: Internal Flow Boundary Condition ------ Location and Type

Required if NKI > 0

The IFB record specifies the location and type of internal flow boundary condition. Records IFB to I8B should be skipped if NKI = 0 in record INF or should be repeated for each internal boundary if NKI>1.

IFB XTI KI

Variable	Type	Value	Description
XTI	float	+	Location internal boundary condition
KI	int	+	Type of internal boundary condition
		1	Time-stage table
		2	Time-discharge table
		3	Discharge-stage table
		4	Weir
		6	Bridge
		8	Radial gate
		11	Combination of Time-discharge table and Discharge-stage table (I02 and I03), only available for unsteady flow simulations

I01

I01: Internal Flow Boundary Condition ------ Time-Stage Table

Optional, required only if KI = 1 in record IFB

The I01 record defines the internal flow boundary condition as a time-stage table. The record ID is followed by one pair of time and stage data. The I01 record is repeated until the entire table is input.

I01 T2 ST2

Variable	Type	Value	Description
T2	float	+	time (hr)
ST2	float	+	river stage (ft or m) at upstream at time T2

I02

I02: Internal Flow Boundary Condition ------ Time-Discharge Table

Optional, required only if KI = 2 or 11 in record IFB

The I02 record defines the internal flow boundary condition as a time-discharge table. The record ID is followed by one pair of time and discharge data. The I02 record is repeated until the entire table is input. For steady flow simulations, this record should not be used.

I02 T2 ST2

Variable	Type	Value	Description
T2	float	+	Time (hr)
ST2	float	+	Discharge (cfs or cms) at internal boundary at time T2

I03

I03: Internal Flow Boundary Condition ------ Discharge-Stage Table

Optional, required only if KI = 3 or 11 in record IFB

The I03 record defines the internal flow boundary condition as a discharge-stage table. The record ID is followed by one pair of discharge and stage data. The I03 record is repeated until the entire table is input.

I03 T2 ST2

Variable	Type	Value	Description
T2	float	+	Discharge (cfs or cms)
ST2	float	+	Stage (ft or m) at internal boundary condition at time T2

I04

I04: Internal Flow Boundary Condition ------ Weir

Optional, required only if KI = 4 in record IFB

The I04 record defines the weir internal flow boundary condition. The record ID is followed by three weir parameters: weir height H_0, weir width B, and weir constant C. For free flowing weirs, the discharge is calculated as $Q = CB(H - H_0)^{3/2}$, where H is the elevation of the total energy head.

I04 WEIR_HEIGHT WEIR_WIDTH WEIR_CONST
WEIR_DIR

Variable	Type	Value	Description
WEIR_HEIGHT	float	+	Weir elevation, H_0 (ft or m)
WEIR_WIDTH	float	+	Weir width, B (ft or m)
WEIR_CONST	float	+	Constant, C ($ft^{1/2}$/s or $m^{1/2}$/s)
WEIR_DIR	int	0/1	Weir direction
		0	Inline weir
		1	Lateral weir

I06, I6A

I06, I6A: Internal Flow Boundary Condition ------ Bridge

Optional, required only if KI = 6 in record IFB

The I06 record defines the bridge internal flow boundary condition. One I06 is used for one bridge, and records I6A are used to input elevation-opening table of the bridge. The record ID I6A is followed by one pair of elevation and opening data. The I6A record is repeated until the entire table is input. The present model uses the equations in FLDWAV (Fread and Lewis, 1998) for highway/railway bridges and their associated earthen embankments. The discharge can be expressed as,

$$Q = \sqrt{2g}CA_{br}(h_i - h_{i+1} + V_i^2/2g - \Delta h_f)^{1/2} + cc_u L_u k_u (h_i - h_{cu})^{3/2} + cc_l L_l k_l (h_i - h_{cl})^{3/2} \quad \text{(C1)}$$

where

$$k_u = 1.0 \quad \text{if} \quad h_{ru} \le 0.76 \quad \text{(C2)}$$

$$k_u = 1.0 - c_u(h_{ru} - 0.76)^3 \quad \text{if} \quad h_{ru} > 0.76 \quad \text{(C3)}$$

$$c_u = 133(h_{ru} - 0.78) + 10 \quad \text{if} \quad 0.76 < h_{ru} \le 0.96 \quad \text{(C4)}$$

$$c_u = 400(h_{ru} - 0.96) + 34 \quad \text{if} \quad h_{ru} > 0.96 \quad \text{(C5)}$$

$$h_{ru} = (h_{i+1} - h_{cu})/(h_i - h_{cu}) \quad \text{(C6)}$$

$$cc_u = 3.02(h_i - h_{cu})^{0.015} \quad \text{if} \quad 0 < h_u \le 0.15 \quad \text{(C7)}$$

$$cc_u = 3.06 + 0.27(h_u - 0.15) \quad \text{if} \quad h_u > 0.15 \quad \text{(C8)}$$

$$h_u = (h_i - h_{cu})/w_u \quad \text{(C9)}$$

$$\Delta h_f = \Delta x_i (Q_{br}/K_i)^2 \quad \text{(C10)}$$

$$Q_{br} = \sqrt{2g}CA_{br}(h_i - h_{i+1} + V_i^2/2g)^{1/2} \quad \text{(C11)}$$

$$V = Q_i / A_i \quad \text{(C12)}$$

where C = bridge coefficient; A_{br} = cross-section flow area of the downstream end of bridge opening which is user-specified via a tabular relation of wetted top width versus elevation; h_{cu} = elevation of the upper embankment crest; h_i = water surface elevation at section i (slightly upstream of bridge); h_{i+1} = water surface elevation at section i+1 (slightly downstream of bridge); V = velocity of flow within the bridge opening; L_u = length of the upper embankment crest perpendicular to the flow direction including the length of bridge at elevation h_{cu}; L_l = length of the lower embankment crest perpendicular to the flow direction including the length of bridge at elevation h_{cl}; k_u , k_l = computed submergence correction factor for flow over the upper, and lower embankment crests, respectively; w_u = width (parallel to flow direction) of the crest of the upper , and lower embankment, respectively; and d_i = maximum depth of flow under the bridge.

When the bridge opening is submerged, C in Eqs. (C1) and (C11) is replaced by C' for orifice flow which is written as

$$C' = c_0 C \quad \text{(C13)}$$

in which

$$c_0 = \begin{cases} 1.0 - (r - 0.09) & \text{if } 0.09 \le r \le 0.31 \\ 1.0 & \text{otherwise} \end{cases} \quad \text{(C14)}$$

and

$$r = (h_i - h_{br}) / d_i \quad \text{(C15)}$$

I06 C HCU LU WU HCL LL WL

I6A ELEV B

Variable	Type	Value	Description
C	float	+	C, bridge coefficient
HCU	float	+	h_{cu}, elevation of the upper embankment crest
LU	float	+	L_u, length of the upper embankment crest perpendicular to the flow direction including the length of bridge at elevation h_{cu}
WU	float	+	w_u, width (parallel to flow direction) of the crest of the upper embankment
HCL	float	+	h_{cl}, elevation of the lower embankment crest
LL	float	+	L_l, length of the lower embankment crest perpendicular to the flow direction including the length of bridge at elevation h_{cl}
WL	float	+	w_l, width (parallel to flow direction) of the crest of the lower embankment
ELEV	float	+	Elevation (ft)
B	float	0/+	Bridge opening B (ft) at Elevation ELEV

I08, I8A, I8B

I08, I8A, I8B: Internal Flow Boundary Condition ------ Radial Gate

I08-optional, required only if KI = 8 in record IFB

I8A-optional, required after I08 if radial gate opening is given by time-opening table.

I8B-optional, required after I08 if radial gate opening is determined by water surface elevation.

The I08 record defines the bridge internal flow boundary condition. One I08 is used for a radial gate. Records I8A are used if the radial gate opening is input as a time-opening table. The record ID I8A is followed by one pair of time and opening data. The I8A record is repeated until the entire table is input. The I8B record is used if the gate opening is governed by the water surface elevation.

I8A C W T ZSP TE BE HE CW GDIR GTYPE

I8A T2 ST2

I8B WSEOpen WSEClose OpenRate CloseRate MaxOpen MinOpen InitOpen

Variable	Type	Value	Description
C	float	+	*C*, discharge coefficient (typically ranges from 0.6-0.8)
W	float	+	*W* (ft or m), width of the gate spillway (ft or m)
T	float	+	*T* (ft or m), Trunnion height (from spillway crest to trunnion pivot point)
ZSP	float	+	Z_{sp} (ft or m), elevation of the spillway crest through the gate (ft or m)
TE	float	+	T_E, trunnion height exponent (typically about 0.16)
BE	float	+	B_E, gate opening exponent (typically about 0.72)
HE	float	+	H_E, head exponent (typically about 0.62)
CW	float	+	C_W ,weir coefficient for weir flow
GDIR	int	0/1	Gate direction
		0	Inline gate

		1	Lateral gate (i.e. flow is taken away from river)
GTYPE	int	0/1	Gate type
		0	Radial gate
		1	Sluice gate
T2	float	+	Time (hr)
ST2	float	0/+	*B* (ft or m), gate opening at time T2
WSEOpen	float	+	Upstream water surface elevation at which gate begins to open (ft or m)
WSEClose	float	+	Upstream water surface elevation at which gate begins to close (ft or m)
OpenRate	float	+	Gate opening rate (ft/min or m/min)
CloseRate	float	+	Gate closing rate (ft/min or m/min)
MaxOpen	float	+	Maximum gate opening (ft or m)
MaxOpen	float	+	Minimum gate opening (ft or m)
InitOpen	float	+	Initial gate opening (ft or m)

I13

I13: Internal Flow Boundary Condition ------ Dam Breach

Optional, required only if KI = 13 in record IFB

The I13 record defines the dam breach internal boundary condition.

I13	B_final	Hb,final	Hb,initial	Z_{left}	Z_{right}	C_d
	Breach_Mech	Init_Critical	Init_Time	Breach_Form		

Variable	Type	Value	Description
B_Final	float	+	Maximum breach width (ft or m)
Hb,final	float	+	Maximum breach elevation (ft or m)
Hb,initial	float	+	Initial breach elevation (ft or m)
Z_{left}	float	+	Side slope of left bank (H:V)
Z_{right}	float	+	Side slope of right bank (H:V)
C_d	float	+	Weir discharge coefficient (-), $Q_b = C_d\sqrt{2g}\frac{2}{3}{A_b}^{1.5}{T_b}^{-0.5}$
Breach_Mech	int	1/2/3	1 = Water Surface Elevation; 2 = Critical unit discharge; 3 = Time
Init_Critical	float	+	Critical value for initial of breach; it will be a water surface elevation (ft or m), unit discharge (ft^2/s or m^2/s), or time (hr)
Init_Time	float	+	Time required above critical value for breach to initiate (hr)
Breach_Form	int	1/2/3	Breach rate method: 1 = linear in time formation, 2 = sinusoidal in time formation, 3 = breaching rate computed based upon shear stress

IBG

IBG: Internal Flow Boundary Condition ------ Dam Breach

Optional, required only if KI = 13 in record IFB

The IBG record defines the rating curve at the dam and the overtopping width of flow during overtopping of the dam. The I1A record is repeated until the entire table is input

IBG   Elevation   Design_Outflow   Overtopping_width

Variable	Type	Value	Description
Elevation	float	+	Elevation of (ft or m)
Design_Outflow	float	+	Outflow from dam's gates and spillway (ft^3/s, m^3/s)
Overtopping_width	float	+	Initial breach elevation (ft or m)

IBT

IBT: Internal Flow Boundary Condition ------ Dam Breach

Optional, required only if Breach_Form = 1 in record I13 is 1 or 2

The I1B record defines the time required for full breach formation

I1B Breach_time

Variable	Type	Value	Description
Breach_time	float	+	time required for full breach formation (hr)

IBS

I1D: Internal Flow Boundary Condition ------ Dam Breach

Optional, required if Breach_Form = 1 in record I13 is 1 or 2

The IBS record defines the dam geometry and dam erodibility parameters necessary to use the shear stress approach to compute a dam breach. This record is for the entire embankment for a homogeneous embankment or the outer portion of the dam in a zoned embankment. For the dam core in a zoned embankment, repeat the same variables using record identifier IBZ.

IBS	Crest_length	DS_slope	US_slope	Face_n	Cohesive_flag
	Crit_shear	Erodibility	D50	Headcut_type	Migrat_rate
	Headcut_crit				

Variable	Type	Value	Description
Crest_length	float	+	Dam crest length (ft or m)
DS_slope	float	+	Slope of downstream face of dam (H:V)
US_slope	float	+	Slope of upstream face of dam (H:V)
Face_n	float	+	Manning's roughness coefficient of dam face
Cohesive_flag	int	0/1	Flag indicating type of dam , 0 = non-cohesive, 1 = cohesive.
Crit_shear	float	+	critical shear stress of dam embankment (lb/ft^2 or Pa)
Erodibility	float	+	Erodibility coefficient (ft^3/lb/s or m^3/N/s)
D50	float	+	Median particle diameter (mm) used for non-cohesive dam
Headcut_type	int	0/1	Method used to compute headcut migration: 0 = headcut not computed, 1 = energy method
Migrat_rate	float	+	Migration rate coefficient (s$^{-2/3}$)
Headcut_crit	float	+	Critical unit stream flow times depth (*qh*) above which headcut migration occurs

Data Group 5. Lateral Flow Inputs

LNF

LNF: Lateral Flows ------ Number

Required

The LNF record specifies the number of lateral flow inputs.

LNF NKQF

Variable	Type	Value	Description
NKQF	int	0/+	number of lateral flow inputs
		0	No lateral flows. Skip records LFL to LFD
		n	n lateral flows, repeat records LFL to LFD for n times

LFL

LFL: Lateral Flow Inputs ------ Location

Optional, required if NKQF > 0 in record LNF.

The LFL record specifies the location of the lateral flows. Records LFL and LFD should be skipped if NKQF = 0 in record LNF and should be repeated if NKQF >1 for each lateral flow.

LFL X1QF X2QF

Variable	Type	Value	Description
X1QF	float	+	Start location (ft or m) of lateral flows. The location coordinate will by multiplied by the scaling factor XFACT in records YSL
X2QF	float	+	End location (ft or m) of lateral flows. If point lateral flow is simulated, X2QF=X1QF. The location coordinate will by multiplied by the scaling factor XFACT in records YSL

LFD

LFD: Lateral Flow Inputs ------ Time-Discharge Table

Optional, required if NKQF > 0 in record LNF.

The LFD record defines the lateral flow input as a time-discharge table. A lateral inflow is defined as positive and an outflow is defined as negative. One record is used for each time-discharge pair. The LFD record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table.. For unsteady flow, the discharges are interpolated for time between the specified T1 values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < T3_1$ the discharge for $T3_1$ is used; if $T > T3_n$ the discharge for $T3_n$ is used, where *n* is the total last row of the table. If there is no discharge before the first value or after the last value, zero discharge should be added at the beginning or end of the table, respectively.

LFD T3 ST3

Variable	Type	Value	Description
T3	float	+	Time (hr)
ST3	float	-/0/+	Lateral flow discharge (cfs or cms) at time T3
		-	Lateral outflow
		+	Lateral inflow

Data Group 6. Channel Geometry and Flow Characteristics

NAM

NAM: Number and name of river

Required

The NAM record specifies the number and name of river. The river numbering must occur in sequential order. The river name may include spaces and be up to 80 characters long.

NAM RNUM RNAM

Variable	Type	Value	Description
RNUM	INT	1+	River number
RNAM	CHAR		Name of River

XIN

XIN: Station ------ Cross section ID and Initial Conditions

Optional

The XIN record specifies the initial condition at a station. The XIN records are only used for unsteady flow. Each station is identified by a set of several required records: XIN, XST, XSP, XRH, XOX, and XFL. There are also several other optional records that can be used to define levees, ineffective flow areas and geo-referenced position. These records are repeated for each station. The stations are entered in order, in the downstream direction, starting at the most upstream cross section.

XIN XCID ZDI QDI

Variable	Type	Value	Description
XCID	String		Identification name of cross section. There can be no spaces in the name and it must be less than 30 characters
ZDI	float	+	Initial water surface elevation
		0	Initial water surface elevation is calculated from steady solution
QDI	float	+	Initial discharge
		0	Initial discharge is calculated from steady solution

XST

XST: Station ------ Locations and Adjustments

Required

The XST record is used to define various cross section properties: its streamwise location, the modification to bed elevations, number of interpolated cross sections. This record also controls if the cross section data is updated during a hot start. A cold start means that the simulation starts from the initial condition. A hot start means that the simulation starts from the end of last simulation, whose results are saved in a binary file. The rate in change in cross section elevation due to subsidence or other geological activity is set here.

XST XT DS_L DS _R BEC NINTERP IHOTC BASELEV

Variable	Type	Value	Description
XT	float	-/0/+	Location of the station, i.e., its coordinate measured from a reference station location downstream. The location coordinate will be multiplied by the scaling factor XFACT in the record YSL.
DS_L	float	0/+	Flow path length along the left floodplain to the downstream cross section (ft or m). If 0, then the distance is assumed to be the same as the channel distance.
DS_R	float	0/+	Flow path length along the left floodplain to the downstream cross section (ft or m). If 0, then the distance is assumed to be the same as the channel distance.
BEC	float	-/0/+	Cross section elevation adjustment factor, BEC, will be added to the given bed elevation across the channel at the present station
NINTERP	int	0/+	Interpolation number, NINTERP, this number of cross sections will be interpolated between the present cross section and the next downstream cross section
		0	No action
IHOTC	int	0/1	Option to restart the calculation with new cross section geometry. This data is ignored during cold start
		0	Use cross section geometry of last calculation during hot start
		1	Use new input of this cross section geometry during hot start
BASELEV	float	-/0/+	Rate of base level change for cross section (ft/yr or m/yr)

XSP

XSP: Station ------ Cross Section Geometry

Required

The XSP record is used to define the cross sectional geometry at the given station. The cross section is described by a set of coordinate pairs. Each coordinate pair contains a lateral location and a bed elevation. The set of data points for each cross section start from the left side of the channel, looking downstream, and progress towards the right-hand side. The number of the coordinate pairs in each XSP record may vary. However, each line is limited to 200 characters and one coordinate pair cannot be separately placed in two XSP records. XSP records are added until all coordinate pairs are input. If YZ = 0 in the YSL record, the cross section geometry must be input using bottom elevation and lateral location pairs instead of the lateral location and bottom elevation pairs as shown below.

XSP CROSLOC BOTTOM

Variable	Type	Value	Description
CROSLOC	float	-/0/+	Lateral coordinate, measured from a reference point, of the data points that define the cross-sectional geometry at the current station (ft or m)
BOTTOM	float	-/0/+	Vertical coordinate (bottom elevation) of the data points that define the cross-section geometry at the current station (ft or m). The cross section elevation adjustment factor, BEC, in record XST is added to BOTTOM

XIX

XIX: Station ------ Ineffective Flow Area

Optional

The XIX record is used to define the ineffective flow areas (areas where the conveyance is zero): their left and right extents, and water surface elevations under which the conveyance is zero. More then one ineffective flow area can be defined in a cross section.

XIX DEADL DEADL HDEAD

Variable	Type	Value	Description
DEADL	float	-/0/+	Lateral coordinate of left location of ineffective flow area
DEADR	float	-/0/+	Lateral coordinate of right location of ineffective flow area
HDEAD	float	-/0/+	Elevation (ft or m) until which the area is ineffective

XPX

XPX: Station ------ Permanent Ineffective Flow Area

Optional

The XPX record is used to define the permanent ineffective flow areas, their left and right extents, and upper elevations. When the water surface elevation is lower than the upper elevation, the area is ineffective. When the water surface elevation is higher than the upper elevations, the area about the elevation is effective and the area below the upper elevation is still ineffective. More then one permanent ineffective flow area can be defined in a cross section.

XPX PDEADL PDEADL PHDEAD

Variable	Type	Value	Description
PDEADL	float	-/0/+	Lateral coordinate of left location of permanent inefficient flow area
PDEADR	float	-/0/+	Lateral coordinate of right location of permanent inefficient flow area
HPDEAD	float	-/0/+	Elevation (ft or m) until which the area is permanent inefficient (conveyance is zero)

XLX

XLX: Station ------ Levee Areas

Optional

The XLX record is used to define levee areas: their left and right extents, and water surface elevation under which the area is dry. More than one leveed area can be defined in a cross section. The area is considered dry until the elevation HLEV is exceeded.

XLX LEVEEL LEVEER HLEV

Variable	Type	Value	Description
LEVEEL	float	-/0/+	Lateral coordinate of left location of dry area
LEVEER	float	-/0/+	Lateral coordinate of right location of dry area
HLEV	float	-/0/+	Elevation (ft or m) until which the area is dry

XBX

XBX: Station ------ Blocked Areas

Optional

The XBX record is used to define blocked areas: their left and right extents, and the upper elevations. More than one blocked area can be defined in a cross section.

XBX BLOCKL BLOCKR HBLOCK

Variable	Type	Value	Description
BLOCKL	float	-/0/+	Lateral coordinate of left location of blocked area
BLOCKR	float	-/0/+	Lateral coordinate of right location of blocked area
HBLOCK	float	-/0/+	Elevation (ft or m) until which the area is blocked

XRX

XRX: Station ------ Rip Rap Locations

Optional

The XRX record is used to define areas of the cross section that have been protected with immovable bank protection such as riprap. The left and right extents are user specified and the elevations of the protection is assumed to be at the elevation of the cross section points. More than one riprap area can be defined in a cross section. The areas protected by riprap are not allowed to erode.

XRX RIPRAPL RIPRAPR

Variable	Type	Value	Description
RIPRAPL	float	-/0/+	Lateral coordinate of left location of riprap area
RIPRAPR	float	-/0/+	Lateral coordinate of right location of riprap area

XBU

XBU: Station ------ Upstream Break Points

Optional

The XBU record is used to define the upstream break points. The break points are used to interpolate cross sections between two input cross sections. The number of upstream break points should be equal to that of downstream break points defined at the upstream cross section. Breakpoints are only used when cross sections are interpolated. The method of interpolation is similar to that performed in HEC-RAS. By default, there are 5 breakpoints defined: 2 for the endpoints, 2 for the overbank points and 1 for the channel thalweg.

XBU LOCBPU(1:n)

Variable	Type	Value	Description
LOCBPU	float	+	location (ft or m) of break point
n	int	+	number of breakpoints

XBD

XBD: Station ------ Downstream Break Points

Optional

The XBD record is used to define the downstream break points. The break points are used to interpolate cross sections between two input cross section. The number of downstream break points should be equal to that of upstream break points defined at the downstream cross section. Breakpoints are only used when cross sections are interpolated. By default, there are 5 breakpoints defined: 2 for the endpoints, 2 for the overbank points and 1 for the channel thalweg.

XBD   LOCBPD(1:n)

Variable	Type	Value	Description
LOCBPD	int	+	Point index of break point, n = number of breakpoints

XRH

XRH: Station ------ Roughness Coefficients.

Required

The XRH record is used to define the roughness coefficients. The roughness coefficients are described by coordinate-coefficient pairs. The coordinates divides the cross sections into subchannels with different roughness coefficients. The coordinates must be given starting from the left side of the channel, looking downstream, and progress towards the right-hand side. The number of the pairs in each XSP record may vary. However, a coordinate pair cannot be separated in two XRH records.

XRH XLOC_LCOEF LCOEF

Variable	Type	Value	Description
XLOC_LCOEF	float	-/0/+	Lateral coordinate (ft or m) under which the roughness coefficient is defined in the pair
LCOEF	float	+	Roughness coefficient when the lateral coordinate is greater than XLOC_RCOEF

XOX

XOX: Station ------ Bank Location

Required

The XOX record is used to define the overbank locations. The overbank points divide the cross section into a left floodplain, a main channel, and a right floodplain. If there is no floodplain on one side of the channel, the overbank location is set at the end point of the cross section.

XOX BANKL BANKR

Variable	Type	Value	Description
BANKL	float	-/0/+	Lateral coordinate of left overbank.
BANKR	float	-/0/+	Lateral coordinate of right overbank.

XSK

XSK: Station ------ skew angle of cross section

Optional

The XSK record is used to define the skew angle in degrees of the cross section.

XFL SKEW

Variable	Type	Value	Description
SKEW	float	0/+	Skew angle of cross section in degrees

XFL

XFL: Station ------ Cross Section Energy Loss Coefficient

Required

The XFL record is used to define the energy loss coefficient at that cross section or downstream of that cross section.

XFL KEXP KCON KLOCAL

Variable	Type	Value	Description
KEXP	float	0/+	Local energy loss coefficient that accounts for energy losses due to flow expansion between this cross section and the one downstream
KCON	float	0/+	Local energy loss coefficient that accounts for energy losses due to flow contraction between this cross section and the one downstream
KLOCAL	float	0/+	Local energy loss coefficient that accounts for energy losses that are proportional to velocity head at that section

XSL

XSL: Station ------ Geo-Referenced Cross section positions

Required

The XSL record is used to define the Geo-Referenced location of the cross section. The data is entered in easting and northing data pairs. This data is not presently used by SRH-1D, but is listed as a data input so that the actual location of cross sections can be referenced. A minimum of two data points must be entered, and the maximum number of point is the number of the points in the cross section. It is assumed that the station elevation data points occur along the geo-referenced points.

This is the end of flow input. This is the last data record required if there is no sediment simulation (ISOLVE = 0 in record YSL). If there is no sediment input, then Data Groups 7 to 15 are skipped.

XSL XGIS YGIS

Variable	Type	Value	Description
XGIS	float	-/0/+	Easting location of cross section point
YGIS	float	-/0/+	Northing location of cross section point

Data Group 7. Sediment Model Parameters

YST

YST: Sediment Solution Parameters

Optional

The YST record is used to define the sediment solution parameters: the number of layers used to represent the river bed, the implicit factor for sediment transport solution, number of sediment time steps to perform during one flow computation, and frequency of angle of repose calculations.

If a river network is simulated, records YST to YSG are used for the entire river network, and records USB to CDI are specific to an individual river and should be repeated for each river.

YST NLAY THETA NTSEDF NREPOSE

Variable	Type	Value	Description
NLAY	int	+	number of bed layers used to represent bed material (default is 3)
THETA	float	0-1	Implicit factor used in the sediment transport solution (default is 1)
NTSEDF	int	+	Number of sediment time steps to perform during one flow computation (default is 1)
NREPOSE	int	+	Bank adjustment is performed every *NREPOSE* time steps (default is 1)
MIN_LAYER	float	+	Minimum bed layer thickness parameter. Minimum thickness is MIN_LAYER times the active layer thickness. Default = 1. Used for layers below active layer.
MAX_LAYER	float	+	Maximum bed layer thickness parameter. Maximum thickness is MAX_LAYER times the active layer thickness. Default = 10. Used for layers below active layer.
MAX_NLAY	int	+	Maximum number of layers in model.

YSP

YSP: Sediment Parameters

Optional

The YSP record is used to specify the value of various constants used in the sediment transport calculations.

CLAY_LIMIT   SILT_LIMIT   SAND_LIMIT   CONCMAX   SPECGRAV

Variable	Type	Value	Description
CLAY_LIMIT	float	+	Size of particle below which sediment is assumed to behave as clay particle (mm). Default is 0.004 mm.
SILT _LIMIT	float	+	Size of particle below which sediment is assumed to behave as silt particle (mm). Default is 0.0625 mm.
SAND _LIMIT	float	+	Size of particle below which sediment is assumed to behave as sand particle (mm). Default is 2 mm.
CONCMAX	float	+	Maximum Volumetric concentration allowed (-). Default is 0.15.
SPECGRAV	float	+	Specific gravity of particles in simulation (-). Default is 2.65.

YSG

YSG: Sediment Size Group

Required

YSG records are used to define the number and diameters of the sediment size classes. The dry specific weight for individual size groups can also be defined in these records. The records must be ordered with increasing sediment sizes.

If the mean sediment size is smaller than the value given for the separation between sand and silt sized sediment (SILT_LIMIT is record YSP), the cohesive sediment transport methods will automatically be activated. For each size group, the program computes the geometric mean grain size as $D_{mean} = \sqrt{DRU \times DRL}$.

YSG   DRL   DRU   BDIN

Variable	Type	Value	Description
DRL	float	+	Lower boundary of the particle size for this group (mm)
DRU	float	+	Upper boundary of the particle size for this group (mm)
BDIN	float	+	Dry specific weight or dry bulk density for the size fraction (lb/ft^3 or N/m^3)
		0	Use the default dry specific weight (99.26 lb/ft^3 or 15580 N/m^3)

Data Group 8. Sedient Boundary Conditions

USB

USB: Upstream Sediment Boundary Condition

Required

The USB record specifies the upstream sediment boundary condition type.

If a river network is simulated, records YST to YSG are used for the entire river network, and records USB to RPL are specific to an individual river and should be repeated for each river.

USB KUS

Variable	Type	Value	Description
KUS	int	0/1/2/3/4	Type of upstream sediment boundary condition
		0	Junction, sediment input comes from upstream rivers
		1	Sediment transport formula
		2	Rating curve
		3	Table (flow, sediment discharge)
		4	Table (time, sediment discharge)
		5	Table (time, sediment discharge by size fraction)

US0

US0: Upstream Sediment Boundary Condition ------ Junction

Optional, required only if KUS = 0 in record USB

The US0 record defines the upstream sediment boundary condition as junction. The sediment input at the upstream will come from the last cross section of upstream river. No variable is required.

US0

US1

US1: Upstream Sediment Boundary Condition ------ Sediment Transport Equation

Optional, required only if KUS = 1 in record US2

The US1 record is used when the upstream sediment input is calculated using a sediment transport equation, defined in record SEQ. The record ID is followed by a scaling factor a_s . The sediment discharge from sediment transport equation will be multiplied by a_s .

US1 AQRC

Variable	Type	Value	Description
AQRC	float	+	Scaling Factor, a_s . The sediment discharge from sediment transport equation will be multiplied by a_s

US2

US2: Upstream Sediment Boundary Condition ------ Rating Curve

Optional, required only if KUS = 2 in record USB

The US2 record defines the upstream flow boundary condition as a rating curve. The record ID is followed by two rating parameters a_s, b_s. The sediment discharge (ton/day) is calculated as $Q_x = a_s Q^{b_s}$, where Q = flow discharge (cfs or cms).

US2 AQRC BQRC

Variable	Type	Value	Description
AQRC	float	+	Rating curve coefficient a_s
BQRC	float	0/+	Rating curve coefficient b_s

US3

US3: Upstream Sediment Boundary Condition ------ Flow-Sediment Discharge Table

Optional, required only if KUS = 3 in record USB

The US3 record defines the upstream sediment boundary condition as a flow-sediment discharge table. One record is used for each flow-sediment discharge pair. The US3 record is repeated until the entire table is input. For values of the discharge outside of the table, no extrapolation is done; i.e., if $Q < QI_1$ the sediment discharge for QI_1 is used; if $Q > QI_n$ the discharge for QI_n is used, where *n* is the last row of the table.

US3 QI QSI

Variable	Type	Value	Description
QI	float	0/+	Flow rate (cfs or cms)
QSI	float	0/+	Sediment discharge (ton/day)

US4

US4: Upstream Sediment Boundary Condition ------ Time-Discharge Table

Optional, required only if KUS = 4 in record USB

The US4 record defines the upstream sediment boundary condition as a time-discharge table. One record is used for each time-discharge pair. The US4 record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table. For unsteady flow, the discharges are interpolated in time between the specified TSI values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < TSI_1$ the discharge for TSI_1 is used; if $T > TSI_n$ the discharge for TSI_n is used, where n is the last row of the table. If there is no sediment discharge before the first value or after the last value, a zero value should be added at the beginning or end of the table, respectively.

US4 TSI QSI

Variable	Type	Value	Description
TSI	float	0/+	Time (hr)
QSI	float	0/+	Sediment discharge (ton/d or metric ton/d)

US5

US5: Upstream Sediment Boundary Condition ------ Time-Discharge Table for Each Size Fraction

Optional, required only if KUS = 5 in record USB

The US5 record defines the upstream sediment boundary condition as a time-discharge table. One record is used for each time-discharge pair. The US5 record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table. For unsteady flow, the discharges are interpolated in time between the specified TSI values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < TSI_1$ the discharge for TSI_1 is used; if $T > TSI_n$ the discharge for TSI_n is used, where n is the last row of the table. If there is no sediment discharge before the first value or after the last value, a zero value should be added at the beginning or end of the table, respectively.

US5 TSI QSI(1:nf)

Variable	Type	Value	Description
TSI	float	0/+	Time (hr)
QSI(1:nf)	float	0/+	Sediment discharge (ton/d or metric ton/d) for each size fraction for *nf* size fractions

USS

USS: Upstream Sediment Boundary Condition ------ Sediment Size Distribution

Optional, required only if KUS = 2, 3, or 4 in record USB

The USS record defines the sediment size distribution at the flow discharge QIC. The size distributions are given from the finest to the coarsest size fractions. The sediment size distributions are interpolated for flow discharges between the specified *QIN* values. For values of the flow discharge outside of the table, no extrapolation is done; i.e., if $Q < QIN_1$ the distribution for QIN_1 is used; if $Q > QIN_n$ the distribution for QIN_n is used, where *n* is the last row of the table.

USS QIN PISID(1:nf)

Variable	Type	Value	Description
QIN	float	+	Flow discharge (cfs or cms) at which sediment size distribution is given
PISID(1:nf)	float	+	Sediment size distribution at one flow discharge for *nf* size fractions.

Data Group 9. Lateral Sediment Inflows

LNS

LNS: Number of Lateral Sediment Inputs

Required

The LNF record specifies the number of lateral sediment inputs.

LNS NKQS

Variable	Type	Value	Description
NKQS	int	0/+	Number of lateral sediment input
		0	No lateral sediment input. Skip records LSL to LSD
		n	n lateral sediment input, Records LSL and LSD will be repeated *n* times

LSL

LSL: Location of Lateral Sediment Input

Optional, required if NKQS>0 in records LNS.

The LQL record specifies the stream location of the lateral sediment input. Records LSL to LSD should be skipped if NKQS = 0 in record LNS and should be repeated if NKQS >1 for each lateral sediment input.

LSL X1QS X2QS LTYPE

Variable	Type	Value	Description
X1QS	float	+	Starting location (ft or m) of the lateral sediment input. The location coordinate will be multiplied by the scaling factor XFACT in the record YSL
X2QS	float	+	End location (ft or m) of lateral sediment input. If point lateral sediment input is simulated, X2QS=X1QS. The location coordinate will be multiplied by the scaling factor XFACT in the record YSL
LTYPE	int	2/3/4/5	Type of lateral flow input sediment boundary condition.
		0	For lateral outflows, the concentration of the outflow will be the same as the concentration in the river
		2	Rating curve
		3	Table (flow, sediment discharge)
		4	Table (time, sediment discharge)
		5	Table (time, sediment discharge for each size fraction)

LS2

LS2: Lateral Sediment Discharge – Rating Curve

Optional, required only if LTYPE = 2 in record LSL

The LS2 record defines the upstream flow boundary condition as a rating curve. The record ID is followed by two rating parameters a_s and b_s. The sediment discharge (ton/day) is calculated as $Q_{x,lat} = a_s Q^{b_s}$, where Q = flow discharge of lateral flow input (cfs or cms).

LS2 LAQRC LBQRC

Variable	Type	Value	Description
LAQRC	float	+	Rating curve coefficient a_s for lateral flow input
LBQRC	float	0/+	Rating curve coefficient b_s for lateral flow input

LS3

LS3: Lateral Sediment Discharge – Flow-Sediment Discharge Table

Optional, required only if LTYPE = 3 in record LSL

The LS3 record defines the upstream sediment boundary condition as a flow-sediment discharge table. One record is used for each flow-sediment discharge pair. The LS3 record is repeated until the entire table is input. For values of the discharge outside of the table, no extrapolation is done; i.e., if $Q_{lat} < QLI_1$ the sediment discharge for QLI_1 is used; if $Q_{lat} > QLI_n$ the discharge for QLI_n is used, where *n* is the last row of the table.

LS3 QLI QSLI

Variable	Type	Value	Description
QLI	float	0/+	Flow rate (cfs or cms)
QSLI	float	0/+	Sediment discharge (ton/day)

LS4

LS4: Lateral Sediment Boundary Condition ------ Time-Discharge Table

Optional, required only if LTYPE = 4 in record LSL

The LS4 record defines the lateral sediment boundary condition as a time-discharge table. One record is used for each time-discharge pair. The LS4 record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table. For unsteady flow, the discharges are interpolated in time between the specified TSLI values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < TSLI_1$ the discharge for $TSLI_1$ is used; if $T > TSLI_n$ the discharge for $TSLI_n$ is used, where n is the last row of the table. If there is no sediment discharge before the first value or after the last value, a zero value should be added at the beginning or end of the table, respectively.

LS4 TSLI QSLI

Variable	Type	Value	Description
TSLI	float	0/+	Time (hr)
QSLI	float	0/+	Sediment discharge (ton/day)

LS5

LS5: Lateral Sediment Boundary Condition ------ Time-Discharge Table for Each Size Fraction

Optional, required only if LTYPE = 5 in record LSL

The LS5 record defines the lateral sediment boundary condition as a time-discharge table. One record is used for each time-discharge pair. The LS5 record is repeated until the entire table is input. For steady flow, no interpolation of discharge is performed and the discharge becomes a step function in time. Changes to the discharge occur at the times input in the time-discharge table. For unsteady flow, the discharges are interpolated in time between the specified TSI values. For values of the discharge outside of the table, no extrapolation is done; i.e., if $T < TSLI_1$ the discharge for $TSLI_1$ is used; if $T > TSLI_n$ the discharge for $TSLI_n$ is used, where n is the last row of the table. If there is no sediment discharge before the first value or after the last value, a zero value should be added at the beginning or end of the table, respectively.

LS4 TSLI QSLI(1:nf)

Variable	Type	Value	Description
TSL	float	0/+	Time (hr)
QSLI(1:nf)	float	0/+	Sediment discharge (ton/day) for each size fraction, nf = number of size fractions

LSS

LSS: Lateral Sediment Discharge Sediment Size Distribution

Optional, required only if LTYPE = 2, 3, or 4 in record LSL

The LSS record defines the sediment size distribution at the flow discharge QIC. The size distributions are given in order from the finest to the coarsest size fractions. The sediment size distributions are interpolated for flow discharges between the specified *QIN* values. For values of the flow discharge outside of the table, no extrapolation is done; i.e., if $Q < QIN_1$ the distribution for QIN_1 is used; if $Q > QIN_n$ the distribution for QIN_n is used, where *n* is the last row of the table.

LSS QLIN PISIDL(1:nf)

Variable	Type	Value	Description
QLIN	float	+	Flow discharge (cfs or cms) at which sediment size distribution is given
PISIDL(1:nf)	float	+	Sediment size distribution at one flow discharge, nf = number of size fractions

Data Group 10. Sediment Bed Material Properties

BT0/BT1/BT2

BT0/BT1/BT2: Bed Properties ------ Location of Thickness

Required

The BT0/BT1/BT2 record specifies the locations where the bed layer thicknesses are given (see Figure 3.10). If the record BT0 is used, the bed thicknesses will be given at each station listed in XST records and no variable is required. If the record BT1 is used, the bed thicknesses will be given at specific stations in the form of station indexes. If the record BT2 is used, the bed thicknesses will be given at specific locations in the form of streamwise coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional BT1/BT2 records can be used until all locations are defined.

BT0	
BT1	II(1:nt)
BT2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where bed thicknesses for each layer will be given
XC	float	0/+	Station Coordinates (ft or m) where bed thicknesses for each layer will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where bed thicknesses for each layer will be given

BTT

BTT: Bed Properties ------ Thickness

Required

The BTT specifies the bed layer thickness at each bed layer (see Figure 3.1) where location is given at the BT0/BT1/BT2 record. If the record BT0 is used, the bed thicknesses are given at each station listed in XST records. If the record BT1/BT2 is given, the bed thicknesses are given at specific locations. The record should be repeated nt times, where nt is the number of locations specified in the BT0/BT1/BT2 record. The last layer's thickness is always considered infinite and is not input.

BTT THICK(1:nlay-1)

Variable	Type	Value	Description
THICK	float	+	Bed layer thickness at given locations

BP0/BP1/BP2

BP0/BPI/BP2: Bed Properties ------ Location of Size Fractions

One of the three is required

The BP0/BP1/BP2 record specifies the locations where the sediment size fractions at each bed layer are given. If the record BP0 is used, the size fractions will be given at each station listed in XST records and no variable is required. If the record BP1 is used, the size fractions will be given at specific stations in the form of station indexes. If the record BP2 is used, the size fractions will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional BP1/BP2 records can be used until all locations are input.

BP0	
BP1	II(1:nt)
BP2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where sediment size fractions for each layer will be given
XC	float	0/+	Station Coordinate (ft or m) where sediment size fraction for each layer will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, , nt = total number of stations where bed fractions are given

BPL

BPL: Bed Material Properties ------ Sediment Size Fractions

Required.

The BPL record specifies the fractions within each sediment size class at each bed layer at the locations given in the BP0/BP1/BP2 record. If the record BP0 is used, the sediment size class fractions are given at each station given in XST records. If the record BP1/BP2 is given, the sediment size class fractions are given at specific locations. The record is repeated for layer number 1 until all the locations are given. Then, this process is repeated for layers 2 to NLAY. The bed fractions for the first layer will be used for the active layer.

For each

BPL PTMP(1:nf)

Variable	Type	Value	Description
PTMP	float	+	sediment size fractions (- or %)

Data Group 11. Water Temperature

TMP

TMP: Water Temperature

Required

The TMP record is used to enter the water temperature of the study reach. A time-temperature table is input in this record. The TMP record is repeated until the entire table is input. The program obtains the temperature at a specific time by interpolation. The temperatures are interpolated between the given times. For times outside of the given times, no extrapolation is done; i.e., if $T < TIME_1$ the temperatures for $TIME_1$ is used; if $T > TIME_n$ the temperatures for $TIME_n$ is used, where *n* is the last row of the table.

TMP TIME TMP

Variable	Type	Value	Description
TIME	float	+	Time (hr)
TMP	float	-/0/+	Temperature (F or C)

Data Group 12. Erosion and Deposition Limits

FI0/FI1/FI2

FI0/FI1/FI2: Bed Limitation Locations

One of three required.

The FI0/FI1/FI2 record specifies the locations where the limits of scour and deposition are defined. These limits correspond to restrictions, geological or man-made, to deposition and/or scour. If the record FI0 is used, the limits will be given at each station listed in XST records and no variable is required. If the record FI1 is used, the limits will be given at specific stations in the form of station indexes. If the record FI2 is used, the limits will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional FI1/FI2 records are used until all locations are defined.

FI0

FI1 II(1:nt)

FI2 XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where width and bed elevation limits will be given
XC	float	0/+	Station Coordinates (ft or m) where width and bed elevation limits will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where bed limits will be given

FIM

FIM: Bed Limitations

Optional

The FIM specifies the vertical limits of scour and deposition at the locations specified in the FI0/FI1/FI2 record. If the record FI0 is used, the vertical and horizontal limits are given at each station listed in XST records. If the record FI1/FI2 is given, the width vertical and horizontal limits are given at specific locations. The record should be repeated until all the stations are given. The table is interpolated for stations within the table. For stations outside of the table, no extrapolation is done. If a specific location is not inside the range of given locations, the first or last of the limits in the table is used, depending on if the specific location is upstream or downstream of the range. Very large or very small numbers are used if scour or deposition is not constrained.

FIM CROSMIN_E CROSMAX_E CROSMIN_D
CROSMAX_D BOTMIN BOTMAX

Variable	Type	Value	Description
CROSMIN_E	float	-/0/+	Lateral location (ft or m) beyond which no erosion is allowed. This location corresponds to the left-hand side restriction, looking downstream
CROSMAX_E	float	-/0/+	Lateral location (ft or m) beyond which no erosion is allowed. This location corresponds to the right-hand side restriction, looking downstream
CROSMIN_D	float	-/0/+	Lateral location (ft or m) beyond which no deposition is allowed. This location corresponds to the left-hand side restriction, looking downstream
CROSMAX_D	float	-/0/+	Lateral location (ft or m) beyond which no deposition is allowed. This location corresponds to the right-hand side restriction, looking downstream
BOTMIN	float	-/0/+	Limit for scour in the vertical direction. No scour is allowed beyond this bottom elevation (ft or m)
BOTMAX	float	-/0/+	Limit for deposition in the vertical direction. No deposition is allowed beyond this bottom elevation (ft or m)

FIW

FIW: Bed Limitations and Erosion Limits Defined by Flow

Optional.

The FIW specifies the vertical limits of scour and deposition at the locations specified in the FI0/FI1/FI2 record. It is also used to specify the erosion width. If the record FI0 is used, the vertical and horizontal limits are given at each station listed in XST records. If the record FI1/FI2 is given, the width vertical and horizontal limits are given at specific locations. The record should be repeated until all the stations are given. The table is interpolated for stations within the table. For stations outside of the table, no extrapolation is done. If a specific location is not inside the range of given locations, the first or last of the limits in the table is used, depending on if the specific location is upstream or downstream of the range. Very large or very small numbers are used if scour or deposition is not constrained. The erosion width, W_e, is determined by: $W_e = aQ^b$, where a and b are user defined values.

FIW CROSMIN_E CROSMAX_E CROSMIN_D CROSMAX_D BOTMIN BOTMAX ACONST BCONST

Variable	Type	Value	Description
CROSMIN_E	float	-/0/+	Lateral location (ft or m) beyond which no erosion is allowed. This location corresponds to the left-hand side restriction
CROSMAX_E	float	-/0/+	Lateral location (ft or m) beyond which no erosion is allowed. This location corresponds to the right-hand side restriction
CROSMIN_D	float	-/0/+	Lateral location (ft or m) beyond which no deposition is allowed. This location corresponds to the left-hand side restriction
CROSMAX_D	float	-/0/+	Lateral location (ft or m) beyond which no deposition is allowed. This location corresponds to the right-hand side restriction
BOTMIN	float	-/0/+	Limit for scour in the vertical direction. No erosion is allowed beyond this bottom elevation (ft or m)
BOTMAX	float	-/0/+	Limit for deposition in the vertical direction. No deposition is allowed beyond this bottom elevation (ft or m)
ACONST	float	-/+	constant in erosion width equation. If negative, then erosion width always is greater then wetted width.
BCONST	float	+	exponent in erosion width equation.

DST

DST: Dredging options

Optional.

The DST specifies the location and timing and dredging. It is assumed that the channel is dredged and the material removed from the system. There needs to be a separate DST record for each cross section dredged. The dredging is assumed to have a trapezoidal shaped aligned with the channel.

DST XST BOT_ELE CROSSTA BOT_WIDTH SIDE SLOPE NUM_TIMES TIMES

Variable	Type	Value	Description
XST	float	-/0/+	River Station that will be dredged.
BOT_ELE	float	-/0/+	The bottom elevation of the trapezoid that will be dredged
CROSSTA	float	-/0/+	Cross section station of midpoint of the dredging trapezoid
BOT_WIDTH	float	-/0/+	Bottom width of the dredging trapezoid
SIDE SLOPE	float	-/0/+	Side slope of the dredging trapezoid
NUM_TIMES	float	-/0/+	Number of dredging occurrences
TIMES	float	-/0/+	Simulation time that dredging occurs (1 to NUM_TIMES)

Data Group 13. Sediment Transport Parameters

SMN

SMN: Sediment Properties ------ Bank Erosion Options

Optional.

The record SMN specifies the type of minimization routine performed and width adjustment parameters.

SMN IMIN WFRAC BFRACMIN BFRACMAX

Variable	Type	Value	Description
IMIN	int	0/1 0 1	Minimization option No minimization (Default) minimization of energy slope
WFRAC	float	0~1	Used to control the rate of widening if IMIN > 0, but not used otherwise. Default is 0.8. Higher numbers increase the rate of widening. Maximum value recommended is 0.95.
BFRACMIN	float	0~1	Minimum weight given to bank adjustment relative to bed adjustment for vertical adjustments. Default is 0.
BFRACMAX	float	0~1	Maximum weight given to bank adjustment relative to bed adjustment for vertical adjustments. Default is 1.

SEQ

SEQ: Sediment Transport Equation

Required

The SEQ record selects the sediment transport equation used to compute sediment carrying capacities for non-cohesive sediment. The PARKER, WILCOCK, and GAEUMAN functions can be modified by a "T", "1", "2" or "3" where "T" refers to the option of using the total shear stress instead of the grain shear stress. Options 1 to 3 refer to the sand transport option as defined in user's manual.

SEQ ISED

Variable	Type	Value	Description
ISED	String	+	Variable to choose the non-cohesive sediment transport equation used to compute sediment carrying capacity
		ENGELUND	Engelund and Hansen's method
		LAURSEN	Laursen method
		LAURSENM	Laursen-Madden method
		ACKERS	Ackers and White's 1973 method
		ACKERSR	Ackers and White's method with revised (1990) coefficients
		YANG73	Yang's 1973 sand and 1984 gravel formulas
		YANG79	Yang's 1979 sand and 1984 gravel formulas
		YANGY	Yang's 1996 modified formula for Yellow River
		BROWNLIE	Brownlie's method
		MEYER	Meyer-Peter and Muller's method
		PARKER	Parker's (1990) method using Einstein's method to calculate grain shear stress
		PARKERT	Parker's (1990) method for bed load without shear stress correction
		PARKER#	Parker's (1990) method in combination with Engelund and Hansen's, where # refers to sand transport option number (See Section 3.1.4.13)
		WILCOCK	Wilcock and Crowe's (2003) method using Einstein's method to calculate grain shear stress. The same options for Parker apply to Wilcock (T and #).
		GAEUMAN	Gaeuman's (2003) method using Einstein's method to calculate grain shear stress. The same options for Parker apply to Gaeuman (T and #).
		WU	Wu et al. (2000) method

SE1

SE1: Coefficients of Sediment Transport Equation

Optional

The SE1 record set the critical or reference shear stress used in transport equations and in computing the relative sediment velocity (θ_c). It is also used to set the value of the hiding factor (α).

SE1 EQ_COEF1 EQ_COEF2

Variable	Type	Value	Description
EQ_COEF1	float	+/-	Critical or reference shear stress (θ_c)
EQ_COEF2	float	+/-	Hiding factor (α_0)

SBS

SBS: Bed Material Mixing Algorithm

Option

The SBS record selects the method for bed mixing.

SBS BED_MIX

Variable	Type	Value	Description
ISED	String	+	Variable to choose the non-cohesive sediment transport equation used to compute sediment carrying capacity
		FIXED	Active layer method where the active layer thickness stays fixed and the number of layers remains constant at the number originally input in the model
		DMAX	The active layer is computed based upon the geometric mean of the maximum size class input into the model. The number of layers changes based upon the erosion and deposition

SA0/SA1/SA2: Sediment Transport ------ Location for Sediment Transport Properties Input

Required one of three.

The SA0/SA1/SA2 record specifies the locations where the SAT record for sediment transport properties is given. If the record SA0 is used, the SAT record will be given at each station listed in XST records and no variable is required. If the record SA1 is used, the SAT record will be given at specific stations in the form of station indexes. If the record SA2 is used, the SAT record will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional SA1/SA2 records are used until all locations are input.

SA0	
SA1	II(1:nt)
SA2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where the SAT record will be given
XC	float	0/+	Station Coordinates (ft or m) where the SAT record will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where records in SAT are given

SAT

SAT: Sediment Transport ------ Properties

Required.

The SAT specifies the sediment transport properties at each location given in the SA0/SA1/SA2 record. These properties include: the sediment angle of repose, the recovery factors for deposition and scour, the transverse and longitudinal dispersion coefficients, the weight given to the bed load during transfer to the sublayer, and coefficient of secondary flow. If the record SA0 is used, the sediment transport properties are given at each station given in XST records. If the record SA1/SA2 is used, the sediment transport properties are given at specific locations. The record should be repeated until all the stations are given.

SAT ANGLE1 ANGLE2 NALT ALPHAD ALPHAS BLENGTH WTDEP DLONG DTRANS

Variable	Type	Value	Description
ANGLE1	float	+	Angle of repose of sediment at and above water Default is 90 degrees
ANGLE2	float	+	Angle of repose of sediment below water Default is 90 degrees
ALPHAD	float	+ 0	Recovery factor for deposition (α) Default value 0.25
ALPHAS	float	+ 0	Recovery factor for scour (α) Default value 1.0
BLENGTH	float	+ 0	Bedload adaptation length coefficient (-) Default value 0
WTDEP	float	0 ~ 1	Weight given to bed load fractions for transfer of material from surface to subsurface layer during deposition Default value is 0
DLONG	float	0/+	Longitudinal dispersion coefficient, K_x (used if ISOLVES = 2), Default value is 0
DTRANS	float	0/+	Transverse dispersion coefficient (not currently used)

Data Group 14. Cohesive Sediment Parameters

CS0/CS1/CS2

CS0/CS1/CS2: Cohesive Sediment Deposition ------ Locations

One is required if cohesive sediment is present

The CS0/CS1/CS2 record specifies the locations where the cohesive sediment deposition parameters are given. If the record CS0 is used, cohesive sediment deposition parameters will be given at each station listed in XST records and no variable is required. If the record CS1 is used, cohesive sediment deposition parameters will be given at specific stations in the form of station indexes. If the record CS2 is used, cohesive sediment deposition parameters will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional CS1/CS2 records can be used until all locations are input.

CS0	
CS1	II(1:nt)
CS2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where cohesive sediment deposition parameters will be given
XC	float	0/+	Station Coordinate (ft or m) where cohesive sediment deposition parameters will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where cohesive parameters are given

CSD

CSD: Cohesive Sediment Deposition ------ Parameters

Required only if cohesive sediment is present

The CSD record specifies the critical shear stress for cohesive sediment deposition, equilibrium sediment concentration during partial deposition, and the threshold value for the percentage of clay in the bed composition above which the erosion rates of gravels, sands, and silts are limited by the erosion rate of clay. These parameters are given at locations defined in the CS0/CS1/CS2 record.

The CSD record to CDI records are used in the cohesive sediment (clay and silt) transport model. If a sediment size group has a geometric mean grain size lower than 0.0625 mm, the cohesive sediment transport methods will be used to predict for the transport for those size groups. The equation specified in record SEQ record will be used for the remaining size groups. If silt and/or clay sizes are not present, these records should not be given.

CSD STDEP_F STDEP_P CONCEQ ER_LIM

Variable	Type	Value	Description
STDEP_F	float	+	Critical shear stress for full deposition of clay and silt (lb/ft^2 or N/m^2)
STDEP_P	float	+	Critical shear stress for partial deposition of clay and silt (lb/ft^2 or N/m^2)
CONCEQ	float	+	Equilibrium sediment concentration during partial deposition. (g/l)
ER_LIM	float	0~1.	Threshold value for the fraction of clay in the bed composition above which the erosion rates of gravels, sands, and silts are limited to the erosion rate of clay

CE0/CE1/CE2

CE0/CE1/CE2: Cohesive Sediment Erosion ------ Locations

One of the three is required if cohesive sediment is present

The CE0/CE1/CE2 record specifies the locations where the cohesive sediment erosion parameters are given. If the record CE0 is used, cohesive sediment erosion parameters will be given at each station listed in XST records and no variable is required. If the record CE1 is used, cohesive sediment erosion parameters will be given at specific stations in the form of station indexes. If the record CE2 is used, cohesive sediment erosion parameters will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional CE1/CE2 records can be used until all locations are input.

CE0	
CE1	II(1:nt)
CE2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where cohesive sediment erosion parameters will be given
XC	float	0/+	Station Coordinate (ft or m) where cohesive sediment erosion parameters will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where cohesive parameters will be given

CER

CER: Cohesive Sediment Erosion ------ Parameters

Required only if cohesive sediment is present.

The CER record specifies parameters for cohesive sediment erosions. Four parameters are used: the critical shear stress of the surface erosion, surface erosion rate, the critical shear stress of the mass erosion, and mass erosion rate. If 8 parameters are used, cohesive sediment transport parameters are calculated from the wet bulk density, ρ_b. The critical shear stress of surface erosion is calculated as $\tau_{se}^c = a_{se}(\rho_b - \rho_l)^{b_{se}} + c_{se}$, and the critical shear stress of mass erosion is calculated as $\tau_{me}^c = a_{me}\rho_b + b_{me}$. The variables are defined in the input table.

CER STPERO ER_STME STMERO ER_MASS

or

CER ASE BSE CSE RO_LSE ER_STME AME BME ER_MASS

Variable	Type	Value	Description
STPERO	float	+	τ_{se}^c, critical shear stress of surface erosion of clay and silt (lb/ft^2 or N/m^2)
ER_STME	float	+	P_{se}, surface erosion constant (lb/ft^2/hr or kg/m^2/hr)
STMERO	float	+	τ_{me}^c, critical shear stress of cohesive sediment mass erosion (lb/ft^2 or N/m^2)
ER_ MASS	float	+	M_{me}, mass erosion constant (lb/ft^2/hr or kg/m^2/hr)
or			
ASE	float	+	a_{se}, coefficient used to calculate critical shear
BSE	float	+	b_{se}, coefficient used to calculate critical shear
CSE	float	+	c_{se}, coefficient (lb/ft^3 or g/cm^3) used to calculate critical shear
RO_LSE	float	+	ρ_l, coefficient used to calculate critical shear
ER_STME	float	+	P_{se}, surface erosion constant (lb/ft^2/hr or kg/m^2/hr)
AME	float	+	a_{me}, coefficient in calculating critical shear
BSE	float	-	b_{me}, coefficient in calculating critical shear
DME	float	+	d_{me}, coefficient used to calculate the mass erosion constant.
ER_ MASS	float	+	M_{me}, mass erosion constant (lb/ft^2/hr or kg/m^2/hr)

CF0/CF1

CF0/CF1: Cohesive Sediment ------ Fall Velocity

Required one of the two only if cohesive sediment is present.

The CF0/CF1 record specifies the relationship between the fall velocity and sediment concentration. If the CF0 record is used, a set of default values are used. If the CF1 record is used, the user needs to input four fall velocities at four specific sediment concentrations.

CF0	FVFORM							
CF1	C1	V1	C2	V2	C3	V3	C4	V4

Variable	Type	Value	Description
FVFORM	INT	+	Default material of cohesive sediment determining the fall velocity
		1	program default for KAOLINITE
		4	program default for SEVERN River
C1	float	+	Cohesive sediment concentration (g/l)
V1	float	+	Cohesive sediment fall velocity (mm/s) at concentration C1
C2	float	+	Cohesive sediment concentration (g/l)
V2	float	+	Cohesive sediment fall velocity (mm/s) at concentration C2
C3	float	+	Cohesive sediment concentration (g/l)
V3	float	+	Cohesive sediment fall velocity (mm/s) at concentration C3
C4	float	+	Cohesive sediment concentration (g/l)
V4	float	+	Cohesive sediment fall velocity (mm/s) at concentration C4

CSC

CSC: Cohesive Sediment ------ Consolidation

Required only if cohesive sediment is present

The CSC record specifies the consolidation parameters of cohesive sediment. The consolidation coefficient is computed from the user input of initial dry bulk density ρ_i, fully consolidated density ρ_f, and density ρ_e at the reference time t_e. All densities are dry bulk densities.

CSC DENSC_I DENSC_F DENSC_E TIME_E

Variable	Type	Value	Description
DENSC_I	float	+	Initial (fresh deposited) sediment dry bulk density (lb/ft^3 or kg/m^3)
DENSC_F	float	+	Fully consolidated sediment dry bulk density (lb/ft^3 or kg/m^3)
DENSC_E	float	+	Reference sediment dry bulk density at reference time TIME_E (lb/ft^3 or kg/m^3)
TIME_E	float	+	Reference time (hr) at which the cohesive sediment dry bulk density DENSC_E is known

CD0/CD1/CD2

CD0/CD1/CD2: Cohesive Sediment ------ Location of Cohesive Sediment Density in Bed

One of three is required only if cohesive sediment is present.

The CD0/CD1/CD2 record specifies the locations where the cohesive sediment dry bulk density in the bed is given. If the record CD0 is used, the cohesive sediment density will be given at each station listed in the XST records and no variable is required. If the record CD1 is used, the cohesive sediment density will be given at specific stations in the form of station indexes. If the record CD2 is used, the cohesive sediment density will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional CD1/CD2 records are used until all data are input.

CD0	
CD1	II(1:nt)
CD2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where cohesive sediment dry bulk density will be given
XC	float	0/+	Station Coordinates (ft or m) where cohesive sediment dry bulk density will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where cohesive sediment dry bulk density will be given

CDI

CDI: Cohesive Sediment ------ Cohesive Sediment Dry Bulk Density in Bed

Required.

The CDI specifies the cohesive sediment dry bulk density at each bed layer at the locations given in the CD0/CD1/CD2 record. If the record CD0 is used, the cohesive sediment density is given at each station given in XST records. If the record CD1 or CD2 is given, the cohesive sediment density is given at specific locations. The record should be repeated until all the stations or locations are given. Since the first layer is the active layer, its cohesive sediment density is not given in this record. The input for second layer cohesive sediment density will be used for the density of both the first and second layers. The cohesive sediment dry bulk density (ρ_d) is input in this record.

CDI DENSITYCLAY0(1:nlay)

Variable	Type	Value	Description
DENSITYCLAY0	float	+	Dry bulk density of cohesive sediment transport from layer 1 to the number of layers (nlay)

Data Group 15. Bedrock Parameters

RST

RST: Bedrock Geometry ------ Locations

Optional

The RST record specifies the locations where the bedrock geometry is given. It should correspond to a cross section given in record XST.

RST RXT

Variable	Type	Value	Description
RST	float	0/+	Station coordinate (ft or m) where bedrock geometry will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL.

RSP

RST: Bedrock Geometry ------ Station Elevation Data

Required if RST is present

The RSP record is used to define the bed rock geometry at the given station. The bed rock is described by a set of coordinate pairs. Each coordinate pair contains a lateral location and a bed elevation. The set of data points for each cross section start from the left side of the channel, looking downstream, and progress towards the right-hand side. The number of the coordinate pairs in each RSP record may vary. However, each line is limited to 200 characters and one coordinate pair cannot be separately placed in two XSP records. RSP records are added until all coordinate pairs are input. If YZ = 0 in the YSL record, the cross section geometry must be input using bottom elevation and lateral location pairs instead of the lateral location and bottom elevation pairs as shown below.

XSP ROCK_STA ROCK_BOT

Variable	Type	Value	Description
ROCK_STA	float	-/0/+	Lateral coordinate, measured from a reference point, of the data points that define the bedrock geometry at the current station (ft or m)
ROCK_BOT	float	-/0/+	Vertical coordinate (bottom elevation) of the data points that define the bedrock geometry at the current station (ft or m)

RS0/RS1/RS2

RS0/RS1/RS2: Bedrock Scour Parameters - Locations

Required if a RST record is present

The RS0/RS1/RS2 record specifies the locations where the RSH record for sediment transport properties is given. If the record RS0 is used, the RSH record will be given at each station listed in XST records and no variable is required. If the record RS1is used, the RSH record will be given at specific stations in the form of station indexes. If the record RS2 is used, the RSH record will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional RS1/RS2 records are used until all locations are input.

RS0	
RS1	II(1:nt)
RS2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where bedrock scour parameters will be given
XC	float	0/+	Station Coordinates (ft or m) where bedrock scour parameters will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = Total number of stations where scour parameters will be given

RSH

RSH: Bedrock Scour Parameters

Required if RST is present.

The RSH specifies the bedrock scour parameters at each location given in the RS0/RS1/RS2 record. If the record RS0 is used, the sediment transport properties are given at each station given in XST records. If the record RS1/RS2 is used, the bedrock scour properties are given at specific locations. The record should be repeated until all the stations are given.

RSH KP KH PCRIT KV MOD_ELAS TENSILE

Variable	Type	Value	Description
KP	float	+	coefficient controlling bedrock scour rate due to hydraulic forces (-)
TAUCRIT	float	+	critical shear stress below which bedrock scour does not occur (lb/ft^2 or Pa)
KV	float	+	abrasive resistance (-)
MOD_ELAS	float	+	modulus of elasticity of bedrock (lb/ft^2 or Pa)
TENSILE	float	+	tensile strength of bedrock (lb/ft^2 or Pa)

RP0/RP1/RP2

RP0/RP1/RP2: Bedrock Scour Erosion Fractions - Locations

Required if a RST record is present

The RP0/RP1/RP2 record specifies the locations where the RPL record for sediment transport properties is given. If the record RP0 is used, the RPL record will be given at each station listed in XST records and no variable is required. If the record RP1is used, the RPL record will be given at specific stations in the form of station indexes. If the record RP2 is used, the RPL record will be given at specific locations in the form of longitudinal coordinates (x). Both location indexes and longitudinal coordinates can be given in ascending or descending order. Additional RP1/RP2 records are used until all locations are input.

RP0	
RP1	II(1:nt)
RP2	XC(1:nt)

Variable	Type	Value	Description
II	int	+	Station index where bedrock scour parameters will be given
XC	float	0/+	Station Coordinates (ft or m) where bedrock scour parameters will be given. The location coordinate will by multiplied by the scaling factor XFACT in the record YSL, nt = total number of stations where scour parameters will be given

RPL

RPL: Bedrock Scour Erosion Fractions

Required if RST is present.

The RPL specifies the mass fractions of each size class into which the bedrock erodes when bedrock scour occurs. The fractions are given at each location given in the RP0/RP1/RP2 record. If the record RP0 is used, the sediment transport properties are given at each station given in XST records. If the record RS1/RS2 is used, the bedrock scour properties are given at specific locations. The record should be repeated until all the stations are given.

RSH PN_ERODED(1:nf)

Variable	Type	Value	Description
PN_ERODED	float	+	fraction of scoured bedrock that enters each size class (- or %)

END

END: End of Input

Required.

The record END is required at the end of the input data file to terminate the data input operations. No variable is required.

END

APPENDIX D

EXAMPLE APPLICATIONS

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EXAMPLE 1 TRAPEZOID CHANNEL

This example shows a SRH-1D data file set-up for a simple trapezoid channel with sediment transport. A 5000-ft long trapezoid channel with bottom width of 200 ft and side slopes of 1V:2H is used. The channel slope is 0.001. The water discharge is 14,900 cfs and the downstream water surface elevation is set at normal depth. The upstream and downstream cross sections were input and then 9 cross sections were interpolated between them.

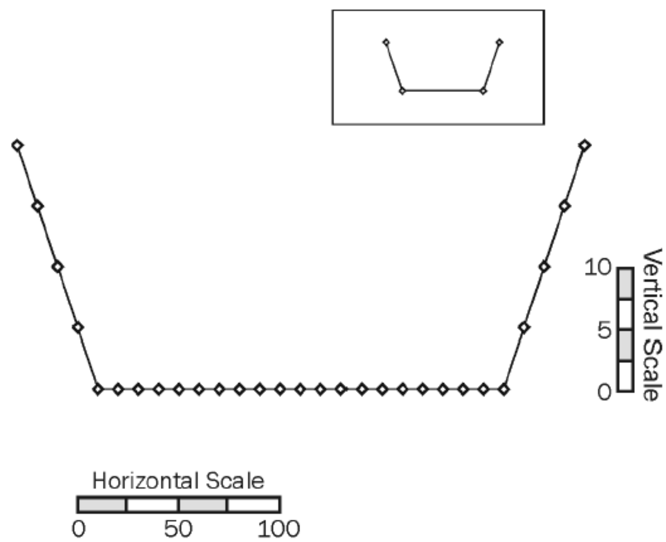

Figure D1.1 Sketch showing the discretization points used in the cross section template to define the channel. The smaller insert shows an equivalent cross section using the minimum possible number of discretisation points.

The upstream and downstream cross section use 29 points, as shown in Figure D1.1. The cross sections are input in (z, y) order and the elevation above datum is set using variable BEC in record XST.

The input sediment load is 48420 ton/day and 11 sediment sizes are used ranging from silt to small cobble. Incoming sediment size distribution is given in record USS. Two bed layers (one active layer and one inactive layer) are used. Only inactive layer thickness is input and the active layer thickness is calculated with input data NALT in record SAT. Bed size distributions are set using BLP records.

D1.1 Output data file

Most lines in the output files are too long to be fitted into the width of the paper. In the following output data files, new lines are started with a black dot for easier reading. Sediment variables are not calculated at the initial time step.

D1.1.1 Main Output File (example1_out.dat)

This file summarizes the dimensions that are used in the model. The total number of cross sections used in the simulation is more than the original input cross sections and interpolated cross sections because one extra cross section for each river is used for unsteady flow calculation. The maximum number of points in each cross section is two times of the original input due to cross section interpolation. The input data is also echoed in output, which is not printed here due to space limit. When input errors occur, the users should first check this file for possible warnings.

```
****************************SUMMARY****************************************
                                                      SRH-1D VERSION =  2.5
                                                     Number of rivers=    1
                                           Number of sediment classes=   11
                                        Number of sediment bed layers=    3
                                Number of cross sections in river   1=    3
                     Total number of cross sections used in simulation=   11
                                           Max number of sub channels=    1
                            Max number of points in each cross section=   62
                  Max number of ineffective area in each cross section=    0
       Max number of permanent ineffective area in each cross section=    0
                        Max number of levee area in each cross section=    0
                      Max number of blocked area in each cross section=    0
                          Total number of internal boundary conditions=    0
***************************************************************************
    1   YTT     SRH-1D version 2.4  Example data file for Appendix D of user's manual.
    2   YTT     Trapezoidal channel with sediment transport.
    3   YTT
..........
```

D1.1.2 HEC-RAS Geometry Output File (example1_HEC_RAS_GEOMETRY.g01)

This file is a HEC-RAS format geometry file. It is updated each DTPLT time step defined in record YDT. User may use HEC_RAS model to check the initial input geometry and the final geometry. This file is too long to be included in this section. It can be found under directory Example 1 in the SRH-1D distribution.

D1.1.3 Bed Profile File (example1_OUT_Profile.DAT)

This file is the bed profile file. The meaning of each variable is explained in the file header.

```
• # output bed profile
• # t         = time(hr)
• # riv       = river number
• # xcid      = identification string for cross section
• # xc        = cross section number
• # xt        = cross section location (ft or m)
• # q         = discharge (cfs or m^3/s)
• # qlatf     = lateral flow discharge (cfs or m^3/s)
• # zb        = current thalweg elevation (ft or m)
• # z         = current water surface elevation (ft or m)
• # zba       = average bed elevation of the main channel (ft or m)
• # fslope    = friction slope (-)
• # topw      = top width (ft or m)
• # hydrad    = hydraulic radius (ft or m)
• # vel       = average velocity for xc (ft/s or m/s)
• # d16       = sediment size d16 in bed layer 1 (mm)
• # d50       = sediment size d50 in bed layer 1 (mm)
• # d84       = sediment size d84 in bed layer 1 (mm)
• # vol_dep   = cumulative volume of sediment deposition (ft^3 or m^3)
• # sed_load  = cumulative weight of sediment passing cross section (ton or metric ton)
• TITLE="bed profile"
```

```
• VARIABLES=t,riv,xcid,xc,xt,q,qlatf,zb,z,zba,fslope,topw,hydrad,vel,d16,d50,d84,vol_dep,sed_load
•  0.00000000      1 0             1  5000.00000      14900.0000      0.00000000      1005.00000
  1015.00036      1007.85714     0.100002733E-02  240.001424      8.99010670      6.77246423
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        2  4500.00000      14900.0000      0.00000000      1004.50000
  1014.50034      1007.35714     0.100003236E-02  240.001365      8.99009459      6.77247518
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        3  4000.00000      14900.0000      0.00000000      1004.00000
  1014.00032      1006.85714     0.100003832E-02  240.001295      8.99008025      6.77248816
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        4  3500.00000      14900.0000      0.00000000      1003.50000
  1013.50030      1006.35714     0.100004537E-02  240.001211      8.99006328      6.77250352
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 0             5  3000.00000      14900.0000      0.00000000      1003.00000
  1013.00028      1005.85714     0.100005373E-02  240.001113      8.99004317      6.77252172
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        6  2500.00000      14900.0000      0.00000000      1002.50000
  1012.50025      1005.35714     0.100006362E-02  240.000996      8.99001936      6.77254326
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        7  2000.00000      14900.0000      0.00000000      1002.00000
  1012.00021      1004.85714     0.100007534E-02  240.000858      8.98999117      6.77256877
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        8  1500.00000      14900.0000      0.00000000      1001.50000
  1011.50017      1004.35714     0.100008921E-02  240.000695      8.98995779      6.77259898
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        9  1000.00000      14900.0000      0.00000000      1001.00000
  1011.00013      1003.85714     0.100010564E-02  240.000501      8.98991826      6.77263475
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 interp        10  500.000000     14900.0000      0.00000000      1000.50000
  1010.50007      1003.35714     0.100012509E-02  240.000272      8.98987145      6.77267711
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  0.00000000      1 0             11  0.00000000     14900.0000      0.00000000      1000.00000
  1010.00000      1002.85714     0.100014813E-02  240.000000      8.98981603      6.77272727
  0.372030801      2.30557757      13.1707542       0.00000000      0.00000000
•  2400.00000      1 0             1  5000.00000      14900.0000      0.00000000      1005.08041
  1015.05151      1007.92644     0.101017416E-02  240.024392      8.96304196      6.79306811
  0.365390044      2.27860953      13.2806775       4850.76496      3300062.94
•  2400.00000      1 interp        2  4500.00000      14900.0000      0.00000000      1004.57869
  1014.54610      1007.42496     0.101143546E-02  240.006141      8.96011830      6.79582947
  0.359892074      2.26590913      13.2249977       9494.52946      3299754.44
•  2400.00000      1 interp        3  4000.00000      14900.0000      0.00000000      1004.07272
  1014.04041      1006.91973     0.101133744E-02  240.001992      8.96045525      6.79567052
  0.359593078      2.26470566      13.2205240       8762.41578      3299558.63
•  2400.00000      1 interp        4  3500.00000      14900.0000      0.00000000      1003.56651
  1013.53479      1006.41426     0.101112851E-02  240.000303      8.96103229      6.79526025
  0.359291580      2.26315882      13.2159668       7996.31263      3299373.93
•  2400.00000      1 0             5  3000.00000      14900.0000      0.00000000      1003.05996
  1013.02932      1005.90855     0.101074798E-02  239.996987      8.96208837      6.79451525
  0.359388400      2.26227932      13.2135154       7196.62346      3299200.54
•  2400.00000      1 interp        6  2500.00000      14900.0000      0.00000000      1002.55370
  1012.52403      1005.40299     0.101040985E-02  239.998899      8.96293126      6.79380459
  0.359087696      2.26025605      13.2053439       6418.39469      3299034.77
•  2400.00000      1 interp        7  2000.00000      14900.0000      0.00000000      1002.04764
  1012.01891      1004.89764     0.101008305E-02  239.998935      8.96378204      6.79313568
  0.358697418      2.25793261      13.1941329       5669.96740      3298876.19
•  2400.00000      1 interp        8  1500.00000      14900.0000      0.00000000      1001.54175
  1011.51395      1004.39238     0.100976398E-02  240.002970      8.96453407      6.79244255
  0.358403376      2.25582305      13.1821891       4932.79064      3298731.83
•  2400.00000      1 interp        9  1000.00000      14900.0000      0.00000000      1001.03623
  1011.00912      1003.88731     0.100953688E-02  240.013925      8.96490991      6.79186851
  0.358278001      2.25445118      13.1727712       4223.21654      3298597.83
•  2400.00000      1 interp        10  500.000000     14900.0000      0.00000000      1000.53121
  1010.50438      1003.38267     0.100945307E-02  240.023739      8.96493472      6.79159909
  0.358057231      2.25321937      13.1631804       3573.95464      3298471.21
•  2400.00000      1 0             11  0.00000000     14900.0000      0.00000000      1000.02278
  1010.00000      1002.87525     0.100805528E-02  240.034023      8.96838037      6.78863420
  0.363391452      2.26496205      13.2094527       1267.41233      3298526.47
```

D1.1.4 Cross Section Geometry File (example1_OUT_XC.DAT)

Due to space limitation, only part of the file is printed here. Interested users may find the complete file under directory Example1.

- # output cross section geometry
- # due to disk space limitation, maxmium times of geometry printed is 20
- # t   = time(hr)
- # riv = river number
- # xc = cross section identification string
- # xc = cross section number
- # y   = transversal coordinate y of bed geometry (ft or m)
- # z   = vertical coordinate z of bed geometry (ft or m)
- TITLE="cross section geometry"
- VARIABLES=tt,riv,xcid,xc,y,z
- 0.00000000   1 0   1 0.00000000   1025.00000
- 0.00000000   1 0   1 10.0000000   1020.00000
- 0.00000000   1 0   1 20.0000000   1015.00000
- 0.00000000   1 0   1 30.0000000   1010.00000
- 0.00000000   1 0   1 40.0000000   1005.00000
- 0.00000000   1 0   1 50.0000000   1005.00000
- 0.00000000   1 0   1 60.0000000   1005.00000
- 0.00000000   1 0   1 70.0000000   1005.00000
- 0.00000000   1 0   1 80.0000000   1005.00000
- 0.00000000   1 0   1 90.0000000   1005.00000
- 0.00000000   1 0   1 100.000000   1005.00000
- 0.00000000   1 0   1 110.000000   1005.00000
- 0.00000000   1 0   1 120.000000   1005.00000
- 0.00000000   1 0   1 130.000000   1005.00000
- 0.00000000   1 0   1 140.000000   1005.00000
- 0.00000000   1 0   1 150.000000   1005.00000
- 0.00000000   1 0   1 160.000000   1005.00000
- 0.00000000   1 0   1 170.000000   1005.00000
- 0.00000000   1 0   1 180.000000   1005.00000
- 0.00000000   1 0   1 190.000000   1005.00000
- 0.00000000   1 0   1 200.000000   1005.00000
- 0.00000000   1 0   1 210.000000   1005.00000
- 0.00000000   1 0   1 220.000000   1005.00000
- 0.00000000   1 0   1 230.000000   1005.00000
- 0.00000000   1 0   1 240.000000   1005.00000
- 0.00000000   1 0   1 250.000000   1010.00000
- 0.00000000   1 0   1 260.000000   1015.00000
- 0.00000000   1 0   1 270.000000   1020.00000
- 0.00000000   1 0   1 280.000000   1025.00000
- 0.00000000   1 interp   2 0.00000000   1024.50000
- 0.00000000   1 interp   2 0.00000000   1024.50000
- 0.00000000   1 interp   2 10.0000000   1019.50000
- 0.00000000   1 interp   2 20.0000000   1014.50000
- 0.00000000   1 interp   2 30.0000000   1009.50000
- 0.00000000   1 interp   2 40.0000000   1004.50000
- 0.00000000   1 interp   2 50.0000000   1004.50000
- 0.00000000   1 interp   2 60.0000000   1004.50000
- 0.00000000   1 interp   2 70.0000000   1004.50000
- 0.00000000   1 interp   2 80.0000000   1004.50000
- 0.00000000   1 interp   2 90.0000000   1004.50000
- 0.00000000   1 interp   2 100.000000   1004.50000
- 0.00000000   1 interp   2 110.000000   1004.50000
- 0.00000000   1 interp   2 120.000000   1004.50000
- 0.00000000   1 interp   2 130.000000   1004.50000
- 0.00000000   1 interp   2 140.000000   1004.50000
- 0.00000000   1 interp   2 150.000000   1004.50000
- 0.00000000   1 interp   2 160.000000   1004.50000
- 0.00000000   1 interp   2 170.000000   1004.50000
- 0.00000000   1 interp   2 180.000000   1004.50000
- 0.00000000   1 interp   2 190.000000   1004.50000
- 0.00000000   1 interp   2 200.000000   1004.50000
- 0.00000000   1 interp   2 210.000000   1004.50000
- 0.00000000   1 interp   2 220.000000   1004.50000
- 0.00000000   1 interp   2 230.000000   1004.50000
- 0.00000000   1 interp   2 240.000000   1004.50000
- 0.00000000   1 interp   2 250.000000   1009.50000

- 0.00000000 1 interp 2 260.000000 1014.50000
- 0.00000000 1 interp 2 270.000000 1019.50000
- 0.00000000 1 interp 2 280.000000 1024.50000
- 0.00000000 1 interp 2 280.000000 1024.50000
- ....

D1.1.5 Material Volume of Deposition in Each Sub-Channel (example1_OUT_MaterialVolume.DAT)

```
• # material volume of deposition in each size fraction
• # t   = time(hr)
• # riv = river number
• # xc  = cross section number
• # xt  = cross section location (ft or m)
• # ssd_mat(0) = material volume of deposition in all size fractions (ft^3 or m^3)
• # ssd_mat(m) = material volume of deposition in m size fraction (ft^3 or m^3)
• TITLE="deposition material volume"
• VARIABLES=
  t,xc,xt,ssd_mat00,ssd_mat01,ssd_mat02,ssd_mat03,ssd_mat04,ssd_mat05,ssd_mat06,ssd_mat07,ssd_mat
  08,ssd_mat09,ssd_mat10,ssd_mat11
•  0.00000000       1     1  5000.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     2  4500.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     3  4000.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     4  3500.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     5  3000.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     6  2500.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     7  2000.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     8  1500.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1     9  1000.00000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1    10  500.000000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  0.00000000       1    11  0.00000000        0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
  0.000000E+00   0.000000E+00   0.000000E+00
•  2400.00000       1     1  5000.00000        0.289724E+04  -0.618960E+03   0.121325E+04
  0.239587E+03   0.405018E+03   0.473013E+03   0.305798E+03   0.135946E+03   0.177905E+03
  0.314537E+03   0.251149E+03   0.000000E+00
•  2400.00000       1     2  4500.00000        0.568114E+04  -0.729692E+03   0.235919E+04
  0.433299E+03   0.742986E+03   0.875560E+03   0.526689E+03   0.202953E+03   0.299759E+03
  0.569963E+03   0.400438E+03   0.000000E+00
•  2400.00000       1     3  4000.00000        0.524198E+04  -0.724503E+03   0.231670E+04
  0.400012E+03   0.689627E+03   0.814778E+03   0.440967E+03   0.145445E+03   0.255982E+03
  0.535088E+03   0.367882E+03   0.000000E+00
•  2400.00000       1     4  3500.00000        0.478259E+04  -0.711966E+03   0.227625E+04
  0.368030E+03   0.638046E+03   0.755635E+03   0.327629E+03   0.877077E+02   0.213440E+03
  0.503176E+03   0.324639E+03   0.000000E+00
•  2400.00000       1     5  3000.00000        0.430319E+04  -0.692304E+03   0.224932E+04
  0.344407E+03   0.598440E+03   0.708337E+03   0.196772E+03   0.340191E+02   0.163186E+03
  0.442817E+03   0.258200E+03   0.000000E+00
•  2400.00000       1     6  2500.00000        0.383610E+04  -0.699633E+03   0.221210E+04
  0.314536E+03   0.549824E+03   0.652155E+03   0.791530E+02  -0.209565E+02   0.124734E+03
  0.422500E+03   0.201684E+03   0.000000E+00
```

- 2400.00000 1 7 2000.00000 0.338670E+04 -0.715748E+03 0.217396E+04 0.283896E+03 0.500635E+03 0.595838E+03 -0.354723E+02 -0.785480E+02 0.969504E+02 0.424048E+03 0.141139E+03 0.000000E+00
- 2400.00000 1 8 1500.00000 0.294376E+04 -0.745233E+03 0.214008E+04 0.256241E+03 0.455886E+03 0.544125E+03 -0.127421E+03 -0.132694E+03 0.649569E+02 0.402705E+03 0.851131E+02 0.000000E+00
- 2400.00000 1 9 1000.00000 0.251802E+04 -0.744868E+03 0.210539E+04 0.228201E+03 0.410951E+03 0.492449E+03 -0.198744E+03 -0.195210E+03 0.195453E+02 0.371932E+03 0.283757E+02 0.000000E+00
- 2400.00000 1 10 500.000000 0.212843E+04 -0.746585E+03 0.206761E+04 0.198832E+03 0.364600E+03 0.440073E+03 -0.250526E+03 -0.259767E+03 -0.213154E+02 0.350721E+03 -0.152182E+02 0.000000E+00
- 2400.00000 1 11 0.00000000 0.747084E+03 -0.625553E+03 0.103221E+04 0.938875E+02 0.170432E+03 0.203358E+03 -0.135768E+03 -0.145907E+03 -0.259411E+02 0.167740E+03 0.126286E+02 0.000000E+00

D1.1.6 Mass Balance File (example1_OUT_MassBalance.DAT)

- # mass balance
- # this mass balance check is only valid for sslove = 1, when negeleting
- # suspended sediment change
- # t = time(hr)
- # riv = river number
- # massbal = balance of material volume (ft^3 or m^3)
- # sumtin = material volume of sediment entering upstream boundary (ft^3 or m^3)
- # sumtex = material volume of erosion exiting downstream boundary (ft^3 or m^3)
- # sumtlt = material volume of sediment entering laterally (ft^3 or m^3)
- # sume = material volume of erosion (ft^3 or m^3)
- TITLE="mass balance"
- VARIABLES= t,riv,massbal00,sumtin00,masstex00,masstlt00,sume00,massbal01,sumtin01,masstex01,masstlt01,sume01,massbal02,sumtin02,masstex02,masstlt02,sume02,massbal03,sumtin03,masstex03,masstlt03,sume03,massbal04,sumtin04,masstex04,masstlt04,sume04,massbal05,sumtin05,masstex05,masstlt05,sume05,massbal06,sumtin06,masstex06,masstlt06,sume06,massbal07,sumtin07,masstex07,masstlt07,sume07,massbal08,sumtin08,masstex08,masstlt08,sume08,massbal09,sumtin09,masstex09,masstlt09,sume09,massbal10,sumtin10,masstex10,masstlt10,sume10,massbal11,sumtin11,masstex11,masstlt11,sume11
- 0.0000E+00 1 0.0000000E+00
- 0.2400E+04 1 0.1909512E-05 0.5858372E+08 0.5854525E+08 0.0000000E+00 -0.3846623E+05 -0.1273293E-10 0.0000000E+00 0.7755045E+04 0.0000000E+00 0.7755045E+04 0.1841505E-05 0.3231215E+08 0.3229001E+08 0.0000000E+00 -0.2214606E+05 0.3636078E-06 0.7288544E+07 0.7285383E+07 0.0000000E+00 -0.3160926E+04 -0.8501520E-06 0.8489630E+07 0.8484104E+07 0.0000000E+00 -0.5526446E+04 0.6078135E-06 0.9180987E+07 0.9174432E+07 0.0000000E+00 -0.6555319E+04 0.1272292E-07 0.1992046E+06 0.1980755E+06 0.0000000E+00 -0.1129077E+04 -0.1855520E-07 0.3163837E+06 0.3166107E+06 0.0000000E+00 0.2270113E+03 -0.1013996E-07 0.3749733E+06 0.3736041E+06 0.0000000E+00 -0.1369202E+04 -0.3788227E-07 0.3866912E+06 0.3821860E+06 0.0000000E+00 -0.4505226E+04 0.6052687E-09 0.3515375E+05 0.3309772E+05 0.0000000E+00 -0.2056031E+04 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00

D1.1.7 Sediment Load File (example1_OUT_SedimentLoad.DAT)

- # cumulative sediment load passing cross section in each sub-channel
- # t = time(hr)
- # riv = river number
- # xc = cross seciton number
- # xt = cross seciton location (ft or m)
- # ssed(j,0) = cumulative sediment load passing in sub-channel j (tons or metric tons)
- # ssed(j,m) = cumulative sediment load passing for size fraction m in sub-channel j (tons or metric tons)
- TITLE = "sediment load"

- VARIABLES=
  t,riv,xc,xt,ssed(01_00),ssed(01_01),ssed(01_02),ssed(01_03),ssed(01_04),ssed(01_05),ssed(01_06)
  ,ssed(01_07),ssed(01_08),ssed(01_09),ssed(01_10),ssed(01_11)
- 0.00000000 1 1 5000.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 2 4500.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 3 4000.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 4 3500.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 5 3000.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 6 2500.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 7 2000.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 8 1500.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 9 1000.00000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 10 500.000000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 0.00000000 1 11 0.00000000 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00
  0.00000000E+00 0.00000000E+00 0.00000000E+00
- 2400.00000 1 1 5000.00000 0.33000629E+07 0.51178663E+02 0.23017043E+07
  0.18027257E+06 0.29695195E+06 0.45415085E+06 0.12452396E+05 0.17598400E+05 0.18538086E+05
  0.16986177E+05 0.13570488E+04 0.00000000E+00
- 2400.00000 1 2 4500.00000 0.32997544E+07 0.11151321E+03 0.23015604E+07
  0.18025283E+06 0.29691108E+06 0.45408477E+06 0.12419685E+05 0.17587473E+05 0.18523649E+05
  0.16961485E+05 0.13415151E+04 0.00000000E+00
- 2400.00000 1 3 4000.00000 0.32995586E+07 0.17141871E+03 0.23013086E+07
  0.18027453E+06 0.29693899E+06 0.45412403E+06 0.12390858E+05 0.17577650E+05 0.18509169E+05
  0.16936300E+05 0.13270673E+04 0.00000000E+00
- 2400.00000 1 4 3500.00000 0.32993739E+07 0.23028756E+03 0.23010743E+07
  0.18029170E+06 0.29695994E+06 0.45415283E+06 0.12369333E+05 0.17571329E+05 0.18497097E+05
  0.16912796E+05 0.13143258E+04 0.00000000E+00
- 2400.00000 1 5 3000.00000 0.32992005E+07 0.28753068E+03 0.23008566E+07
  0.18030404E+06 0.29697336E+06 0.45417031E+06 0.12356190E+05 0.17568265E+05 0.18487794E+05
  0.16892203E+05 0.13041905E+04 0.00000000E+00
- 2400.00000 1 6 2500.00000 0.32990348E+07 0.34537976E+03 0.23006630E+07
  0.18030948E+06 0.29697590E+06 0.45417134E+06 0.12350756E+05 0.17568751E+05 0.18480909E+05
  0.16872976E+05 0.12962934E+04 0.00000000E+00
- 2400.00000 1 7 2000.00000 0.32988762E+07 0.40456134E+03 0.23004919E+07
  0.18030844E+06 0.29696822E+06 0.45415692E+06 0.12352762E+05 0.17572816E+05 0.18475794E+05
  0.16854041E+05 0.12907813E+04 0.00000000E+00
- 2400.00000 1 8 1500.00000 0.32987318E+07 0.46618084E+03 0.23003347E+07
  0.18030392E+06 0.29695528E+06 0.45413459E+06 0.12360706E+05 0.17580155E+05 0.18472533E+05
  0.16836293E+05 0.12874685E+04 0.00000000E+00
- 2400.00000 1 9 1000.00000 0.32985978E+07 0.52777020E+03 0.23001939E+07
  0.18029513E+06 0.29693571E+06 0.45410229E+06 0.12373336E+05 0.17591285E+05 0.18471848E+05
  0.16820198E+05 0.12863869E+04 0.00000000E+00
- 2400.00000 1 10 500.000000 0.32984712E+07 0.58950151E+03 0.23000704E+07
  0.18028172E+06 0.29690898E+06 0.45405915E+06 0.12389405E+05 0.17606289E+05 0.18473481E+05
  0.16805305E+05 0.12870231E+04 0.00000000E+00
- 2400.00000 1 11 0.00000000 0.32985265E+07 0.64122523E+03 0.22998916E+07
  0.18031777E+06 0.29696625E+06 0.45414580E+06 0.12396472E+05 0.17612374E+05 0.18472628E+05
  0.16795976E+05 0.12863666E+04 0.00000000E+00

D1.1.8 Sediment Concentration File (example1_OUT_Conc.DAT)

- # concentration in each sub-channel

- # t = time(hr)
- # riv = river number
- # xc = cross section number
- # xt = cross section location (ft or m)
- # conc(j,0) = total concentration in sub-channel j (mg/l)
- # conc(j,m) = concentration of size m in sub-channel j (mg/l)
- TITLE = "concentration"
- VARIABLES= t,riv,xc,xt,conc(01_00),conc(01_01),conc(01_02),conc(01_03),conc(01_04),conc(01_05),conc(01_06),conc(01_07),conc(01_08),conc(01_09),conc(01_10),conc(01_11)
- 0.00000000 1 1 5000.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 2 4500.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 3 4000.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 4 3500.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 5 3000.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 6 2500.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 7 2000.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 8 1500.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 9 1000.00000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 10 500.000000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 0.00000000 1 11 0.00000000 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
- 2400.00000 1 1 5000.00000 0.1206E+04 0.8567E-02 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4101E+01 0.6514E+01 0.7720E+01 0.7961E+01 0.7226E+00 0.0000E+00
- 2400.00000 1 2 4500.00000 0.1206E+04 0.2115E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4100E+01 0.6514E+01 0.7720E+01 0.7961E+01 0.7207E+00 0.0000E+00
- 2400.00000 1 3 4000.00000 0.1206E+04 0.3388E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4097E+01 0.6513E+01 0.7720E+01 0.7961E+01 0.7183E+00 0.0000E+00
- 2400.00000 1 4 3500.00000 0.1206E+04 0.4669E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4091E+01 0.6513E+01 0.7720E+01 0.7961E+01 0.7147E+00 0.0000E+00
- 2400.00000 1 5 3000.00000 0.1206E+04 0.5833E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4085E+01 0.6512E+01 0.7720E+01 0.7961E+01 0.7101E+00 0.0000E+00
- 2400.00000 1 6 2500.00000 0.1206E+04 0.6999E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4077E+01 0.6511E+01 0.7720E+01 0.7961E+01 0.7042E+00 0.0000E+00
- 2400.00000 1 7 2000.00000 0.1206E+04 0.8173E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4070E+01 0.6510E+01 0.7719E+01 0.7961E+01 0.6977E+00 0.0000E+00
- 2400.00000 1 8 1500.00000 0.1206E+04 0.9443E-01 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4065E+01 0.6508E+01 0.7719E+01 0.7961E+01 0.6910E+00 0.0000E+00
- 2400.00000 1 9 1000.00000 0.1206E+04 0.1071E+00 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4063E+01 0.6505E+01 0.7718E+01 0.7961E+01 0.6859E+00 0.0000E+00
- 2400.00000 1 10 500.000000 0.1206E+04 0.1199E+00 0.6653E+03 0.1501E+03 0.1748E+03 0.1890E+03 0.4064E+01 0.6503E+01 0.7715E+01 0.7960E+01 0.6825E+00 0.0000E+00

- 2400.00000 1 11 0.00000000 0.1206E+04 0.1286E+00 0.6653E+03 0.1501E+03
  0.1748E+03 0.1890E+03 0.4065E+01 0.6502E+01 0.7714E+01 0.7959E+01 0.6807E+00
  0.0000E+00

D1.1.9 Bed Fraction File (example1_OUT_BedFraction.DAT)

- # bed fraction by mass in each sub-channel
- # t=time(hr)
- # riv = river number
- # xc = cross seciton number
- # xt = cross seciton location (ft or m)
- # pn_mass(n,m) = bed fraction by mass of layer n and size m (1/1)
- TITLE="bed fraction"
- VARIABLES=
  t,riv,xc,xt,pn_01_01,pn_01_02,pn_01_03,pn_01_04,pn_01_05,pn_01_06,pn_01_07,pn_01_08,pn_01_09,pn
  _01_10,pn_01_11,pn_02_01,pn_02_02,pn_02_03,pn_02_04,pn_02_05,pn_02_06,pn_02_07,pn_02_08,pn_02_0
  9,pn_02_10,pn_02_11
- 0.00000000 1 1 5000.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 2 4500.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 3 4000.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 4 3500.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 5 3000.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 6 2500.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 7 2000.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 8 1500.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 9 1000.00000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 10 500.000000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 0.00000000 1 11 0.00000000 0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00
  0.1446E+00 0.1545E+00 0.1396E+00 0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
  0.9901E-02 0.1030E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1545E+00 0.1396E+00
  0.1079E+00 0.8515E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 1 5000.00000 0.4530E-02 0.1105E+00 0.8219E-01 0.1290E+00
  0.1450E+00 0.1533E+00 0.1374E+00 0.1068E+00 0.8572E-01 0.3301E-01 0.1257E-01
  0.9891E-02 0.1031E+00 0.8217E-01 0.1287E+00 0.1446E+00 0.1544E+00 0.1395E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 2 4500.00000 0.6649E-02 0.1102E+00 0.8204E-01 0.1288E+00
  0.1448E+00 0.1530E+00 0.1372E+00 0.1066E+00 0.8552E-01 0.3260E-01 0.1257E-01
  0.9892E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1544E+00 0.1395E+00
  0.1079E+00 0.8513E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 3 4000.00000 0.6724E-02 0.1102E+00 0.8205E-01 0.1288E+00
  0.1448E+00 0.1529E+00 0.1372E+00 0.1067E+00 0.8553E-01 0.3252E-01 0.1259E-01
  0.9892E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8513E-01 0.3168E-01 0.1287E-01

- 2400.00000 1 4 3500.00000 0.6771E-02 0.1103E+00 0.8207E-01 0.1288E+00
  0.1448E+00 0.1528E+00 0.1372E+00 0.1067E+00 0.8556E-01 0.3240E-01 0.1262E-01
  0.9892E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8513E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 5 3000.00000 0.6645E-02 0.1104E+00 0.8212E-01 0.1289E+00
  0.1449E+00 0.1526E+00 0.1373E+00 0.1067E+00 0.8562E-01 0.3228E-01 0.1264E-01
  0.9893E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1446E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8513E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 6 2500.00000 0.6658E-02 0.1104E+00 0.8216E-01 0.1289E+00
  0.1449E+00 0.1524E+00 0.1373E+00 0.1068E+00 0.8567E-01 0.3209E-01 0.1267E-01
  0.9895E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8513E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 7 2000.00000 0.6705E-02 0.1105E+00 0.8220E-01 0.1290E+00
  0.1450E+00 0.1522E+00 0.1373E+00 0.1068E+00 0.8572E-01 0.3187E-01 0.1269E-01
  0.9896E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 8 1500.00000 0.6721E-02 0.1105E+00 0.8224E-01 0.1290E+00
  0.1451E+00 0.1521E+00 0.1374E+00 0.1069E+00 0.8578E-01 0.3164E-01 0.1271E-01
  0.9897E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 9 1000.00000 0.6703E-02 0.1106E+00 0.8227E-01 0.1291E+00
  0.1451E+00 0.1520E+00 0.1373E+00 0.1069E+00 0.8581E-01 0.3147E-01 0.1274E-01
  0.9898E-02 0.1031E+00 0.8218E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 10 500.000000 0.6753E-02 0.1106E+00 0.8228E-01 0.1291E+00
  0.1451E+00 0.1521E+00 0.1373E+00 0.1069E+00 0.8581E-01 0.3134E-01 0.1276E-01
  0.9898E-02 0.1030E+00 0.8217E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01
- 2400.00000 1 11 0.00000000 0.4640E-02 0.1109E+00 0.8245E-01 0.1293E+00
  0.1454E+00 0.1524E+00 0.1375E+00 0.1070E+00 0.8602E-01 0.3159E-01 0.1279E-01
  0.9898E-02 0.1030E+00 0.8217E-01 0.1287E+00 0.1445E+00 0.1544E+00 0.1396E+00
  0.1079E+00 0.8514E-01 0.3168E-01 0.1287E-01

D1.1.10 Sediment Porosity File (example1_OUT_Porosity.DAT)

- # maximum porosity in each sub-channel and layer of bed
- # t=time(hr)
- # riv = river number
- # xc=cross seciton number
- # xt=cross seciton location (ft or m)
- # porsty(n,0) = porosity in bed layer n (-)
- # porsty(n,m) = relative porosity in bed of size m in layer n (-)
- TITLE="porosity"
- VARIABLES=
  t,riv,xc,xt,porsty01_00,porsty01_01,porsty01_02,porsty01_03,porsty01_04,porsty01_05,porsty01_06
  ,porsty01_07,porsty01_08,porsty01_09,porsty01_10,porsty01_11,porsty02_00,porsty02_01,porsty02_0
  2,porsty02_03,porsty02_04,porsty02_05,porsty02_06,porsty02_07,porsty02_08,porsty02_09,porsty02_
  10,porsty02_11
- 0.00000000 1 1 0.5000E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 2 0.4500E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 3 0.4000E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 4 0.3500E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 5 0.3000E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 6 0.2500E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
- 0.00000000 1 7 0.2000E+04 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01
  0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01 0.1000E+01

```
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
•   0.00000000      1     8     0.1500E+04     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
•   0.00000000      1     9     0.1000E+04     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
•   0.00000000      1    10     0.5000E+03     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
   0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01     0.1000E+01
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   0.4000E+00     0.3999E+00     0.3869E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
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   0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
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   0.4000E+00     0.3999E+00     0.3869E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
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   0.4000E+00     0.3999E+00     0.3869E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
   0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
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   0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
•   2400.00000      1    11     0.0000E+00     0.3999E+00     0.3869E+00     0.4000E+00     0.4000E+00
   0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
   0.4000E+00     0.3999E+00     0.3869E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
   0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00     0.4000E+00
```

D1.2 Profile Results

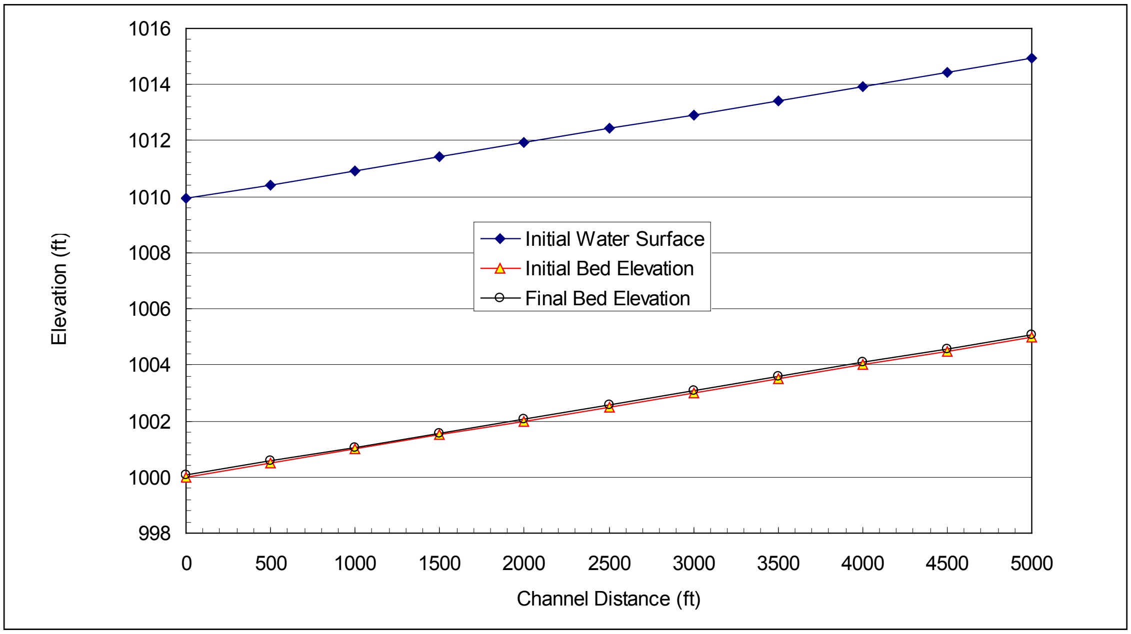

Figure D1.2 Bed elevation and water surface

Figure D1.2 shows the initial and final bed elevation and water surface elevation profiles. The incoming sediment load near equilibrium condition, the bed elevation change is small. The user may change the incoming sediment load to see the result of erosion and deposition.

EXAMPLE 2   CHANNEL NETWORK

This example shows a SRH-1D input data file set-up for a simple network channel with sediment transport. The network is composed of 4 trapezoid channels as shown in Figure D2.1. Rivers are numbered in ascending order from upstream to downstream. Each channel is 1 mile (5,280 ft) long with a trapezoid cross section of bottom width of 200 ft and side slopes of 1V:2H. The upstream water discharge is 14,900 cfs and the downstream water surface elevation is set to a fixed depth. Each channel was input with two original cross sections and 9 interpolated cross sections.

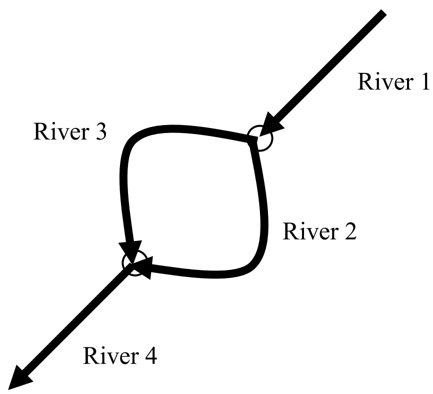

Figure D2.1 Sketch showing the river network

The downstream boundary of river 1 is defined in Record D00 (D00 -2, -3). This record shows river 1 is connected with rivers 2 and 3 at downstream. Negative numbers represent that flow directions in river 2 and river 3 are out of the junction. The upstream boundary of river 2 is defined in Record U00 (U00 1, -3). The record shows river 2 is connected with rivers 1 and 3 at its upstream end. A positive number 1 represents that the flow direction in river 1 is into the junction. Negative number -3 represents that the flow direction in river 3 is out of the junction. The boundary conditions of junction are defined in the same way for rivers 3 and 4.

The input sediment load is 57709 ton/day and 11 sediment sizes are used ranging from silt to small cobble. The incoming sediment size distribution is given in record USS. Two bed layers (one active layer and one inactive layer) are used. The active layer thickness is calculated from the input value of NALT in record SAT.

D2.1 Results

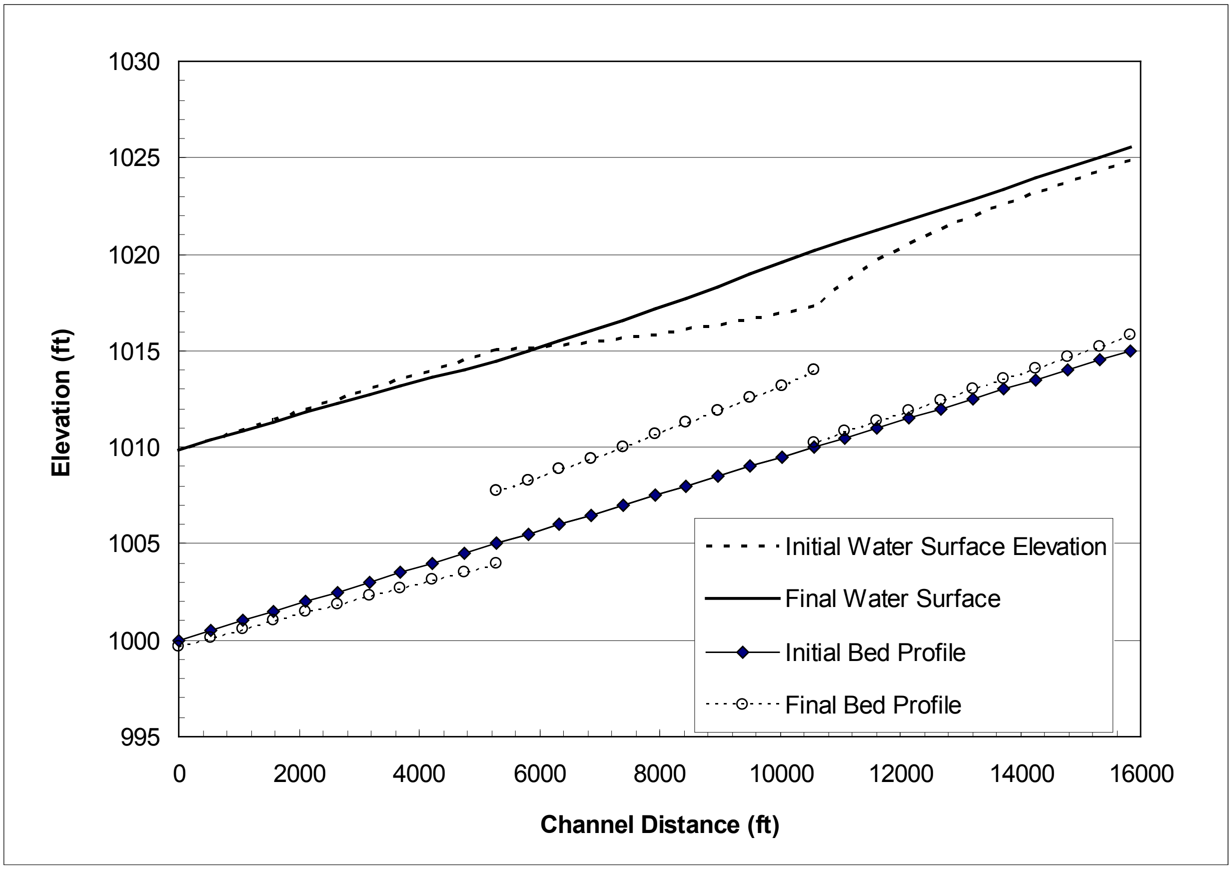

Figure D2.2 Bed elevation and water surface

Figure D2.2 shows the initial and final bed elevation and water surface elevation profiles. The middle section is the profiles for river 2 and 3, which are identical in the calculation. Due to larger conveyances and lower energy slopes in rivers 2 and 3, the sediment transport capacity is lower and sediment deposition occurs in rivers 2 and 3. The lower section expericnces erosions because some of the sediments are deposited in rivers 2 and 3, and there is not enough sediment supply. The deposition in river 2 and 3 also raises the water surface elevation in river 1, resulting in sediment deposition in river 1.

EXAMPLE 3 CALIFORNIA AQUEDUCT

This example illustrates the use of the unsteady flow and sediment transport features of SRH-1D. The files referenced in this and the next sections are part of the main SRH-1D distribution package. They can be found under directory Example3. In this example, the model was applied to the California Aqueduct near Arroyo Pasajero to study the influence of rainfall-runoff on sedimentation (Klumpp, et al., 2003). An unsteady flow and unsteady sediment model was used to simulate a duration of 2000 hrs. The studied reach of the California Aqueduct, or San Luis Canal (SLC), extends 75 miles from Check Structure 15 to Check Structure 21. The SLC was designed and built to distribute water for both agricultural and municipal uses. It was built with drain inlet structures to capture floodwaters generated west of the SLC. Rainfall-runoff is admitted to the SLC when the capacity of ponding areas or bypass structures is exceeded. The runoff carries many tons of sediment into the aqueduct. The input data includes the cross-section geometry, the six check structures and their radial gate operations. The flow in the canal prior to the flood is assumed to be 2000 cfs. In this example, only one of the six lateral inflows that carry storm water into the aqueduct is modeled.

The lateral inflow is modeled in terms of discharge hydrograph and sediment inflow. The bed material along the aqueduct is approximately 2% sand (non-cohesive sediment) and 98% silt and clay (cohesive sediment).

An equilibrium sediment concentration for partial deposition of 265 mg/l was observed at the downstream end of the channel, therefore an equilibrium concentration of 265 mg/l was used in the model.

The present model used a modified version of Eq. (D3.1) for surface erosion

$$Q_{se} = \begin{cases} P_{se}\left(\dfrac{\tau - \tau_{se}^{c}}{\tau_{me}^{c} - \tau_{se}^{c}}\right) & \tau \ge \tau_{se}^{c} \\ 0 & \tau < \tau_{se}^{c} \end{cases} \qquad \text{(D3.1)}$$

where τ_{se}^{c}, τ_{me}^{c} = critical surface and mass erosion shear stress, respectively.

The modified relationship is more consistent with the mass erosion rate used below. The parameters τ_{se}^{c} and P_{se} are site-specific and have to be determined experimentally. Mass erosion is usually arbitrarily dependent on the model setup and its time scale used. The presented example takes the similar equation for mass erosion as the surface erosion.

$$Q_{me} = P_{me}\left(\frac{\tau - \tau_{me}^{c}}{\tau_{me}^{c}}\right) + P_{se} \qquad \tau \ge \tau_{me}^{c} \qquad \text{(D3.2)}$$

where Q_{me} = mass erosion rate,

τ and τ_{me}^{c} = bed shear stress and critical mass erosion shear stress, respectively, and

P_{me} = mass erosion constant.

Because physical experiments were not performed, the cohesive sediment transport parameters were calibrated to the available observations. The critical shear stresses for full deposition, partial deposition, surface erosion, and mass erosion were determined from the observations in the channel during various discharges. These parameters are listed in Table D3.1.

Process	Discharge (cfs)	Shear Stress (lb/ft^2)
Full deposition	2,000	0.003
Partial deposition	2,000	0.003
Surface erosion	8,000	0.005
Mass erosion	>>10,000	0.01

Table D3.1.— Cohesive sediment parameters for erosion and deposition

The surface erosion rate was calibrated and found to equal 0.3 $lb/ft^2/hr$. The settling velocities are found in Figure 3.4. The parameters used in this example are listed in Table D3.2.

Point	C (mg/l)	V (mm/s)
1	200	0.2
2	6,000	0.2
3	20,000	0.35
4	100,000	0.35

Table D3.2.— Cohesive sediment parameters for fall velocity used in the SRH-1D example.

D3.1 Results

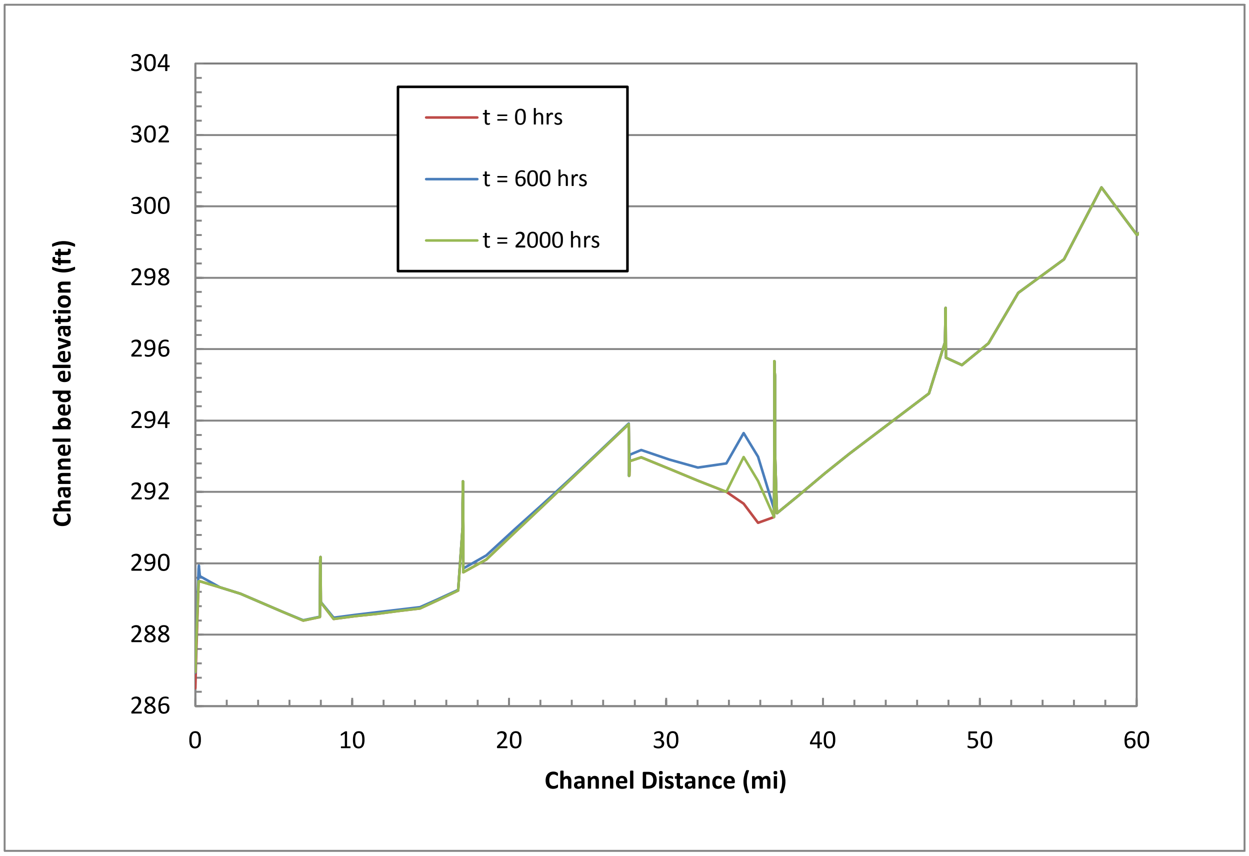

Figure D3.1 Bed elevation change of the SLC before and after a flood event.

Figure D3.1 shows the bed elevations before and after the flood. The sediments allowed into the aqueduct are deposited just downstream of the inlet, raising the channel bed elevation. Some of the fine sediments are eroded after the flood, but the sand is not mobile.

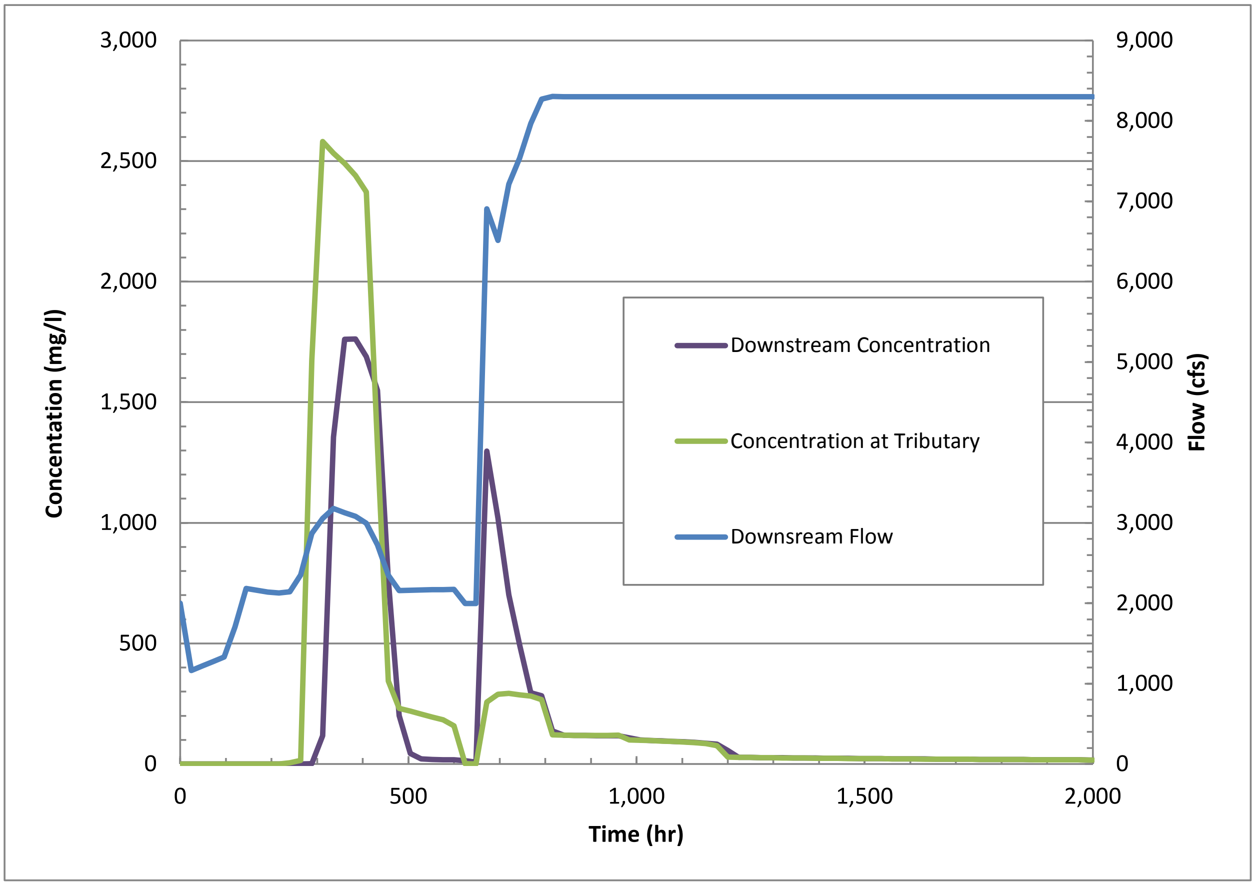

Figure D3.2 Sediment concentration changes with time

Figure D3.2 shows concentration changes with the sediment lateral inflow. The peak sediment inflow concentration just downstream of the lateral inflow is about 2600 mg/l. After time of about 700 hr, the contration just downstream of the lateral inlet increases to 300 mg/l. This increase is due to the increase in flow rate that erodes sediment that was deposited by the lateral inflow. Fifteen miles downstream of the lateral inflow the concentration increases to over 1300 mg/l after 700 hours because of the sediment that is picked up from the canal.