Knowledge to Go Places

The Hydroscience and Training Center of Colorado State University

Archived Versions of GSTARS

Background

The GSTARS is a series of Generalized Stream Tube computer models for Alluvial River Simulation developed by the U.S. Bureau of Reclamation for steady and quasi-steady flows. The first version of GSTARS was developed by Molinas and Yang (1985) for mainframe computers to simulate the flow conditions in a semi-two-dimensional manner and the change of channel geometry in a semi-three-dimensional manner based on the stream tube concept. GSTARS 2.0 (Yang et. al.1988) significantly revised and expanded the capabilities of GSTARS for PC applications. With a new graphical interface, GSTARS 2.1(Yang and Simões, 2000) replaced GSTARS 2.0 for cohesive and non-cohesive sediment transport in rivers. GSTARS 3 (Yang and Simões, 2002) further expanded the capabilities of GSTARS 2.1 for cohesive and non-cohesive sediment transport in rivers and reservoirs.

The Bureau of Reclamation no longer supports GSTARS 2.1 and GSTARS 3.0, the Hydroscience and Training Center of Colorado State University has been asked by the Bureau of Reclamation, since 2005, to make GSTARS 2.1 and GSTARS 3.0 available for downloading.

Disclaimer

The GSTARS program and information contained in this manual have been developed for the Bureau of Reclamation. The Hydroscience and Training Center of Colorado State University does not guarantee the performance of GSTARS nor provide user support for the software. The Hydroscience and Training Center assumes no responsibility for the correct use of GSTARS and make no warranties concerning the accuracy, completeness, reliability, usability, or suitability for particular purpose of the software or the information contained in this manual. GSTARS is a complex program that requires engineering expertise to be used correctly. Like any computer program, GSTARS cannot be certified infallible. 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. The Hydroscience and Training Center will not be liable for any special, collateral, incidental, or consequential damages in connection with the use of the software.

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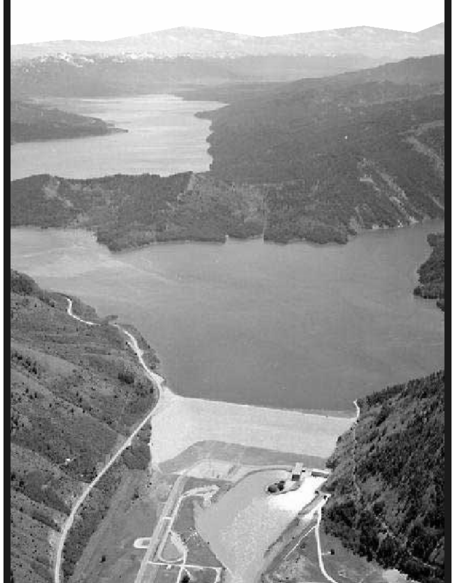
User's Manual for

GSTARS3

(Generalized Sediment Transport model for Alluvial River Simulation version 3.0)

by
Chih Ted Yang
and
Francisco J.M. Simões

December 2002



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

United States Department of the Interior

The mission of the Department of the Interior
is to protect and provide access to our
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honor our trust responsibilities to tribes.

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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.

Acknowledgement

The authors appreciate the financial supports provided by the
Bureau of Reclamation's Technical Service Center
and Taiwan's Water Resources Agency
for the development, testing, and application
of the GSTARS computer programs.

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Denver, Colorado

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CHAPTER

1

INTRODUCTION

GSTARS3 (Generalized Sediment Transport model for Alluvial River Simulation version 3.0) is the most recent version of a series of numerical models for simulating the flow of water and sediment transport in alluvial rivers developed at the Sedimentation and River Hydraulics Group of the Technical Service Center, U.S. Bureau of Reclamation, Denver, Colorado. It is an enhanced version of the GSTARS 2.0 and 2.1 models (Yang et al., 1998; Yang and Simões, 2000). This manual describes the overall theoretical background of the model and its most important implementation details in a computer program. It also guides the interested user in all the steps necessary for data preparation and input. Examples of the application of GSTARS3 are also given.

1.1 Purpose and Capabilities

The GSTARS series of programs were developed due to the need for a generalized water and sediment-routing computer model that could be used to solve complex river engineering problems for which limited data and resources were available. In order to be successful, such a model should have a number of capabilities, namely:

- It should be able to compute hydraulic parameters for open channels with fixed as well as with movable boundaries;
- It should have the capability of computing water surface profiles in the subcritical, supercritical, and mixed flow regimes, i.e., in combinations of subcritical and supercritical flows without interruption;

- It should be able to simulate and predict the hydraulic and sediment variations both in the longitudinal and in the transverse directions;
- It should be able to simulate and predict the change of alluvial channel profile and cross-sectional geometry, regardless of whether the channel width is variable or fixed; and
- It should incorporate site specific conditions such as channel side stability and erosion limits.

GSTARS version 3.0 is based on GSTARS version 2.1 (Yang and Simões, 2000) and consists of four major parts. The first part is the use of both the energy and the momentum equations for the backwater computations. This feature allows the program to compute the water surface profiles through combinations of subcritical and supercritical flows. In these computations, GSTARS3 can handle irregular cross sections regardless of whether single channel or multiple channels separated by small islands or sand bars.

The second part is the use of the stream tube concept, which is used in the sediment routing computations. Hydraulic parameters and sediment routing are computed for each stream tube, thereby providing a transverse variation in the cross section in a semi-two-dimensional manner. Although no flow can be transported across the boundary of a stream tube, transverse bed slope and secondary flows are phenomena accounted for in GSTARS3 that contribute to the exchange of sediments between stream tubes. The position and width of each stream tube may change after each step of computation. The scour or deposition computed in each stream tube give the variation of channel geometry in the vertical (or lateral) direction. The water surface profiles are computed first. The channel is then divided into a selected number of stream tubes with the following characteristics: (1) the total discharge carried by the channel is distributed equally among the stream tubes; (2) stream tubes are bounded by channel boundaries and by imaginary vertical walls; (3) the discharge along a stream tube is constant (i.e., there is no exchange of water through stream tube boundaries).

Bed sorting and armoring in each stream tube follows the method proposed by Bennett and Nordin (1977), and the rate of sediment transport can be computed using any of the following methods:

- DuBoys' 1879 method.
- Meyer-Peter and Müller's 1948 method.
- Laursen's 1958 method.
- Modified Laursen's method by Madden (1993).
- Toffaleti's 1969 method.
- Engelund and Hansen's 1972 method.
- Ackers and White's 1973 method.

- Revised Ackers and White's 1990 method.
- Yang's 1973 sand and 1984 gravel transport methods.
- Yang's 1979 sand and 1984 gravel transport methods.
- Parker's 1990 method.
- Yang's 1996 modified method for high concentration of wash load.
- Ashida and Michiue's 1972 method.
- Tsinghua University method (IRTCES, 1985).
- Krone's 1962 and Ariathurai and Krone's 1976 methods for cohesive sediment transport.

The third part is the use of the theory of minimum energy dissipation rate (Yang, 1971, 1976; Yang and Song, 1979, 1986) in its simplified version of minimum total stream power to compute channel width and depth adjustments. The use of this theory allows the channel width to be treated as an unknown variable. Treating the channel width as an unknown variable is one of the most important capabilities of GSTARS3. Whether a channel width or depth is adjusted at a given cross section and at a given time step depends on which condition results in less total stream power.

The fourth part is the inclusion of a channel bank side stability criteria based on the angle of repose of bank materials and sediment continuity.

Some of the potential applications and/or features of GSTARS3 are:

- GSTARS3 can be used for water surface profile computations with or without sediment transport.
- GSTARS3 can compute water surface profiles through subcritical and supercritical flow conditions, including hydraulic jumps, without interruption.
- GSTARS3 can compute the longitudinal and transversal variations of flow and sediment conditions in a semi-two-dimensional manner based on the stream tube concept. If only one stream tube is selected, the model becomes one-dimensional. If multiple stream tubes are selected, both the lateral and vertical bed elevation changes can be simulated.
- The bed sorting and armoring algorithm is based on sediment size fractions and can provide a realistic simulation of the bed armoring process.
- GSTARS3 can simulate channel geometry changes in width and depth simultaneously based on minimum total stream power.
- The channel side stability option allows simulation of channel geometry change based on the angle of repose of bank materials and sediment continuity.

1.1.1 What is New in GSTARS3

GSTARS3 is based on GSTARS 2.1 with the following modifications and improvements:

- Reservoir routing.
- GSTARS3 was written using the Fortran 90/95 programming language. Algorithms were improved for accuracy and speed. Dynamic memory allocation is now used instead of static, fixed-size arrays.
- Three sediment transport equations were added. Two of those apply to specific aspects of reservoir sedimentation.
- Multiple bed layers of different particle size distribution.
- Cohesive sediment transport methods were extended for high concentrations of fines, including flocculation and hindered settling.
- Methods of computing sediment transport across stream tube boundaries.
- Transmissive cross sections and input sediment rates based on equilibrium principles.
- Correction of a few known code bugs.
- Expanded user's manual.

Although most data files prepared for GSTARS 2.1 are fully compatible with GSTARS3, a few exceptions exist (more details are given in section 6.8). Therefore, conversion of data files from GSTARS 2.1 to GSTARS3 is easy and straightforward. The Bureau of Reclamation will continue to provide support and distribution of GSTARS 2.1.

1.2 Limits of Application

GSTARS3 is a general numerical model developed for a personal computer to simulate and predict river and reservoir morphological changes caused by natural and engineering events. Although GSTARS3 is intended to be used as a general engineering tool for solving fluvial hydraulic problems, it does have the following limitations from a theoretical point of view:

1 GSTARS3 is a quasi-steady flow model. Water discharge hydrographs are approximated by bursts of constant discharges. Consequently, GSTARS3 should not be applied to rapid, varied, unsteady flow conditions.

2 GSTARS3 is a semi-two-dimensional model for flow simulation and a semi-three-dimensional model for simulation of channel geometry change. It should not be applied to situations where a truly two-dimensional or truly three-dimensional model is needed for detailed simulation of local conditions. However, GSTARS3 should be adequate for solving many river engineering problems.

3 GSTARS3 is based on the stream tube concept. Secondary currents are empirically accounted for. The phenomena of diffusion, and superelevation are ignored.

4 Many of the methods and concepts used in GSTARS3 are simplified approximations of real phenomena. Those approximations and their limits of validity are, therefore, embedded in the model.

1.3 Overview of the Manual

This manual is organized into six chapters (including this one) and four appendices. Chapter 2 describes the backwater model, and chapter 3 describes the basis of the sediment routing model, including the use of the stream tube concept. Chapter 4 presents the concepts and the methodology used in the channel width adjustment model. Chapter 5 presents the concepts used for water and sediment routing in reservoirs. Finally, the main data requirements for GSTARS3 are discussed in chapter 6. The appendices provide additional information: appendix A gives a detailed description of the input records used by GSTARS3; appendix B provides several examples to show some of the model's features and to help the user get started; appendix C contains a reprint of the paper by Molinas and Yang (1985) that describes with more detail the basis of the backwater algorithm used in GSTARS3; and appendix D contains a reprint of the paper by Yang and Huang (2000) that offers guidelines on how to use selected sediment transport capacity equations.

1.4 Acquiring GSTARS3

The latest information about the GSTARS3 program is placed on the World Wide Web. The GSTARS3 Web page can be found by going to http://www.usbr.gov/pmts/sediment/ and following the links therein. Alternatively, requests may be sent directly to the Bureau of Reclamation's Sedimentation and River Hydraulics Group (U.S. Bureau of Reclamation, Sedimentation and River Hydraulics Group, P.O. Box 25007 (D-8540), Denver, CO 80225).

All questions regarding GSTARS3 should preferably be sent to the first author. Dr. Chih Ted Yang is the Manager of the Sedimentation and River Hydraulics Group, U.S. Bureau of Reclamation, P.O. Box 25007 (D-8540), Denver, CO 80225 (tyang@do.usbr.gov). Dr. Francisco J.M. Simões is a Research Hydrologist at the U.S. Geological Survey, National Research Program (NRP), P.O. Box 25046, Mail Stop 413, Lakewood, CO 80225 (frsimoes@usgs.gov).

GSTARS3 is in a stage of continuous evolution and unannounced changes may be made at any time. The user is encouraged to check regularly the GSTARS3 Web page. Updates to the code and documentation will be posted there as they become available.

1.5 Disclaimer

The program and information contained in this manual are developed for the Bureau of Reclamation (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 GSTARS3 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. GSTARS3 is a complex program that requires engineering expertise to be used correctly. Like any computer program, GSTARS3 cannot be certified infallible. 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.

CHAPTER

2

THE BACKWATER MODEL

The hydraulic computations in GSTARS3 are based on a model of gradually varied flow. Mixed flow regimes and hydraulic jumps can be calculated by selectively using the energy and the momentum equations. This section presents the basic governing equations for flow computations.

The basic concepts and backwater computational procedures can be found in most open channel hydraulics text books. For quasi-steady flows, discharge hydrographs are approximated by bursts of constant discharge, as shown in figure 2.1. During each constant discharge burst, steady state equations are used for the backwater computations. GSTARS3 solves the energy equation based on the standard-step method. However, when a hydraulic jump occurs, the momentum equation is used instead. Details of these computations were presented by Molinas and Yang (1985) and are given in appendix C. Reservoir routing uses a modified standard step method and level-pool flood routing.

2.1 Energy Equation

Using the notation of figure 2.2, the energy equation can be written as

$$z + Y + \alpha\frac{V^2}{2g} = H \tag{1}$$

where z = bed elevation; Y = water depth; V = flow velocity; α = velocity distribution coefficient; H = elevation of the energy line above the datum; and g = gravitational acceleration. Eq. (1) is used for most water profile computations. This equation is valid when the channel's bottom slope is small, i.e., when $S_0 < 5\%$, in which case $\sin\theta \approx \tan\theta \approx \theta$. Hydrostatic pressure distribution is also assumed.

Figure 2.1 Representation of a hydrograph by a series of steps with constant discharge (Q_i) and finite duration (Δt_i).

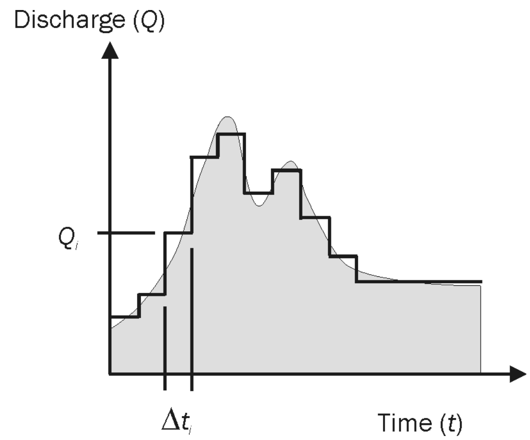
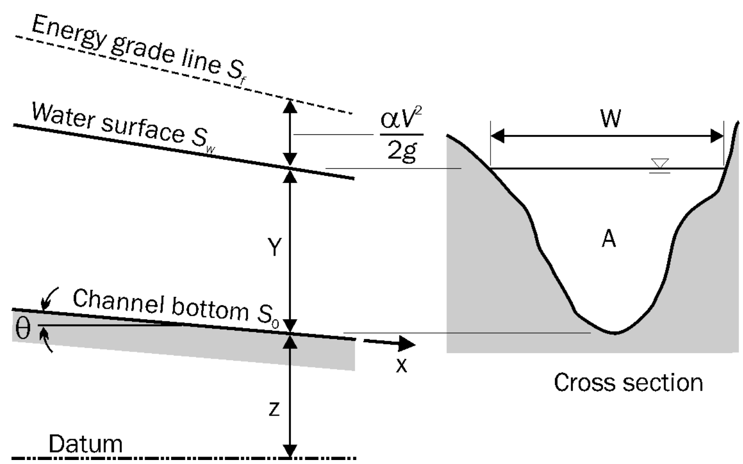


Figure 2.2 Definition of variables.



Eq. (1) is solved using a trial-and-error procedure based on the standard step method (Henderson, 1966). The initial surface elevation is guessed, and that guess is iteratively improved by using

$$Z = \tilde{Z} - \frac{H - \tilde{H}}{1 - \tilde{F}_r^2(1 \mp 0.5 C_L) \mp \dfrac{3\tilde{h}_f}{2\tilde{R}}} \tag{2}$$

where Z = water surface elevation; F_r = Froude number; R = hydraulic radius; h_f = friction loss; C_L = energy loss coefficient; and the tilde is used to denote that the respective quantities are computed from the guessed value for the first iteration, and from the previously computed values for the remaining iterations. The iterative procedure ends when $|H - \tilde{H}|$ is very small (say, $|H - \tilde{H}| < 0.01$ ft). Note that $\tilde{H}$ is computed using eq. (1), and H is computed by adding or subtracting the head losses from an adjacent section with known hydraulic parameters. Computations proceed in the upstream direction for subcritical flows and in the downstream direction for supercritical flows. The Froude number is computed from

$$F_r^2 = \frac{\alpha V^2}{gW\cos\theta} \tag{3}$$

where W = cross section width.

2.2 Flow Transitions

The energy equation is applied if there is no change of flow regime throughout the study reach. If there are changes in flow regime, GSTARS3 employs the algorithm described by Molinas and Yang (1985) to compute the water profiles through the regime changes without interruption. The interested reader should refer to that paper for a more detailed description of the algorithm (the paper is included in appendix C of this manual). There are 6 possible changes in the flow regime: from subcritical to critical or supercritical; from supercritical to critical or subcritical; and from critical to supercritical or subcritical. In this section we will address changes between supercritical (or critical) and subcritical, i.e., when an hydraulic jump occurs. In an hydraulic jump there is high curvature of the streamlines, the pressure is not hydrostatic, and the flow is referred to as rapidly varied flow.

Before starting the backwater computations, it is necessary to determine the flow regime, i.e., whether the flow conditions are supercritical, subcritical, or critical. For that purpose, the normal and critical depths are computed along the study reach. This computation is carried out in the upstream direction for subcritical flow and in the downstream direction for supercritical flow. The normal depth is set equal to a very large value when horizontal or adverse slopes are encountered. For the reaches where an hydraulic jump is detected, the momentum equation is used:

$$\frac{Q\gamma}{g}(\beta_2 V_2 - \beta_1 V_1) = p_1 - p_2 + W_g \sin\theta - F_f \tag{4}$$

where γ = unit weight of water; β = momentum coefficient; p = pressure acting on a given cross section; W_g = weight of water enclosed between sections 1 and 2; θ = angle of inclination of channel; and F_f = total external friction force acting along the channel boundary. If the value of θ is small $(\sin\theta \cong 0)$ and if $\beta_1 = \beta_2 = 1$, equation (4) becomes

$$\frac{Q^2}{A_1 g} + A_1\bar{y}_1 = \frac{Q^2}{A_2 g} + A_2\bar{y}_2 \tag{5}$$

where $\bar{y}$ = depth measured from water surface to the centroid of the cross section containing flow. Eq. (5) is solved by an iterative trial-and-error procedure.

2.2.1 Normal, Critical, and Sequent Depth Computations

Detailed procedures for normal, critical, and sequent depth computations can be found in open channel hydraulics books (e.g., Chow, 1959; Henderson, 1966) and are given here for completeness. The normal depth is computed by satisfying the equation

$$g(D) = Q - K(Y)\sqrt{S_0} = 0 \tag{6}$$

where $K(Y)$ = conveyance, which is a function of the depth Y; and S_0 = bottom slope. For adverse and horizontal slopes, the normal depth is set to a very high value.

Critical depth occurs where the Froude number has a value of 1 for a given discharge. In GSTARS3, the critical depth is calculated by satisfying equation

$$f(D) = 1 - \alpha(Y)\frac{Q^2 W(Y)}{gA^3(Y)} = 0 \tag{7}$$

where $W(Y)$ = channel's top width at a depth Y; and $A(Y)$ = channel cross-sectional area at depth Y.

Sequent depths for a given discharge are the depths with equal specific forces. The specific force of a natural channel can be expressed by

$$SF(Y) = \frac{Q^2}{A_t g} + A_m\bar{y} \tag{8}$$

where $SF(Y)$ = specific force corresponding to a water depth Y; A_t = total flow area; and A_m = flow area in which motion exists. In GSTARS3, the sequent depth is computed where hydraulic jumps occur. An iterative trial-and-error procedure is used to find the sequent water surface elevation. The process starts with two guesses: the critical water surface elevation with the theoretical minimum specific force, and the maximum bottom elevation for the cross section. The subcritical sequent water surface elevation is located within these two values. The bisection method is used to solve equation

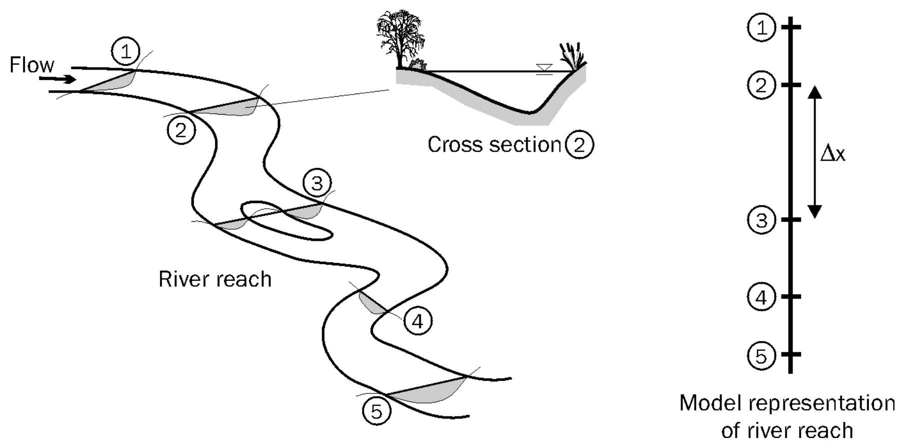
$$SF(Z_a) - SF(Z_b) = 0 \tag{9}$$

where Z_a = computed supercritical water surface elevation, and Z_b = desired subcritical sequent water surface elevation.

2.3 Model Representation

In GSTARS3, as in most one-dimensional numerical models, the representation of the region of the watercourse to be modeled is made by discrete cross sections located at specific points throughout the river channel (see figure 2.3). The region between each cross section is called a reach.

Figure 2.3 Conceptual representation of a river reach by discrete cross sections in GSTARS3.



GSTARS3 uses information associated with each cross section to compute the water surface profiles (and the bed changes in movable bed rivers, as described in the next chapter). The water surface elevation is computed at each cross section location, but not between cross sections. Therefore, choosing the appropriate cross section location is very important. Some guidance is given in the next sections on how to optimize a data collection program for computer modeling with GSTARS3.

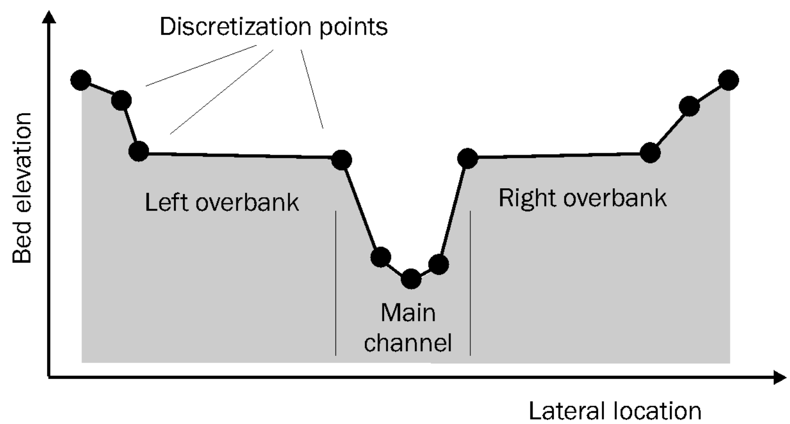
2.3.1 Description of Cross Sections

When setting up a GSTARS3 simulation, the first step is usually the definition and input of the desired channel reach geometry. This is accomplished by selecting cross sections along the channel reach. Each cross section is identified by a number that represents its location expressed as a distance from a downstream reference station. This allows the computer to have a clear representation of the upstream/downstream relationship among the cross sections, as well as to compute reach lengths (Δx in figure 2.3).

Channel geometry is discretized by a set of points, such as those obtained in a surveying field trip, each having an assigned vertical bottom elevation and lateral cross-section location (distance from a reference point situated at the left bank, looking downstream). Linear interpolation is used between these points, as in figure 2.4. This information is used to compute the hydraulic parameters necessary for the backwater computations, such as flow area, wetted perimeter, hydraulic radius, top width, centroid of the cross section, etc.

As mentioned previously, each cross section is discretized by a set of points defined by the bed elevation and cross-section location. The cross sections should be perpendicular to the direction of the flow streamlines and extend all the way from margin to margin of the river, that is, they should extend completely across the channel between high ground of both banks. Although two points are enough to define a region of the cross section with constant side slope, the algorithms implemented in GSTARS3 will work better if more points are given. This will become clearer later, when the usage of stream tubes in GSTARS3 is presented.

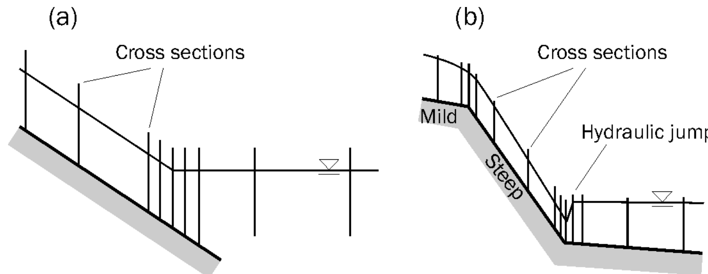
Figure 2.4 Representation of a cross section by a discrete set of points.



The number and positions of the cross sections are arbitrary. However, it is recommended that they be chosen to best represent the geometry of the study channel reach. Accurate data of channel cross sections is essential to ensure that the model works properly. Each cross section represents a portion of the channel upstream and downstream from its actual location. Therefore, the location of each cross section should be chosen to best reflect that approximation. More cross sections are required where there are significant changes in channel geometry and/or hydraulic characteristics. A larger number of cross sections will approximate the channel reach geometry with more accuracy than a smaller number will. Ideally, the user should use as many cross sections as practicable. In the case where too few measured cross sections are available, they may have to be interpolated, especially at abrupt transitions.

Cross section proximity is important where hydraulic jumps occur. Rapidly varied flow usually takes place over much shorter distances than gradually varied flow. Therefore, in order to capture accurately the location of the hydraulic jump, more closely spaced cross sections should be placed in the region where the hydraulic jump is expected to occur. Figure 2.5 schematically shows how to locate cross sections near hydraulic jumps and regions of abrupt slope change.

Figure 2.5 Examples of reduction of Δx at points where the gradients are high: (a) backwater pool, and (b) change in bottom slope and flow regime transition.



There are several published articles about the optimal choice of cross section location for numerical models. Here, the cross section selection rules of Samuels (1990) are presented:

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 section 20W apart.

5 Select sections a maximum of $0.2Y/S_w$ apart.

6 For unsteady flow modeling, select sections a maximum of $L/30$ apart, where L is the length scale of the physically important wave (flood or tide).

7 Select sections a minimum of $10^{INT(\log Z)-\varepsilon}/(\delta S - S_w)$ apart, where ε is the machine precision, $INT()$ is the function that represents the integer part of its argument, and δS is the relative error in the slope.

8 The ratio of the areas between two adjacent cross sections should lie between 2/3 and 3/2.

9 Cross-sectional spacing may have to be reduced for shallow flows when the averaging rule is used for the friction slope (more about this in the next section).

2.3.2 Flow Resistance

One of the fundamental assumptions in GSTARS3 is that a uniform flow formula can be used to compute the friction losses. This formula is used to compute the total conveyance, K. The total conveyance K is used to determine the friction slope, S_f, for a specified discharge:

$$S_f = \left(\frac{Q}{K}\right)^2 \qquad (10)$$

In GSTARS3, any of the following formulae can be used to compute K:

Manning's formula:

$$Q = KS_f^{1/2} = \left(\frac{1.49}{n}AR^{2/3}\right)S_f^{1/2} \quad (11)$$

Chézy's formula:

$$Q = KS_f^{1/2} = (CAR^{1/2})S_f^{1/2} \quad (12)$$

or Darcy–Weisbach's formula:

$$Q = KS_f^{1/2} = \left[\left(\frac{8gR}{f}\right)^{1/2}A\right]S_f^{1/2} \quad (13)$$

where n, C, f = roughness coefficients in Manning, Chézy, and Darcy–Weisbach's formulae, respectively; g = acceleration due to gravity; A = cross-sectional area; and R = hydraulic radius.

For each cross section, the desired roughness coefficients are assigned to different regions of the cross section. Using the example in figure 2.4, the left overbank could have one value, the main channel another value, and the right overbank yet another value. The conveyance of each section is computed separately and the total conveyance is taken to be the sum of the individual conveyances. This method is geared towards natural river cross-sectional geometries with large width-to-depth ratios, and it may introduce errors in the water surface elevations in narrow, rectangle-like cross sections.

Estimating roughness is not a trivial task and requires considerable judgment. There are published flow resistance formulae that are more or less successful when applied to specific situations, but their lack of generality precludes its use in a numerical model for broad applications. See, for example, Klaassen et al. (1986) for more details. Some help exists in the form of tables, such as the ones that can be found in Chow (1959) and Henderson (1966). Barnes (1967) provides a photographic guide. The method by Cowan (1956) is summarized here. The basis of this method is on selecting a basic Manning's n value from a short set and to apply modifiers according to the different characteristics of the channel. The method can be applied in steps, with the help of table 2.1:

1 Select a basic n_0.

2 Add a modifier n_1 for roughness or degree of irregularity.

3 Add a modifier n_2 for variations in size and shape of the cross section.

4 Add a modifier n_3 for obstructions (debris, stumps, exposed roots, logs,...).

5 Add a modifier n_4 for vegetation.

6 Add a modifier n_5 for meandering.

The final value of the Manning's n is given by

$$n = n_0 + n_1 + n_2 + n_3 + n_4 + n_5 \quad (14)$$

Table 2.1 Modifiers for basic Manning's *n* in the method by Cowan (1956) with modifications from Arcement and Schneider (1987).

Basic Manning's roughness values (n_0)			
Concrete	0.011–0.018	Gravel	0.028–0.035
Rock cut	0.025	Coarse gravel	0.026
Firm soil	0.020–0.032	Cobble	0.030–0.050
Coarse sand	0.026–0.035	Boulder	0.040–0.070
Fine Gravel	0.024		
Modifier for degree of irregularity (n_1)			
Smooth	0.000	Moderate	0.006–0.010
Minor	0.001–0.005	Severe	0.011–0.020
Modifier for cross sectional changes in size and shape (n_2)			
Gradual	0.000	Frequent	0.010–0.015
Occasional	0.005		
Modifier for effect of obstructions (n_3)			
Negligible	0.000–0.004	Appreciable	0.020–0.030
Minor	0.005–0.019	Severe	0.060
Modifier for vegetation (n_4)			
Small	0.001–0.010	Very large	0.050–0.100
Medium	0.011–0.025	Extreme	0.100–0.200
Large	0.025–0.050		
Modifier for channel meander (n_5)			
L_m/L_s		n_5	
1.0–1.2 (minor)		0.0	
1.2–1.5 (appreciable)		$0.15(n_0 + n_1 + n_2 + n_3 + n_4)$	
> 1.5 (severe)		$0.30(n_0 + n_1 + n_2 + n_3 + n_4)$	
L_m = meander length		L_s = length of straight reach	

The friction loss, h_f, through each reach is the product of friction slope and the reach length, Δx. The friction slope at the cross section can be determined from one of the following four choices:

from the average friction slope of the adjacent reaches:

$$h_f = \frac{1}{2}(S_{f1} + S_{f2})\Delta x \tag{15}$$

from the geometric mean:

$$h_f = \Delta x \sqrt{S_{f1} S_{f2}} \tag{16}$$

from the average conveyance:

$$h_f = \left(\frac{2Q}{K_1 + K_2}\right)^2 L\Delta x \quad (17)$$

or from the harmonic mean:

$$h_f = \left(\frac{2S_{f1}S_{f2}}{S_{f1} + S_{f2}}\right)\Delta x \quad (18)$$

Although other choices exist for calculating the friction slope, they are not recommended — see, for example, Reed and Wolfkill (1976).

The distance between discretized cross sections (the reach length) is important for proper convergence and accuracy of the methods used in the model. In practice, the reach length used will vary from case to case. A small, nonuniform channel may require much shorter reach lengths than a large, uniform channel with mild slopes. A reach length may be measured along the center line in an artificial channel, along the thalweg in a natural channel, or along the flow path in overbank areas. Note that, for a given reach of a channel, these lengths may vary. However, reach lengths may be optimized by using an appropriate friction slope equation. Table 2.2 shows the methods recommended by Reed and Wolfkill (1976) and those used by the HEC-2 computer model. Laurenson (1986) showed that eq. (15) provides the lowest maximum error, but that it doesn't insure the lowest possible error.

Table 2.2 Recommended friction slope methods (adopted from French, 1985). See figure 2.6 for profile types.

Profile type	Friction slope method recommended by Reed and Wolfkill (1976)	Friction slope method used by HEC-2
M1	Eq. (17)	Eq. (17)
M2	Eq. (16)	Eq. (16)
M3	Eq. (18)	Eq. (15)
S1	Eq. (16)	Eq. (17)
S2	Eq. (17)	Eq. (17)
S3	Eq. (15)	Eq. (15)

The local loss caused by channel expansion and contraction, h_E, is computed from

$$h_E = C_E\left|\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right| \quad (19)$$

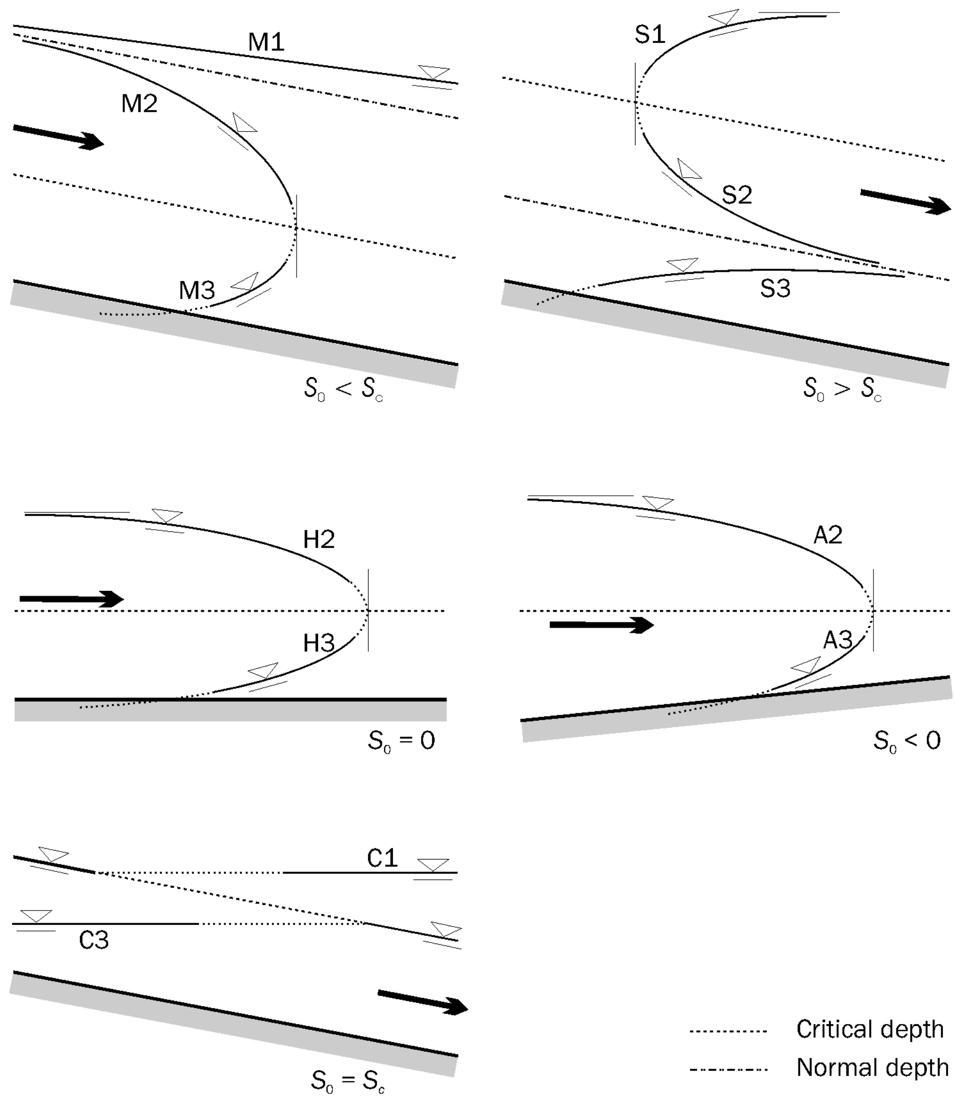
where C_E = energy loss coefficient. In GSTARS3, C_E is internally set to 0.1 for contractions and to 0.3 for expansions.

Other local losses, such as losses due to channel bends or man-made constructions, are computed from

$$h_B = C_B\frac{V_2^2}{2g} \quad (20)$$

where C_B is an energy loss coefficient supplied by the user. For most natural rivers, C_B values are assumed to be zero. The total energy loss between two adjacent cross sections is the sum of friction loss and the local losses.

Figure 2.6 Water surface profile types in gradually varied flow.

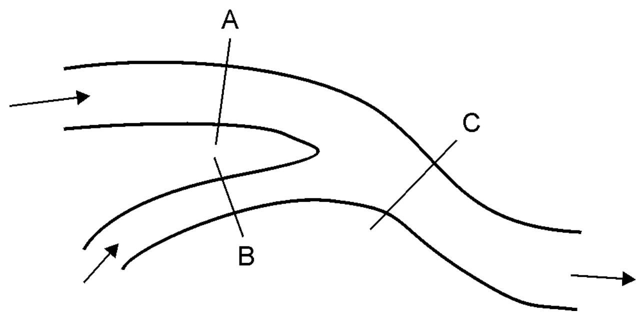


2.4 Tributary Inflows

Although GSTARS3 is limited to single stem rivers, it is possible to include the contributions of water and sediment by tributaries into the modeled reach. At channel junctions (see figure 2.7) continuity requires that

$$Q_C = Q_A + Q_B \tag{21}$$

Figure 2.7 Channel junction.



Let cross section B be located at the tributary, and cross sections A and C represent the computational cross sections used to model the tributary effects. Conservation of energy is used, i.e.,

$$\left(z + Y + \alpha\frac{V^2}{2g}\right)_A = \left(z + Y + \alpha\frac{V^2}{2g}\right)_C + h_f \tag{22}$$

The energy losses, h_f, are computed from friction alone, i.e., losses due to bends, contraction/expansion losses, and user defined values are ignored. (See section 2.1 and following for details.) A more complete description of this approach to computing flow across channel junctions can be found in many standard textbook references—see, for example, Cunge et al. (1980).

CHAPTER

3

SEDIMENT ROUTING AND CHANNEL GEOMETRY ADJUSTMENT

Sediment transport occurs when the flow exceeds a certain threshold and becomes capable of moving the particles that constitute the bed. When the channel's bed becomes mobile, erosion or deposition may occur. These bed changes depend on many parameters, including hydraulic conditions (such as flow velocity and depth), bed composition (such as size of the particles that constitute the bed), and supply rates (amount and type of sediments entering the channel). In this chapter, the sediment transport and bed evolution model employed by GSTARS3 is presented with some detail.

From the user point of view, the backwater and the sediment transport computations can be viewed as two modules belonging to the same numerical model. The backwater module can be used without the need to use the sediment transport module. For fixed bed channels (such as the flow of clear water over lined channels or spillways), the sediment transport computations can be turned off, reducing the data requirements of the model (the description of the bed composition) and allowing faster set-up and shorter run times. The user wishing to employ GSTARS3 to fixed bed channels can safely skip chapters 3 and 4 of this manual.

3.1 Governing Equations

3.1.1 Theoretical Background

It is convenient to distinguish two main types of transportation of sediments: in *suspension* in the water column, and as *bed load*. The particles in motion that remain close to the channel's bed are said to belong to the bed load. These particles move by rolling over the bed and by saltating over relatively short lengths, and constitute a layer of relatively small thickness. In contrast, the particles transported in suspension may span the entire water column above the bed load layer. They are transported by the turbulent forces of the fluid, i.e., the turbulent eddies, and are generally of smaller dimensions than the particles in the bed load. These two layers have different composition and move at different speeds.

The distinction between the two layers is problematic and it is not easy to locate a clear interface at a certain elevation above the bed. The difficulties are compounded by the fact that there is a continuous exchange of particles between the bed load layer and the suspended load. Furthermore, the separation of the two layers requires distinct governing equations for each layer, each with its own sets of variables and coefficients, some of which are very difficult to determine.

An alternate approach lumps the suspended load and the bed load together in what is called the *bed-material load*. This eliminates the need to describe the interface between the bed load and the suspended load and the sediment fluxes crossing it, which is difficult and, with the present state-of-the-art, imprecise. It also is computationally more efficient, since that a fewer number of equations needs to be solved. Consequently, the bed-material load approach requires less data, some of which is very difficult to obtain (such as the diffusion coefficients necessary to compute the transport of suspended load). The trade-off is in the loss of accuracy, since this approach does not distinguish the two essentially different modes of transport. In GSTARS3 the bed-material load approach was chosen to describe the transport of sediments.

3.1.2 Sediment Continuity Equation

The basis for sediment routing computations in GSTARS3 is the conservation of sediment mass. In one-dimensional unsteady flow, the sediment continuity equation can be written as

$$\frac{\partial Q_s}{\partial x} + \eta \frac{\partial A_d}{\partial t} + \frac{\partial A_s}{\partial t} - q_{lat} = 0 \qquad (23)$$

where η = volume of sediment in a unit bed layer volume (one minus porosity); A_d = volume of bed sediment per unit length; A_s = volume of sediment in suspension at the cross section per unit length; Q_s = volumetric sediment discharge; and q_{lat} = lateral sediment inflow. A number of assumptions are made to simplify this equation.

Firstly, it is assumed that the change in suspended sediment concentration in a cross section is much smaller than the change of the river bed, i.e.:

$$\frac{\partial A_s}{\partial t} \ll \eta \frac{\partial A_d}{\partial t} \qquad (24)$$

Secondly, during a time step, the parameters in the sediment transport function for a cross section are assumed to remain constant:

$$\frac{\partial Q_s}{\partial t} = 0 \text{ or } \frac{\partial Q_s}{\partial x} = \frac{dQ_s}{dx} \qquad (25)$$

With these assumptions, eq. (23) becomes

$$\eta \frac{\partial A_d}{\partial t} + \frac{dQ_s}{dx} = q_{lat} \qquad (26)$$

which is the governing equation used in GSTARS3 for routing sediments in rivers and streams.

3.2 Streamlines and Stream Tubes

GSTARS3 routes sediments using stream tubes. The basic concept and theory regarding streamlines, stream tubes, and stream functions can be found in most basic text books of fluid mechanics. In this section, only some of the basic concepts are given, as they are applied in the model.

By definition, a streamline is a conceptual line to which the velocity vector of the fluid is tangent at each and every point, at each instant in time. Stream tubes are conceptual tubes whose walls are defined by streamlines. The discharge of water is constant along a stream tube because no fluid can cross the stream tube boundaries. Therefore, the variation of the velocity along a stream tube is inversely proportional to the stream tube area. Figure 3.1 illustrates the basic concept of stream tubes used in GSTARS3.

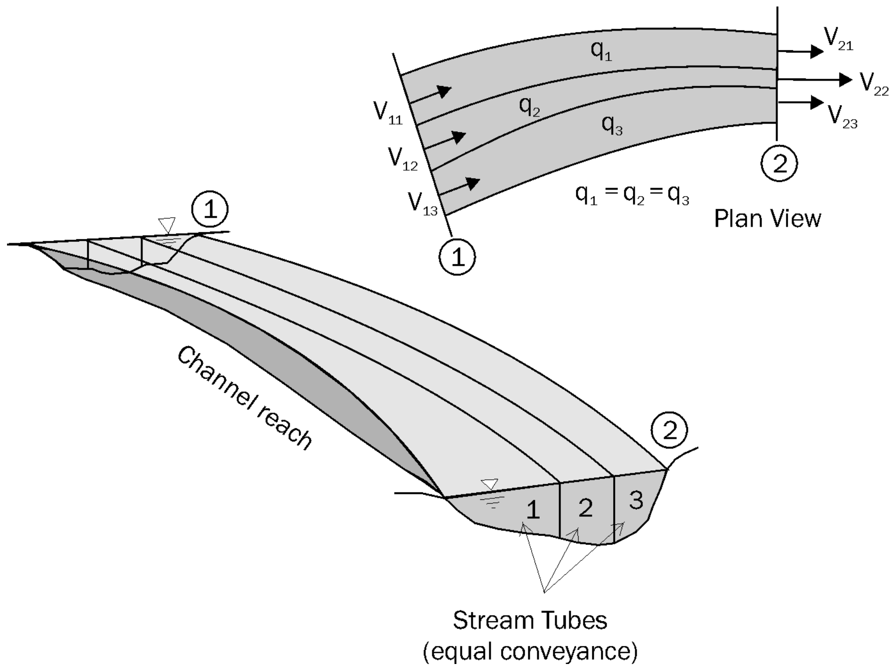
For steady and incompressible fluids, the total head, H_t, along a stream tube of an ideal fluid is constant:

$$\frac{p}{\gamma} + \frac{V^2}{2g} + h = H_t = \text{Constant} \qquad (27)$$

where p = pressure acting on the cross section; γ = unit weight of water; V = velocity; g = acceleration due to gravity; and h = hydraulic head. In GSTARS3, however, H_t is reduced along the direction of the flow due to friction and other local losses, as described earlier in section 2.3.2.

In GSTARS3, the backwater profiles are computed first. Then, the cross sections are divided into several sections of equal conveyance. These regions of equal conveyance are treated as stream tubes, and the (computed) locations of their boundaries are the defining streamlines, across which no water can pass. The thus defined stream tubes are used as if they were conventional one-dimensional channels with known hydraulic properties, and sediment routing can be carried out within each stream tube almost as if they were independent channels.

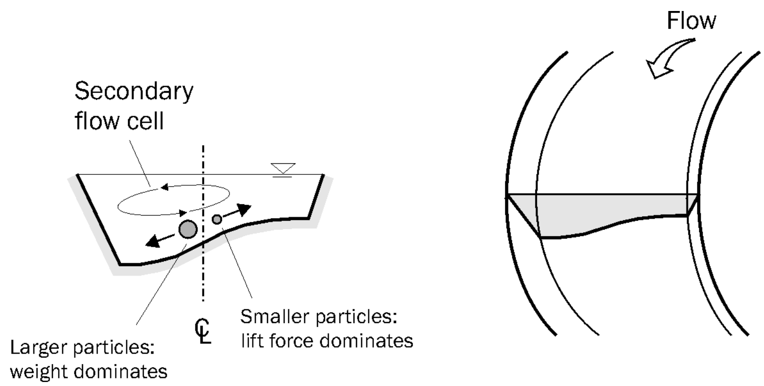
Figure 3.1 Schematic representation illustrating the use of stream tubes by GSTARS3.



Stream tube locations are computed for each time step, therefore they are allowed to vary with time. Sediment routing is carried out for each stream tube and for each time step. Bed material composition is computed for each tube at the beginning of the time step, and bed sorting and armoring computations are also carried out separately for each stream tube. In GSTARS3, lateral variations of bed material composition are accounted for, and this variation is included in the computations of the bed material composition and sorting for each stream tube. This approach allows the computation of cross-sectional variations in the hydraulic and sediment parameters in a quasi-two-dimensional manner. For example, aggradation and degradation can occur simultaneously at a given cross section. Conventional one-dimensional models are unable to deal with this situation, but GSTARS3 can model it, since erosion or deposition are computed separately within each stream tube, depending on the hydraulics, bed composition, transport capacity, and sediment supply conditions for each stream tube.

The movement of a sediment particle will have a direction which, in general, is neither the direction of the flow nor the direction of the bed shear stress. For example, in a bend of a channel with a sloping bed such as the one in figure 3.2, the larger particles will tend to roll down the slope (gravitational forces dominate) while the smaller particles may move up the slope (lift forces due to secondary currents dominate) — see, for example, Ikeda et al., (1987). A non-zero transverse flux results in exchange of sediments across stream tube boundaries. Note that this exchange does not violate the theoretical assumptions behind the use of stream tubes because the trajectories of the sediment particles are not the same as the trajectories of the fluid elements (streamlines). Therefore, although there is no net exchange of water between stream tubes, sediment can cross stream tube boundaries, and the use of stream tubes may still be theoretically justified.

Figure 3.2 Bed sorting in bends due to transverse bed slope and secondary currents.



GSTARS3 includes the effects of stream curvature that contribute to the radial (transverse) flux of sediments, q_r, near the bed. The two effects considered are transverse bed slope and secondary flows. The effects due to secondary flows are modeled following Kikkawa et al. (1976), in which the angle that the bed shear stress vector makes with the downstream direction, β, is given by

$$\beta = \frac{vh}{u^* A_r R}\left(-4.167 + 2.640\frac{u^*}{\kappa v}\right) \quad (28)$$

where v = average velocity along the channel's centerline; u^* = shear velocity along the centerline; h = water depth; R = radius of curvature of the channel; A_r = an empirical coefficient (for rough boundaries A_r = 8.5); and κ = von Kàrmàn constant (= 0.41).

In a bed with transverse slope, the gravity forces cause the direction of the sediment particles to be different from that of the water particles. Following Ikeda et al. (1987), the effects due to a transverse bed slope can be added to those due to curvature such that

$$\frac{q_r}{q_s} = \tan\sigma = \tan\beta + \frac{1+\alpha\mu}{\lambda\mu}\sqrt{\frac{\tau_0^*}{\tau^*}}\tan\delta \quad (29)$$

where q_s = unit sediment transport rate in the channel's longitudinal direction; σ = the angle between the direction of transport and the channel's downstream direction; τ_0^*, τ^* = nondimentional critical shear stress and bed shear stress, respectively; δ = transverse bed slope; α = rate of lift to drag coefficients on sediment particles (determined experimentally to be equal to 0.85); λ = sheltering coefficient (= 0.59); and μ = dynamic Coulomb friction factor (= 0.43). The direction of sediment transport is calculated from eq. (29). The components of the sediment transport direction vector are given by

$$q_s = q_t \cos\sigma \tag{30}$$

$$q_r = q_t \sin\sigma \tag{31}$$

where q_t = sediment transport rate per unit width computed by any of the sediment transport equations discussed in section 3.5. Eq. (26) is then solved using $Q_s = q_s \Delta y$ and $q_{lat} = q_r$, where Δy = stream tube width.

Note that the above methods are applied only to sediment moving as bed load. Sediment moving as suspended load is not allowed to cross stream tube boundaries. GSTARS3 uses van Rijn's (1984) method to determine if a particle of a given size is in suspension or moves as bed load:

$$u^*_{cr,\,s} = \begin{cases} \dfrac{4\omega_s}{D^*} & \text{if } 1 < D^* \le 10 \\ 0.4\omega_s & \text{if } \quad D^* > 10 \end{cases} \tag{32}$$

where $u^*_{cr,\,s}$ = critical shear velocity for suspension; ω_s = fall velocity of sediment particles; and D^* = dimensionless grain size defined as

$$D^* = d\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \tag{33}$$

where d = sediment particle diameter; s = specific gravity of sediment in water; g = acceleration due to gravity; and ν = viscosity of water.

There are some limitations to the use of stream tubes in the manner described in the present section. Firstly, the backwater curves result from an essentially one-dimensional model, where the water surface elevation is assumed to be horizontal across each cross section. Therefore extrapolation to two-dimensional distributions using the described method has some limitations. Consequently, the maximum recommended number of stream tubes employed is 5 (this is the maximum number of stream tubes allowed by the GSTARS3 program). GSTARS3 is not a truly two-dimensional program, therefore it cannot simulate areas with recirculating flows or eddies. Other limitations include the inability of simulate secondary flows, reverse flows, water surface variations in the transverse direction, hydrograph attenuation, and others that result from the use of the simplified governing equations described in this and the previous chapters.

3.3 Discretization of the Governing Equations

In this section we describe the basic steps to solve eq. (26) numerically. Note that eq. (26) is a partial differential equation, but that the computer can only solve algebraic equations. The term *discretization* means the transformation of the partial differential equation into a set of algebraic equations that can be solved numerically by a computer. The numerical solution of differential equations is a very large field of applied mathematics. The reader interested in its particular application to fluid mechanics should refer to one of many text books dedicated to the subject, such as the ones by Hirsch (1988) or Anderson et al. (1997), for example.

The approach used in GSTARS3 uses a finite difference uncoupled approach. This means that finite differences are used to discretize the governing differential equation. By *uncoupled* solution it is meant that first the backwater profiles are computed; the sediment routing and bed changes are computed afterwords, keeping all the hydraulic parameters frozen during the calculations.

In order to accomplish the discretization process, the change in the volume of bed sediment due to deposition or scour, ΔA_d, is written as

$$\Delta A_d = (aT_{i-1} + bT_i + cT_{i+1})\Delta Z_i \tag{34}$$

where T = top width; ΔZ = change in bed elevation (positive for aggradation, negative for scour); i = cross section index; and a, b, and c are constants that must satisfy

$$a + b + c = 1 \tag{35}$$

There are many possible choices for the values of a, b, and c. For example, $a = c = 0$ and $b = 1$ is a frequently used combination that is equivalent to assuming that the wetted perimeter at station i represents the perimeter for the entire reach. If $b = c = 0.5$ and $a = 0$, emphasis is given to the downstream end of the reach.

In practice, it is observed that giving emphasis to the downstream end of the reach may improve the stability of the calculations. Such a scheme may be represented by using the following expressions:

$$a = 0\text{; } b = 1 - \theta\text{; and } c = \theta \tag{36}$$

where θ is a weighting parameter ($\theta > 0.5$). In GSTARS3, the standard values are $a = c = 0.25$ and $b = 0.5$, but the user can change those to any combination that satisfies eq. (35). Using eq. (34), the partial derivative terms are approximated as follows:

$$\frac{\partial A_d}{\partial t} \approx \frac{(aT_{i-1} + bT_i + cT_{i+1})\Delta Z_i}{\Delta t} \tag{37}$$

$$\frac{dQ_s}{dx} \approx \frac{Q_{s,i} - Q_{s,i-1}}{1/2(\Delta x_i + \Delta x_{i-1})} \tag{38}$$

where Δx_i = distance between cross sections i and $i+1$; Δt = time step interval; and $Q_{s,i}$ = sediment transport rate at cross section i. The sediment continuity equation, eq. (26), can be used to compute the change in bed elevation, ΔZ_i, which is done for each individual sediment size fraction within each stream tube. Inserting expressions (37) and (38) into eq. (26) we obtain

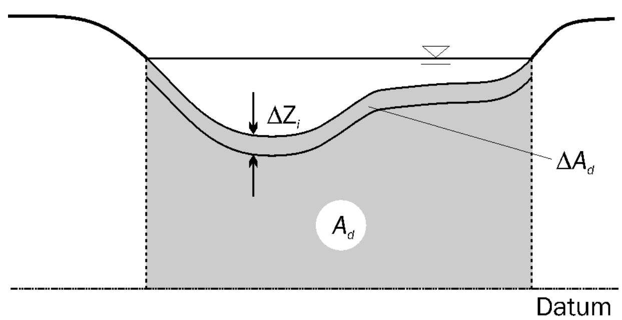
$$\Delta Z_{i,k} = \frac{\Delta t}{\eta_i} \cdot \frac{q_{lat}(\Delta x_i + \Delta x_{i-1}) + 2(Q_{s,i-1,k} - Q_{s,i,k})}{(aT_{i-1} + bT_i + cT_{i+1})(\Delta x_i + \Delta x_{i-1})} \tag{39}$$

where k = size fraction index; η_i = volume of sediment in a unit bed layer at cross section i; and $Q_{s,i,k}$ = computed volumetric sediment discharge for size class k at cross section i. The total bed elevation change for a stream tube at cross section i, ΔZ_i, is computed from

$$\Delta Z_i = \sum_{k=1}^{N} \Delta Z_{i,k} \tag{40}$$

where N = total number of size fractions present in cross section i. The new channel cross section at station i, to be used at the next time iteration, is determined by adding the bed elevation change to the old bed elevation. Figure 3.3 provides a schematic definition of some of the variables.

Figure 3.3 Definition of variables for a cross section.



3.3.1 Transmissive Cross Sections

A transmissive cross section is defined as a cross section that passes sediment through without erosion nor deposition. As a result of the definition, the sediment in transport exiting a transmissive cross section is equal to the sediment entering the control volume associated with that cross section.

GSTARS3 implements two types of transmissive cross sections. The first type is the *mixing* type, which means that sediment mixes fully across stream tubes. At the exit of the cross section, the transport rates and size distributions of sediments are equal for all the stream tubes. Mixing is accomplished taking into consideration the principle of mass conservation. The second type is a *non-mixing* type, in which the sediment exiting the cross section is equal to the sediment entering the control volume, but the identity holds for each individual stream tube.

Because there are no bed changes associated with transmissive cross sections, the distribution of the bed material specified for this type of cross sections is irrelevant, i.e., it does not impact sediment routing computations. See record ST in appendix A for instructions on how to use transmissive cross sections in GSTARS3.

3.3.2 Numerical Stability

The formulation described above is subject to numerical stability constraints. A numerical scheme is said to be stable if, for a certain condition, the solution values constructed with that scheme remain finite for the set of all solutions that take an initial state (at $t = 0$) to its final state (at $t = T$). The condition for which the solution is stable is called the Courant-Friedrichs-Lewy, or CFL, condition. The CFL stability condition is usually expressed via the Courant number

$$C_r = \frac{\text{celerity of propagation in the analytical solution}}{\text{celerity of propagation in the numerical solution}} \tag{41}$$

so that the CFL condition becomes $C_r \le 1$ for stability. Although implicit schemes are generally unconditionally stable (i.e., are not restricted by Courant number values), explicit schemes have stability limits that translate into limits to the maximum size of the time step. GSTARS3 uses an explicit method to solve the sediment routing equation. In this case, the CFL stability criterion is given by

$$\Delta t \le \frac{\Delta x}{c_s} \tag{42}$$

where c_s is the kinematic wave speed of the bed changes.

In practice, instability is observed by the presence of spurious oscillations in an otherwise smooth solution, that is, in the hydraulic parameters and/or bed elevations. These oscillations are purely of numerical nature, having no physical meaning, and they creep into the solution as the time step is increased. Their amplitude increases with simulation time (i.e., with the number of time steps) and eventually causes the computations to stop prematurely due to numerical errors. This phenomenon can be avoided by reducing the time step until the CFL condition is met. In general, the time step has to be smaller when the computational cross sections are placed closer together, and vice versa. Numerical experimentation is required to determine a suitable value for Δt.

3.3.3 Additional Comments

The solution procedure used by GSTARS3 decouples the governing equation for the flow from the governing equation for the sediment routing. For each time step, the backwater computations are solved first. The hydraulic properties are then assumed constant for the remainder of the time step. Sediment routing is carried out in this hydraulically "frozen" state, using a sediment transport formula for steady flow (eq. (25) expresses this simplification). The change in bed levels are computed from the sediment continuity equation and are updated before the algorithm proceeds to the next time step. The time marching proceeds sequentially in this manner, until the desired time is reached.

This is the most common type of solution approach in numerical modeling. It requires that the variations in the sedimentological parameters, such as bed level and composition, be small when compared to the variation in the hydraulic properties. In general, this can be accomplished by having a computational time step Δt that is small enough. One way to work this out in practice is to have a small enough Δt such that

$$\Delta Z_i \ll h_i \tag{43}$$

for all the computational cross sections and for all time steps. In eq. (43), h_i is the hydraulic depth of cross section i.

There are other limitations to the uncoupled approach. First, it should not be used in the region $0.8 < F_r < 1.2$, where F_r is the Froude number (see de Vries (1969) for details about the derivation of this constraint). Second, it does not handle rapidly varying boundary conditions. The first limitation means that the approach is not valid in flow regime transitions. However, in nature regime transitions on movable beds do no occur often, are very localized, and are mostly temporary, therefore this limitation does not pose a serious obstacle to the use of uncoupled models such as GSTARS3.

The second limitation mentioned was treated by Lyn (1987). He shows that uncoupled models are limited to the situations were the input hydrograph obeys the following approximate relationship:

$$\frac{T}{(L/V)} \geq 100 \tag{44}$$

where T = duration of the hydrograph; L = length of the reach being modeled; and V = a characteristic velocity in the channel. V can be computed from

$$V = \sqrt{gh} \tag{45}$$

where g = acceleration due to gravity and h = hydraulic depth. Note, however, that GSTARS3 is limited to stepped hydrographs, and should not be used for situations where the unsteady effects are important. In the quasi-steady range of applications targeted by GSTARS3, it is unlikely that the limitations associated with uncoupling hydraulics and sediment transport are significant.

3.4 Bed Sorting and Armoring

GSTARS3 computes sediment transport by size fraction. As a result, particles of different sizes are transported at different rates. Depending on the hydraulic parameters, the incoming sediment distribution, and the bed composition, some particle sizes may be eroded, while others may be deposited or may be immovable. GSTARS3 computes the carrying capacity for each size fraction present in the bed, but the amount of material actually moved is computed by the sediment routing equation —eq. (26). Consequently, several different processes may take place. For example, all the finer particles may be eroded, leaving a layer of coarser particles for which there is no carrying capacity. No more erosion may occur for those hydraulic conditions, and the bed is said to be armored. This armor layer prevents the scour of the underlying materials and the sediment available for transport becomes limited to the amount of sediment entering the reach. However, future hydraulic events, such as an increase of flow velocity, may increase the flow carrying capacity, causing the armor layer to break and restart the erosion processes in the reach.

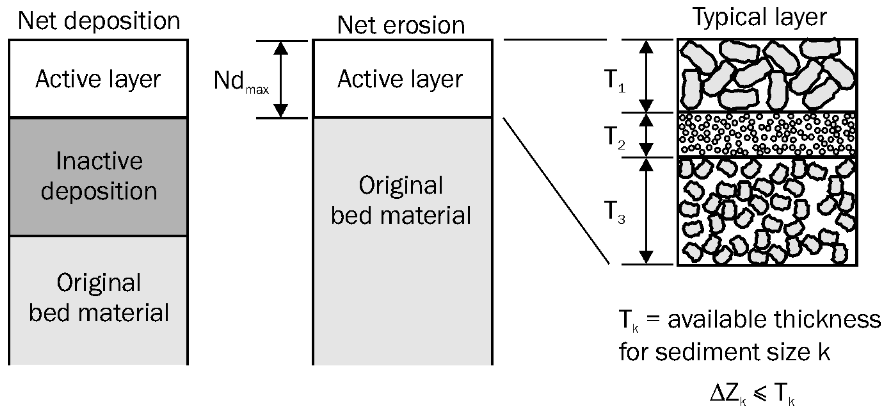
Many different processes may occur simultaneously within the same channel reach. These depend not only on the composition of the supplied sediment, i.e., the sediment entering the reach, but also on bed composition within that reach. The bed composition may vary within the reach both in space and time. In order to model these type of events, GSTARS3 uses the bed composition accounting procedure proposed by Bennett and Nordin (1977).

In Bennett and Nordin's method, bed accounting is accomplished by the use of two or three conceptual layers (three layers for deposition and two layers for scour). The process is schematically illustrated in figure 3.4. The top layer, which contains the bed material available for transport, is called the *active layer*. Beneath the active layer is the *inactive layer*, which is the layer used for storage. Below these two layers there is the undisturbed bed, with the initial bed material composition.

The active layer is the most important concept in this procedure. It contains all the sediment that is available for transport at each time step. The thickness of the active layer is defined by the user as proportional to the geometric mean of the largest size class containing at least 1 percent of the bed material at that location. Active layer thickness is, therefore, closely related to the time step duration. Erosion of a particular size class of bed material is limited by the amount of sediments of that size class present in the active layer. If the flow carrying capacity for a particular size class is greater than what is available for transport in the active layer, the term availability limited is used (Bennett and Nordin, 1977). On the other hand, if more material is available than that necessary to fulfill the carrying capacity computed by a particular sediment transport equation, the term capacity limited is used.

The inactive layer is used when net deposition occurs. The deposition thickness of each size fraction is added to the inactive layer, which in turn is added to the thickness of the active layer. The size composition and thickness of the inactive layer is computed first, after which a new active layer is recomputed and the channel bed elevation updated.

Figure 3.4 Bed composition accounting procedures. ΔZ_k represents the amount of material in size class k eroded during a time step, and T_k is the amount of material of size k present in the active layer, i.e., available for erosion.



The overall process is illustrated in figure 3.5. The procedures described above are carried out separately along each stream tube. Since the locations of stream tube boundaries change with changing flow conditions and channel geometry, those processes had to be adapted for use in GSTARS3. Bed material is accounted for at the end of each time step for each stream tube. Bed material composition is stored at each point used to describe the geometry for all the cross sections. The values of the active and inactive layer thickness are also stored at those points. At the beginning of the next time step, after the new locations of the stream tube boundaries are determined, these values are used to compute the new layer thicknesses and bed composition for each stream tube. The relations used are

$$P_{i,k} = \frac{1}{X_i}\sum_{m=1}^{NPTS} P_{i,k,m} \cdot \Delta X_i \qquad (46)$$

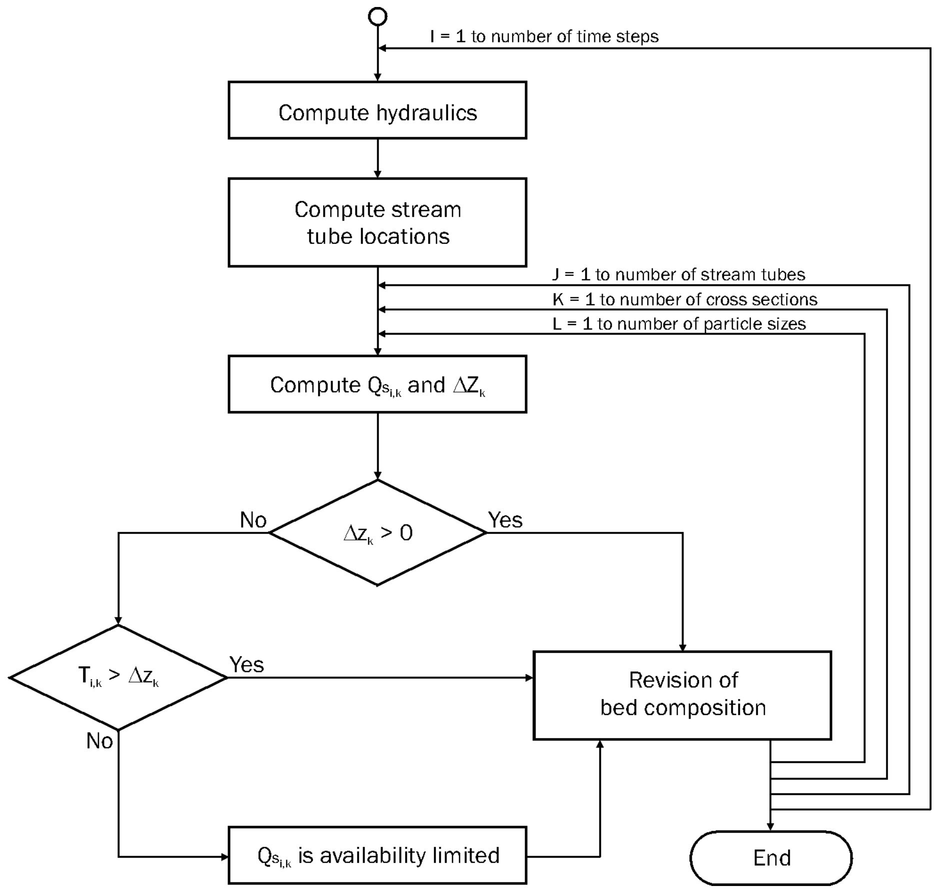
$$TAL_{i,k} = \frac{1}{X_i}\sum_{m=1}^{NPTS} TAL_{i,k,m} \cdot \Delta X_i \qquad (47)$$

and

$$TIL_{i,k} = \frac{1}{X_i}\sum_{m=1}^{N} TIL_{i,k,m} \cdot \Delta X_i \qquad (48)$$

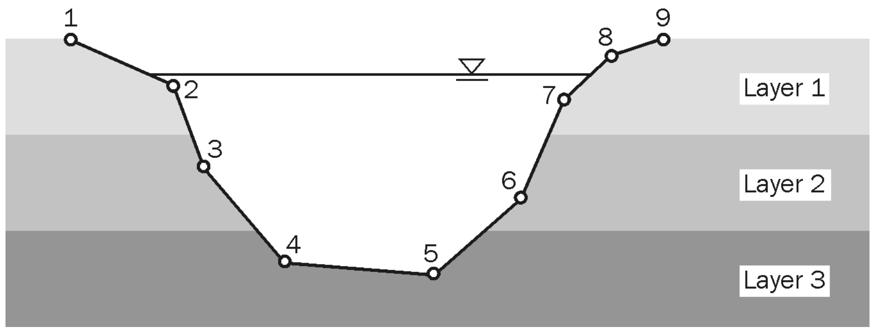
where $P_{i,k}$ = percentage of sediment in size k at station i; $TAL_{i,k}$ = active layer thickness of size fraction k at station i; $TIL_{i,k}$ = active layer thickness of size fraction k at station i; $TAL_{i,k,m}$ and $TIL_{i,k,m}$ = active and inactive layer thickness corresponding to point m for size fraction k at station i, respectively; X_i = wetted perimeter of the stream tube at station i; ΔX_i = averaged distance between adjacent points across the channel; and N = number of points across the channel falling within the stream tube.

Figure 3.5 Simplified diagram for the bed sorting and armoring processes. Adopted from Bennett and Nordin (1977), with modifications.



Note that GSTARS3 allows for layered beds, in which each layer contains a different particle distribution. In the case of multiple bed layers, an average bed composition is computed from the particle distribution information stored at each point in the cross section. For example, for the case pictured in figure 3.6, the substratum is composed of three different layers, each layer with its own sediment particle distribution. For the conditions shown — and considering only one stream tube, for the sake of brevity — a weighted average is composed from the particle distributions of layer 1 (points 2 and 7), layer 2 (points 3 and 6), and layer 3 (points 4 and 5). Points 1, 8, and 9 are above the water line, therefore they do not contribute to the averaging process. The weighting factor is given by the percentage of wetted perimeter associated with each discretization point.

Figure 3.6 Cross section showing how individual discretization points may have different sediment particle distributions.



3.4.1 Remarks

For a given time step, erosion of the bed or banks will take place when the sediment transport capacity at a given cross section exceeds the load incoming from the upstream cross section. When erosion takes place, sediment transport may be constrained by availability. The materials available for entrainment are those exposed at the bed surface. The concept of the active layer is fundamental. The active layer is the surface layer from which materials can be entrained by the flow. In other words, for each simulation time step, the only material available for erosion is the sediment contained in the active layer. Therefore, the active layer thickness, $\delta = Nd_{max}$, should always be at least as thick as the expected maximum depth of scour (ΔZ). The recommended way to achieve this is by defining the active layer thickness first and then appropriately choosing the time step for sediment transport calculations (Δt_s). A trial-and-error process can be used to ensure that $\Delta Z \le \delta$.

Alternatively, an estimate of Δt_s can be obtained from a simplified form of eq. (39):

$$\frac{Q_{s,\,i-1} - Q_{si}}{\eta \Delta x_i P_i} = \frac{\Delta Z}{\Delta t_s} \tag{49}$$

where ΔZ is prescribed to satisfy the above criterion (i.e., $\Delta Z \le \delta$). In this case, the estimate should be obtained using the peak inflow discharge.

3.5 Sediment Transport Functions

The literature contains many sediment transport 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. With the exception of Yang's formulae, most transport functions are intended for subcritical flows. GSTARS3 has 15 transport functions for cohesionless material, presented in table 3.1. More detailed descriptions of these functions were published by Yang (1996), which also includes a number of different comparisons and evaluations. None of the transport functions can be applied to all flow and sediment conditions with accuracy. Yang and Huang (2001) made detailed analysis and recommendations on the selection of sediment transport functions under different flow and sediment conditions (Yang and Huang's paper is presented in appendix D). Other useful assessments of sediment transport formulae can be found in White et al. (1975), Alonso (1980), Alonso et al. (1982), ASCE (1982), Vetter (1987, 1988), Gomez and Church (1989), and Yang and Wan (1991). Some of these analyses rank the equations by reliability and applicability. Not surprisingly, the ranking is quite different among the authors.

Table 3.1 Sediment transport functions implemented in GSTARS3 and its type (B = bed load; BM = bed-material load).

Equation	Type
DuBoys (1879)	B
Meyer-Peter and Müller (1948)	B
Laursen (1958)	BM
Laursen modified by Madden (1993)	BM
Toffaleti (1969)	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
Parker (1990)	B
Yang et al. (1996)	BM
Ashida and Michiue (1972)	BM
Tsinghua University (IRTCES, 1985)	BM

Most sediment transport formulae were developed for computing the total bed-material load without breaking it into load by size fraction. In GSTARS3, these formulae have been modified to account for transport by size. The total carrying capacity for a particular river section, C_t, is computed by using the following relationship:

$$C_t = \sum_{i=1}^{N} [rp_i + (1-r)p_i^*]C_i \qquad (50)$$

where p_i = percentage of material of size fraction i available in the bed; p_i^* = percentage of material of size fraction i incoming into the reach; C_i = capacity for each size fraction; r = a factor ($0 \le r \le 1$); and N = number of size fractions. C_i is computed by the formulae presented in the following sections for each size fraction as if the entire bed was composed of that size fraction alone.

The factor r is a weighting factor that allows the inclusion of incoming sediment into the carrying capacity of the flow. Most models use a value of $r = 1$. However, in this case, any material entering a reach that is not already present in the bed (i.e., with $p_i = 0$) will deposit instantaneously due to sudden loss in capacity. In other words, if material with a certain size fraction enters a reach ($p_i^* \neq 0$) with $p_i = 0$, then $r = 0$ implies $C_t = 0$. This is an unrealistic situation. Nevertheless, the values of the parameter *r* should remain in the vicinity of 1. For example, for mountain rivers a value of $r = 0.7$ was found to work well.

The hydraulic parameters used to compute the sediment carrying capacities in each reach are computed as weighted averages from the hydraulic parameters from nearby stations. For each station *i*, the representative values of the area (A_{Ri}), depth (D_{Ri}), velocity (V_{Ri}), and friction slope (S_{Ri}) are computed as follows:

$$A_{Ri} = aA_{i-1} + bA_i + cA_{i+1} \tag{51}$$

$$D_{Ri} = aD_{i-1} + bD_i + cD_{i+1} \tag{52}$$

$$V_{Ri} = aV_{i-1} + bV_i + cV_{i+1} \tag{53}$$

$$S_{Ri} = aS_{i-1} + bS_i + cS_{i+1} \tag{54}$$

The weighting parameters a, b, and c can be chosen in any combination that satisfies eq. (35). By default, GSTARS3 assumes the values of $a = c = 0$ and $b = 1$, but these values can be changed by the user. For example, in rivers whose properties change more rapidly from section to section, a scheme incorporating information from the upstream and downstream reaches may be more appropriate. The values of $a = c = 0.25$ and $b = 0.5$ may be adopted in those circumstances. By changing *a*, *b*, and *c* appropriately, the user can use the parameters that favor stability or that favor sensitivity. Usually, more sensitive schemes are the less stable, and vice-versa.

For the station located farthest downstream (station $i = NSTA$), the values for the parameters at station $i+1$ are not defined; therefore only parameters *a* and *b* are necessary. For that station, GSTARS3 defines $a = 0$ and $b = 1$. These values can be changed by the user. For the example given above, a possible combination of values might be $a = b = 0.5$.

For the first upstream station (station $i = 1$), station $i-1$ is not defined, therefore parameter *a* is not used. GSTARS3 defaults to $b = 1$ and $c = 0$, but these values can be changed by the user.

Note that the coefficients *a*, *b*, and *c* may be numerically different and are independent from those used in eq. (34), although they have a similar function.

3.5.1 DuBoys' Method (1879)

The pioneering work of DuBoys (1879) is based on the premise that the sediment moves in layers that slide over each other. Although the concept was ultimately proven unrealistic, it was found that his equation could still be used to describe the data. DuBoys reached an expression that is based on the excess of shear stress:

$$q_b = K\tau(\tau - \tau_c) \tag{55}$$

where q_b = bed load discharge by volume per unit channel width; τ = bed shear stress; and τ_c = critical tractive force along the bed. τ_c can be computed from Shields diagram. Straub (1935) found the following relationship for K:

$$K = \frac{0.173}{d^{3/4}} \tag{56}$$

where d = particle size.

3.5.2 Meyer-Peter and Müller's formula (1948)

The Meyer-Peter and Müller's formula (1948) is a bed load formula for gravel or coarse materials:

$$\gamma RS\left(\frac{K_s}{K_r}\right)^{3/2} = 0.047(\gamma_s - \gamma)d + 0.25\rho^{1/3}q_b^{2/3} \tag{57}$$

where γ and γ_s = specific weights of water and sediment (metric tons/m^3), respectively; R = hydraulic radius (m); S = energy slope; d = mean particle diameter (m); ρ = specific mass of water (metric ton-s/m^4); q_b = bedload rate in underwater weight per unit time and width ([metric tons/s]/m); and $(K_s/K_r)S$ = a kind of slope, which is adjusted such that only a portion of the total energy loss, namely, that caused by the grain resistance, S_r, is responsible for the bed-load motion.

Eq. (57) can also be expressed in dimensionless form as

$$q_b^{2/3}\left(\frac{\gamma}{g}\right)^{1/3}\frac{0.25}{(\gamma_s - \gamma)d} = \frac{(K_s/K_r)^{3/2}\gamma RS}{(\gamma_s - \gamma)d} - 0.047 \tag{58}$$

where

$$\left(\frac{K_s}{K_r}\right)^{3/2} = \frac{S_r}{S} \tag{59}$$

and

$$K_r = \frac{26}{d_{90}^{1/6}} \tag{60}$$

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

3.5.3 Laursen's Formula (1958) and Modification by Madden (1993)

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

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{D}\right)^{7/6} \left(\frac{\tau'}{\tau_{ci}} - 1\right) f\left(\frac{U^*}{\omega_i}\right) \tag{61}$$

where C_t = sediment concentration by weight per unit volume; $U^* = \sqrt{gDS}$; p_i = percentage of materials available in size fraction i; ω_i = fall velocity of particles of mean size d_i in water; D = average water depth; and τ_{ci} = critical tractive force for sediment size d_i as given by the Shields diagram. Laursen's bed shear stress, τ', caused by grain resistance resulting from the use of the Manning equation is

$$\tau' = \frac{\rho V^2}{58}\left(\frac{d_{50}}{D}\right)^{1/3} \tag{62}$$

In eq. (61), the parameter $\tau'/\tau_{ci} - 1$ is important in determining bed load, and the parameter U^*/ω_i relates to suspended load. The functional relation $f(U^*/\omega_i)$ is given by Laursen (1958) in a graphical form.

Madden (1993) used three sets of data from the Arkansas River to develop a modified functional relationship in Laursen’s formula, which includes an adjustment for the Froude number effects. The modified Laursen formula has been applied in the range of very fine silt (non-cohesive) to very fine gravel, flow depths ranging from 0.25 to 54 ft, flow velocities from 0.85 to 7.7 ft/s, energy gradients from 10^{-5} to 0.1, temperatures from 36 to 90 degrees F, and Froude numbers from 0.07 to 1.7. GSTARS3 includes both the original and the modified Laursen formulae.

3.5.4 Toffaleti's Method (1969)

Toffaleti's method (1969) is based on the concept of Einstein (1950) and Einstein and Chien (1953) with the following simplifications: (1) channel width with sediment discharge is equal to that of a rectangular channel of width B and depth R, with R being the hydraulic radius of the actual channel; (2) the total depth of flow is divided into four zones. The bed material, Q_{ti}, for sediment of size d_i is

$$Q_{ti} = B(q_{bi} + q_{sui} + q_{smi} + q_{sli}) \tag{63}$$

where B = channel width; and q_{bi}, q_{sui}, q_{smi}, q_{sli} = sediment load per unit width in the bed zone, upper zone, middle zone, and lower zone, respectively. Semi-empirical and graphical methods were used by Toffaleti for the computation of sediment load in each zone.

3.5.5 Engelund and Hansen's Method (1972)

Engelund and Hansen (1972) proposed the following transport function:

$$f'\phi = 0.1\theta^{5/2} \tag{64}$$

$$f' = \frac{2gSD}{V^2} \tag{65}$$

$$\phi = \frac{q_t}{\gamma_s}\left[\left(\frac{\gamma_s - \gamma}{\gamma}\right) g d^3\right]^{-1/2} \tag{66}$$

$$\theta = \frac{\tau}{(\gamma_s - \gamma) d} \tag{67}$$

where g = gravitational acceleration; S = energy slope; V = average flow velocity; q_t = total sediment discharge by weight per unit width; γ_s and γ = specific weights of sediment and water, respectively; d = median particle diameter; D = mean water depth; and τ = shear stress along the bed.

3.5.6 Ackers and White's Method (1973) and (1990)

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

$$F_{gr} = U^{*n}\left[gd\left(\frac{\gamma_s}{\gamma} - 1\right)\right]^{-1/2}\left[\frac{V}{\sqrt{32}\log(\alpha D / d)}\right]^{1-n} \tag{68}$$

where U^* = shear velocity; n = transition exponent, depending on sediment size; $\alpha = 10$, in turbulent flow; d = sediment particle size; and D = water depth. They also expressed the sediment size by a dimensionless grain diameter:

$$d_{gr} = d\left[\frac{g}{\nu^2}\left(\frac{\gamma_s}{\gamma} - 1\right)\right]^{1/3} \tag{69}$$

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

$$G_{gr} = f(F_{gr}, d_{gr}) \tag{70}$$

with

$$G_{gr} = \frac{XD}{(d\gamma_s)/\gamma}\left(\frac{U^*}{V}\right)^n \tag{71}$$

where X = rate of sediment transport in terms of mass flow per unit mass flow rate, i.e., concentration by weight of fluid flux. The generalized dimensionless sediment transport function can also be expressed as

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^m \tag{72}$$

The values of A, C, m, and n were determined by Ackers and White (1973) based on best-fit curves of laboratory data with sediment size greater than 0.04 mm and Froude number less than 0.8.

The original Ackers and White formula is known to overpredict transport rates for fine sediments (smaller than 0.2 mm) and for relatively coarse sediments. To correct that tendency, a revised form of the coefficients was published in 1990 (HR

Wallingford, 1990). Both versions of the coefficients are included in GSTARS3. The comparison between the original and the revised coefficients is given in table 3.2.

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

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

3.5.7 Yang's Sand (1973) and Gravel (1984) Transport Formulae

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

$$\log C_{ts} = 5.435 - 0.286 \log \frac{\omega d}{\nu} - 0.457 \log \frac{U^*}{\omega} + \left(1.799 - 0.409 \log \frac{\omega d}{\nu} - 0.314 \log \frac{U^*}{\omega}\right) \log\left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega}\right) \tag{73}$$

where C_{ts} = total sand concentration in parts per million by weight; ω = 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. (73) were determined from 463 sets of laboratory flume data. Eq. (73) should be applied to sand transport with particle diameter less than 2 mm.

The critical dimensionless unit stream power, $V_{cr} S / \omega$, is the product of dimensionless critical velocity V_{cr} / ω and energy slope S, where

$$\frac{V_{cr}}{\omega} = \begin{cases} \dfrac{2.5}{\log(U^* d / \nu) - 0.06} + 0.66 & \text{if } 1.2 < \dfrac{U^* d}{\nu} < 70 \\ 2.05 & \text{if } 70 \le \dfrac{U^* d}{\nu} \end{cases} \tag{74}$$

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

$$\log C_{tg} = 6.681 - 0.633\log\frac{\omega d}{\nu} - 4.816\log\frac{U^*}{\omega} + \left(2.784 - 0.305\log\frac{\omega d}{\nu} - 0.282\log\frac{U^*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (75)$$

where C_{tg} = total gravel concentration in parts per million by weight. The coefficients in eq. (75) were determined from 167 sets of laboratory flume data.

The incipient motion criteria given in eq. (74) should be used for eqs. (73) and (75). Because of the range of data used for the determination of the coefficients in eq. (75), the equation should be applied to gravel with median particle size between 2 and 10 mm. However, published literature suggests that eq. (75) may be applicable to materials coarser than 10 mm. GSTARS3 uses eq. (75) for sizes up to 100 mm. Eqs. (73) and (75) were originally derived for uniform materials. When they are applied to nonuniform materials, the total sediment concentration should be computed by using eq. (50).

For natural rivers, the bed-material size may vary from sand to gravel. In this case, the use of both eqs. (73) and (75) should be considered. GSTARS3 uses the appropriate equation for a given particle size.

3.5.8 Yang's Sand (1979) and Gravel (1984) Transport Formulae

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

$$\log C_{ts} = 5.165 - 0.153\log\frac{\omega d}{\nu} - 0.297\log\frac{U^*}{\omega} + \left(1.780 - 0.360\log\frac{\omega d}{\nu} - 0.480\log\frac{U^*}{\omega}\right)\log\frac{VS}{\omega} \quad (76)$$

The coefficients in eq. (76) were determined from 452 sets of laboratory flume data. Eqs. (73) and (76) give about the same degree of accuracy when the bed-material concentration is greater than about 100 parts per million by weight. Users can either use a combination of eqs. (73) and (75) or (76) and (75) for the computation of bed material concentration in a river, depending on sediment size in that river. If bed materials are not uniform, equation (50) is also applied in GSTARS3.

3.5.9 Parker's Method (1990)

Parker (1990) developed an empirical gravel transport function based on the equal mobility concept and field data. Parker's dimensionless bed-load transport function, W_i^* , and dimensionless shear stress parameter, ϕ_i, are defined as

$$W_i^* = \left(\frac{\gamma_s}{\gamma} - 1\right)\frac{q_{bi}}{p_i DS\sqrt{gDS}} \tag{77}$$

$$\phi_i = \frac{DS}{d_i \tau_{ri}^*}\left(\frac{\gamma_s}{\gamma} - 1\right)^{-1} \tag{78}$$

The value of τ_{ri}^* based on d_{50} is 0.875, i.e.,

$$\tau_{ri}^* = 0.875\frac{d_{50}}{d_i} \tag{79}$$

where q_{bi} = bed-load per unit channel width in size fraction d_i; D = water depth; S = slope; and p_i = fraction by weight in size d_i.

Because of equal mobility of all sizes, only one grain size, namely, the subpavement size, d_{50}, is used to characterize bed-load discharge as a function of the dimensionless shear stress, i.e.,

$$W^* = \begin{cases} 0.0025\phi_{50}^{14.2} & \text{if} \quad \phi_{50} < 1.0 \\ 0.0025\exp\left\{14.2(\phi_{50} - 1) - 9.28(\phi_{50} - 1)^2\right\} & \text{if} \quad 1.0 \le \phi_{50} \le 1.59 \\ 13.685\left(1 - \frac{0.853}{\phi_{50}}\right)^{4.5} & \text{if} \quad \phi_{50} > 1.59 \end{cases} \tag{80}$$

In eq. (80), ϕ_{50} is based on the subpavement size, d_{50}. This equation was empirically fitted using field data with sediment size ranging from 18 to 28 mm.

3.5.10 Yang'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:

$$\log C_{ts} = 5.165 - 0.153\log\frac{\omega_m d}{\nu_m} - 0.297\log\frac{U^*}{\omega_m} + \left(1.780 - 0.360\log\frac{\omega_m d}{\nu_m} - 0.480\log\frac{U^*}{\omega_m}\right)\log\left[\left(\frac{\gamma_m}{\gamma_s - \gamma_m}\right)\frac{VS}{\omega_m}\right] \quad (81)$$

where ω_m = 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. (81) are identical to those in eq. (76). 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. Similar to the applications of eqs. (73), (75), and (76), eq. (81) is used in conjunction with eq. (50) for nonuniform bed materials.

3.5.11 Tsinghua University Equation for Reservoir Flushing

Most sediment transport equations were developed for rivers and channels, and make assumptions that restrict their application outside the range for which they were developed. They may not be valid, for example, for flows in reservoirs. The Tsinghua University equation (IRTCES, 1985) is an empirical equation especially derived for calculating the transport capacity of flushing flows in reservoirs:

$$Q_s = \Omega\frac{Q^{1.6}S^{1.2}}{W^{0.6}} \quad (82)$$

where Q_s = sediment discharge (metric tons/s); Q = water discharge (m^3/s); W = channel width (m); S = bed slope; and Ω is a factor that depends on sediment type. The recommended values for Ω are presented in table 3.3.

Table 3.3 Values of the factor Ω in Tsinghua University's equation.

Value of Ω	Type of sediments
1600	Loess sediments
650	Other sediments with median size finer than 0.1 mm
300	Sediments with median size larger than 0.1 mm
180	For flushing with a low discharge

The Tsinghua University equation was derived from data on flushing reservoirs in China. The scatter of the data used is considerable, but not unusually high. Furthermore, the practice in China is to flush the reservoirs annually, therefore little consolidation takes place between flushing events. In these conditions, the importance of reservoir operations is reduced.

In GSTARS3, eq. (82) was adapted for fractional sediment transport. Note, however, that eq. (82) was derived for the flushing practices and sediment characteristics of Chinese reservoirs. Extrapolation to other reservoirs and conditions should be done with caution.

Note that when Tsinghua's sediment transport equation is selected for GSTARS3 runs, the methods for cohesive sediment transport are not used, irrespective of the particle size. This is an exception to the usual way in which cohesive sediment transport computations take place (see section 3.6 for more details about the cohesive sediment transport methodologies implemented in GSTARS3).

3.5.12 Ashida and Michiue Method (1972)

Ashida and Michiue's (1972) bed load relationship for the transport rate of sediment grains with diameter d_i is

$$\frac{q_{bi}}{p_i u_e^* d_i} = 17\tau_{ei}^*\left(1 - \frac{\tau_{ci}^*}{\tau_i^*}\right)\left(1 - \sqrt{\frac{\tau_{ci}^*}{\tau_i^*}}\right) \tag{83}$$

where q_{bi} = bed load transport rate for size fraction i per unit width; d_i = diameter of the particles in size class i; p_i = percentage of size fraction i;

$$\tau_i^* = \frac{u^{*2}}{Ggd_i} \tag{84}$$

$$\tau_{ci}^* = \frac{u_{ci}^{*2}}{Ggd_i} \tag{85}$$

$$\tau_{ei}^* = \frac{u_e^{*2}}{Ggd_i} \tag{86}$$

u^* = shear velocity ($\sqrt{gR_hS_e}$); G = specific gravity of sediments in water; g = acceleration due to gravity; R_h = hydraulic radius; S_e = slope of the energy line; u_e^* = effective shear velocity, computed from

$$\frac{V}{u_e^*} = 5.75\log\left(\frac{R_h/d_{50}}{1 + 2\tau^*}\right) + 6.0 \tag{87}$$

where d_{50} = mean diameter of the bed material. The critical shear stress for each size class is expressed following Egiazaroff (1965):

$$\frac{u_{ci}^{*2}}{u_{c50}^{*2}} = \begin{cases} 0.85 & \text{if } \dfrac{d_i}{d_{50}} < 0.4 \\ \left(\dfrac{\log 19}{\log\left(\dfrac{19d_i}{d_{50}}\right)}\right)^2 & \text{if } \dfrac{d_i}{d_{50}} \geq 0.4 \end{cases} \tag{88}$$

where u^*_{c50} = nondimensional critical shear velocity for the d_{50} fraction:

$$u^*_{c50} = \sqrt{\tau^*_{c50} G g d_{50}} \tag{89}$$

τ^*_{c50} is taken equal to 0.05.

Although the original expression due to Ashida and Michiue (1972) is for bed load only, in GSTARS3 the method of Ashida and Mishiue (1970) is used to compute the suspended load, therefore the implementation falls in the bed-material load category.

The transport rate per unit width of the suspended load, for size fraction *i*, is computed following Ashida and Michiue (1970):

$$q_{si} = C_{ai} v (e^{-c_1 a} - e^{-c_1 h}) \frac{e^{c_1 a}}{c_1} \tag{90}$$

where C_{ai} = concentration at a reference level (assumed to be $a = 0.05h$, where h is the water depth), which is given by

$$C_{ai} = p_i K \left[\frac{f(\xi_0)}{\xi_0} - F(\xi_0) \right] \tag{91}$$

with

$$f(\xi_0) = \frac{1}{\sqrt{2\pi}} \exp\left\{ -0.5 \xi_0^2 \right\} \tag{92}$$

$$F(\xi_0) = \frac{1}{\sqrt{2\pi}} \int_{\xi_0}^{\infty} \exp\{-0.5\xi^2\} d\xi \tag{93}$$

where $K = 0.025$, $\xi_0 = \omega_i / (0.75 u^*)$, and ω_i is the fall velocity of sediment particles with diameter d_i. In eq. (90), c_1 is computed as

$$c_1 = \frac{6\omega_i}{\kappa u^* h} \tag{94}$$

where κ is the von Kàrmàn constant (= 0.412).

The total load per unit width for size fraction i is found by adding the bed load and the suspended load obtained by eqs. (83) and (90), respectively: $q_i = q_{bi} + q_{si}$. Ashida and Michiue's formulation has been widely used, with success, by Japanese engineers and scientists working in river and reservoir sedimentation.

Due to the nature of Ashida and Michiue's method, the parameter *r* in eq. (50) should be set to 1 when the method is used in GSTARS3 runs.

3.6 Cohesive Sediment Transport

At present, the equations for computing the transport potential of cohesive sediments† implemented in GSTARS3 are considered state-of-the-art (Partheniades, 1986; Mehta et al., 1989). However, in spite of the progress of recent years in modeling cohesive sediment transport, reliable predictive techniques are still not available. In practice, modeling of fines still relies on extensive calibration and sensitivity analysis, techniques that are useful and can yield excellent results, but that are costly and time consuming. Our knowledge of the basic physical processes that govern erosion, deposition, and consolidation of cohesive sediments is still incomplete. The present models suffer from this limitation, but are further aggravated from frequent discrepancies observed between laboratory experiments and prototype behavior.

Table 3.4 Sediment grade size scale for particle sizes smaller than the finest sand (62.5 μm) according to the American Geophysical Union (Lane, 1947).

Classification	d_{mean} (μm)
Coarse silt	62 - 31
Medium silt	31 - 16
Fine silt	16 - 8
Very fine silt	8 - 4
Coarse clay	4 - 2
Medium clay	2 - 1
Fine clay	1 - 0.5
Very fine clay	0.5 - 0.25
Colloids	< 0.25

The main difficulty in describing the behavior of muds stems from the fact that cohesive sediments are not characterized by their particle properties alone. All the governing parameters for non-cohesive sediments (those with diameter larger than 62.5 μm) can be known from the particle properties, such as density, diameter, and shape. These parameters are enough to define the fall velocity and the erosion and deposition processes of the sediment. However, the properties of muds do not depend on the sediment mixture alone. The medium where the sediment is contained, that is, its surrounding aqueous mixture, plays a more fundamental role in defining sedimentation characteristics. Parameters such as temperature of the water, its pH, salinity and other mineral composition, organic content, and biological processes, are necessary to characterize the mud and its intrinsic properties. Unfortunately, these highly variable and site dependent parameters are too complex and poorly understood to be used directly by a model. This fact also elucidates why stud-

† In this manual, cohesive sediments are sediments whose particles pass through a 62.5 μm sieve, a definition that follows the nomenclature of the American Geophysical Union (Lane, 1947). We also use the terms mud and fines to refer to this type of sediment. See table 3.4 for more detailed description of the subclasses.

ies of cohesive sediments are empirical, site specific, and seldom of a fundamental nature. Table 3.5 shows some of the parameters that can be used to characterize cohesive sediments.

Table 3.5 List of some the parameters used by the European Community's MAST-1 G6M project to characterize cohesive sediment processes. Note that some of these parameters are interdependent.

Physico-chemical properties of the overflowing fluid	Physico-chemical properties of the sediments
Chlorinity	Chlorinity
Temperature	Temperature
Oxygen content	Oxygen content
Redox potential	Redox potential
pH	Gas content
Ions (Na-, K-, Mg-, Ca-, Fe-, and Al-)	Ions (Na-, K-, Mg-, Ca-, Fe-, and Al-)
Sodium adsorption ratio	Organic content
Suspended sediment concentration	Cation exchange capacity (CEC)
Characteristics of bed structure	Bulk density (profile)
Consolidation:	Specific surface area
(a) consolidation curve & density profile	Mineralogical composition
(b) permeability	Grain size distribution
(c) pore pressure & effective stress	Sand content
Rheological parameters:	**Water-bed exchange process**
(a) upper & lower yield stress	Settling velocity (laboratory & field):
(b) Bingham viscosity	(a) as function of sediment concentration and floc density
(c) equilibrium slope of deposits	
Atterberg limits	(b) as function of salinity
	Critical shear stress for deposition
	Critical shear stress for erosion
	Erosion rate

In GSTARS3, the transport of silt and clay is computed separately from the remaining size fractions. GSTARS3 recognizes the presence of clay if any of the particle size fractions given in the input has a geometric mean grain size, d_{mean}, smaller than 0.004 mm (see table 3.4). Similarly, the presence of silt is recognized if a size faction has a d_{mean} between 0.004 and 0.0625 mm. There can be any number of particle groups in the clay or silt sizes, up to a maximum of 10 combined groups (i.e., including cohesive and non-cohesive sediment size groups). While the transport of fractions with $d_{mean} \geq 0.0625$ mm is computed by the traditional transport equations presented in section 3.5, for smaller fractions the methods described in this section are used.

3.6.1 Deposition

The occurrence of erosion or deposition is controlled by the value of the bed shear stress, τ_b. Deposition of clay and silt takes place when τ_b is smaller than the critical bed shear stress for deposition, τ_{cd}. τ_{cd} is the critical value of the bed shear stress above which no deposition occurs. In this case, the deposition is governed by integrating

$$\frac{dC}{dt} = -\frac{P\omega_s C}{h} \tag{95}$$

where C = depth-averaged concentration of sediments, h = the water depth, and ω_s = the settling velocity of the sediment. P is a parameter representing the probability for deposition, and is computed from

$$P = \begin{cases} 1 - \dfrac{\tau_b}{\tau_{cd}} & \text{when} \quad \tau_b < \tau_{cd} \\ 0 & \text{when} \quad \tau_b \geq \tau_{cd} \end{cases} \tag{96}$$

When ω_s does not depend on the concentration of suspended sediments (unhindered settling), eq. (95) can be integrated analytically to yield

$$\frac{C}{C_0} = \exp\left\{-\frac{\omega_s \Delta t}{h}\left(1 - \frac{\tau_b}{\tau_{cd}}\right)\right\} \tag{97}$$

where C_0 and C are the concentration at the beginning and end of time step. The time of residence, Δt, is obtained from $\Delta x/V$, where Δx is the reach length and V is the velocity of the flow.

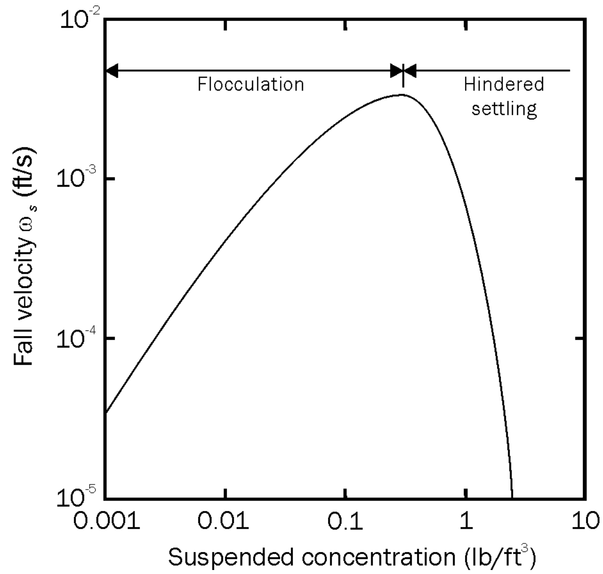
For higher concentrations of suspended sediments, ω_s becomes dependent of concentration via effects of flocculation and hindered settling (see figure 3.7). In those cases, eq. (95) does not offer a closed form solution. For high concentrations, GSTARS3 integrates eq. (95) numerically:

$$C = C_0 - \frac{\omega_s C_0 \Delta t}{h}\left(1 - \frac{\tau_b}{\tau_{cd}}\right) \tag{98}$$

in which ω_s is computed from expressions discussed later, in section 3.8, and is assumed to remain constant during the time step. Eqs. (97) and (98) are both included in GSTARS3. The concentration obtained from their solution is converted into volume and deposited on the bed.

It was mentioned that the adoption of eq. (97) requires unhindered settling conditions of the sediment particles. Unhindered settling is a condition under which the particles retain their individuality, and only occurs at relatively low concentrations, say $C < C_1$. At higher concentrations, particles flocculate together, forming larger aggregates that behave differently from the individual particles. Values of C_1 are in the range of 100 to 700 mg/l. At these values of the concentration, fall velocity increases due to the increased weight of the aggregates. At even higher concentrations, say $C > C_2$, the larger size of the aggregates actually works to slow down their fall velocities, in a similar effect as that of a parachute. Typical values of C_2 are in the range of 5 to 10 g/l. However, these limits are highly variable and case dependent, therefore the application of GSTARS3 to these problems should be done carefully and with ample support from field data.

Figure 3.7 Fall velocity of cohesive sediment aggregates in high concentration transport, showing the effects of flocculation and hindered settling.



The concept of critical shear stress for deposition is not without its problems. For example, Krone (1962) found a concentration-dependent τ_{cd} for the San Francisco Bay sediments. The values of τ_{cd} were found to vary between 0.06 N/m^2 for $C < 300$ mg/l, and 0.078 N/m^2 for the higher values of C, ranging from 300 to 10,000 mg/l. Furthermore, when the sediment distribution in the bed has a large range of particle sizes, τ_{cd} may not have a unique value. The particular behavior of τ_{cd} for the case at hand should always be considered and supported by field data.

3.6.2 Erosion

Erosion of silt and clay takes place when τ_b is greater than the critical bed shear stress for particle scour, τ_{cs}. GSTARS3 recognizes two modes of erosion of cohesive beds: particle erosion and mass erosion. The first mode, also referred to as surface erosion, corresponds to the state where the erosion proceeds particle by particle, or aggregate by aggregate. The second mode corresponds to a state where the bed is destroyed by the eroding currents and entire blocks of mud are swept away. This type of phenomenological schematization of the erosion process of cohesive beds is shared by many (e.g., Ohtsubo and Muraoka, 1986). A third mode of erosion is sometimes mentioned, which corresponds to the re-entrainment of a stationary suspension (Mehta et al., 1989).

The current methods compute the rate of erosion, $E^{\dagger}$, as a linear function of the excess of the bed shear stress with respect to a critical shear stress for erosion:

$$E = M_i\left(\frac{\tau_b - \tau_{ci}}{\tau_{ci}}\right) \tag{99}$$

where $i = 1,2$ for particle or mass erosion, respectively, M_i is an experimental parameter, and τ_{ci} are the critical shear stresses for erosion. M_i and τ_{ci} vary with type of sediment, salinity and mineral contents of the water, its pH and temperature, but do not correlate well with the parameters usually used to characterize non-cohesive sediments (particle diameter, specific gravity, Atterberg limits, etc. — see table 3.5). Therefore, to compute the erosion rate of mud beds we need to know how M_1, M_2, τ_{c1}, and τ_{c2} vary within the domain of interest. This variation may be in space and/or time.

Unfortunately, the literature does not provide methods of estimating M_i, therefore eq. (99) was implemented in two stages. Particle erosion takes place when $\tau_b > \tau_{cs}$. Mass erosion takes place when τ_b increases past the critical bed shear stress, τ_{cm}, for mass erosion. The following equations are used for the particle and mass erosion rates, respectively (Partheniades 1965; Ariathurai and Krone 1976):

$\tau_{cs} < \tau_b \le \tau_{cm}$:

$$E_1 = \frac{1}{A}\frac{dm}{dt} = M_1\left(\frac{\tau_b}{\tau_{cs}} - 1\right) \tag{100}$$

$\tau_b > \tau_{cm}$:

$$E_2 = \frac{1}{A}\frac{dm}{dt} = M_2\left(\frac{T_e}{\Delta t}\right) \tag{101}$$

where m = mass; t = time; Δt = time step; M_1, M_2 = material constants that depend on mineral composition, salinity, organic material, etc., with units of mass per unit area and time; A = bottom area; and E_1 = particle erosion rate per unit of area; E_2 = mass erosion rate per unit of area; and T_e = characteristic time of erosion.

The presence of clay in the active layer may increase the cohesive forces between particles. As a result, the shear stress necessary to move the cohesive materials may be greater than that necessary to move the individual particles, which in turn limits the rates of bed erosion. To model this effect, GSTARS3 uses an input parameter that indicates a threshold value for the percentage of clay in the composition of the bed, above which the erosion rates of silts, sands, and gravel are limited to the erosion rate of clay. For example, if that parameter is set to 0.3 (i.e., 30 percent), whenever the composition of the bed contains 30 percent or more clay, the erosion of silts, sands, and gravels will be limited to the erosion rate of clay. On the other

† Units of mass of eroded sediment per unit of bed area and per unit of time.

hand, if the composition of the bed contains less than 30 percent of clay, the erosion rates of the other materials are not constrained by the erosion rate of clay. This methodology prevents erosion of those materials before the erosion of clay begins to take place, which would otherwise occur when the bed shear stress is large enough to erode those particles, but smaller than τ_{cs}.

The equations used for erosion of cohesive sediments do not constrain the concentration of clay and silt being transported. To prevent unlimited growth of the transport of these materials, a maximum mud flow concentration of 800,000 parts per million by weight is allowed (U.S. Army Corps of Engineers, 1993). When the total concentration of silt and clay exceeds this value, each of the grain size fractions is reduced proportionally to meet the 800,000 parts per million limit of fines.

3.7 Non-equilibrium Sediment Transport

In rivers and streams, it is usually acceptable to assume that the bed-material load discharge is equal to the sediment transport capacity of the flow; i.e., the bed-material load is transported in an equilibrium mode. In other words, the exchange of sediment between the bed and the fractions in transport is instantaneous. However, there are circumstances in which the spatial-delay and/or time-delay effects are important. For example, reservoir sedimentation processes and the siltation of estuaries are essentially non-equilibrium processes. In the laboratory, it has been observed that it may take a significant distance for a clear water inflow to reach its saturation sediment concentration. To model these effects, GSTARS3 uses the method developed by Han (1980). In this method, which is based in the analytical solution of the convection-diffusion equation, the non-equilibrium sediment transport rate is computed from

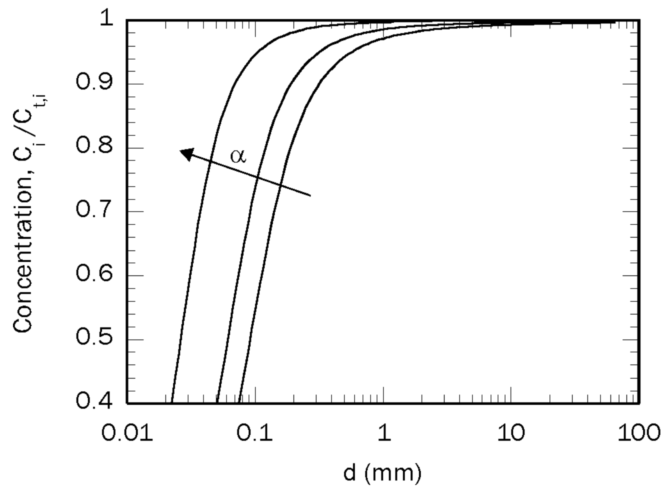
$$C_i = C_{t,i} + (C_{i-1} - C_{t,i-1})\exp\left\{-\frac{\alpha\omega_s\Delta x}{q}\right\} + (C_{t,i-1} - C_{t,i})\left(\frac{q}{\alpha\omega_s\Delta x}\right)\left[1 - \exp\left\{-\frac{\alpha\omega_s\Delta x}{q}\right\}\right] \tag{102}$$

where C = sediment concentration; C_t = sediment carrying capacity, computed from eq. (50); q = discharge of flow per unit width; Δx = reach length; ω_s = sediment fall velocity; i = cross-section index (increasing from upstream to downstream); and α = a dimensionless parameter. Eq. (102) is employed for each of the particle size fractions in the cohesionless range, i.e., with diameter greater than 62.5 μm. The parameter α is a recovery factor. Han and He (1990) recommend a value of 0.25 for deposition and 1.0 for entrainment.

Although eq. (102) was derived for suspended load, its application to bed-material load is reasonable. The asymptotic behavior of eq. (102) for the larger particles (higher values of ω_s) is correct in the sense that $C_i \to C_{t,i}$ as ω_s becomes larger.

Therefore, for the larger particles that are transported near the bed as bed load, the non-equilibrium correction due to eq. (102) becomes negligible and $C_i \cong C_{t,i}$. Figure 3.8 shows the ratio $C_i/C_{t,i}$ as a function of particle size, for the case of erosion (the correction is similar for the case of aggradation). The non-equilibrium capacity becomes almost identical for gravel and larger particle sizes.

Figure 3.8 Ratio between non-equilibrium concentration and carrying capacity as a function of sediment particle size.



The influence of the recovery parameter α is illustrated in figure 3.9. The depositional case represents a situation in which there is a sudden loss of carrying capacity ($C_{t,i} = 0$) from an upstream equilibrium condition ($C_{i-1} = C_{t,i-1}$). 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 gain of carrying capacity, such as what happens when clear water enters a channel with erodible bed. In this case, $C_{i-1} = C_{t,i-1} = 0$ and $C_{t,i} > 0$. The same trend is observed as before, i.e., the non-equilibrium effects tend to diminish with increasing particle sizes and recovery factor.

Another important factor in non-equilibrium calculations is distance between computational cross sections, Δx. Figure 3.10 shows how the non-equilibrium effects vary with distance for the same situations and particle sizes in figure 3.9. In practice, the values of α can vary widely. For example, a value of $\alpha = 0.001$ has been used for depositional rivers with high concentrations of fine material in suspension, such as the Rio Grande in the U.S., and the Yellow River in China. Values of α greater than 1.0 have been used in some occasions, on erosional rivers.

Figure 3.9 Effect of the recovery parameter α on the computation of non-equilibrium sediment concentrations for two sediment particle sizes. (a) deposition and (b) erosion.

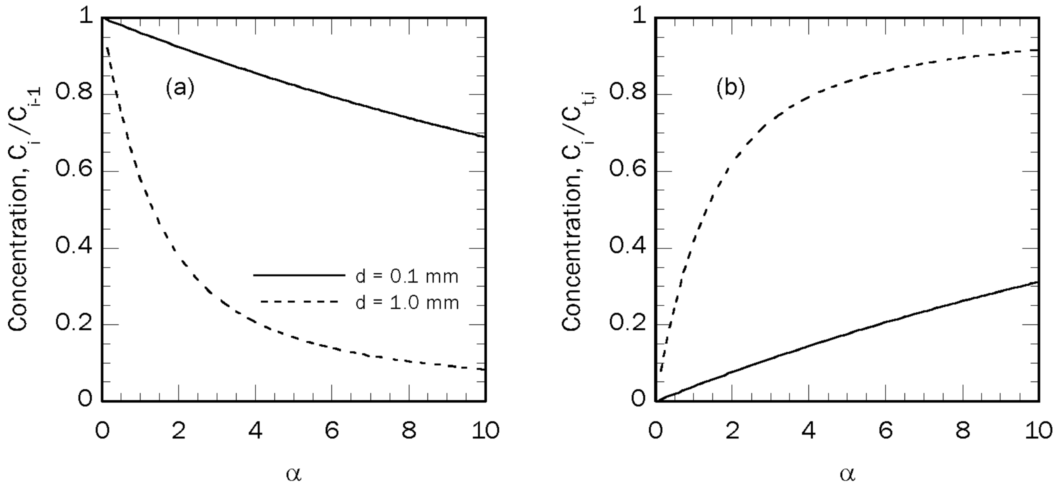
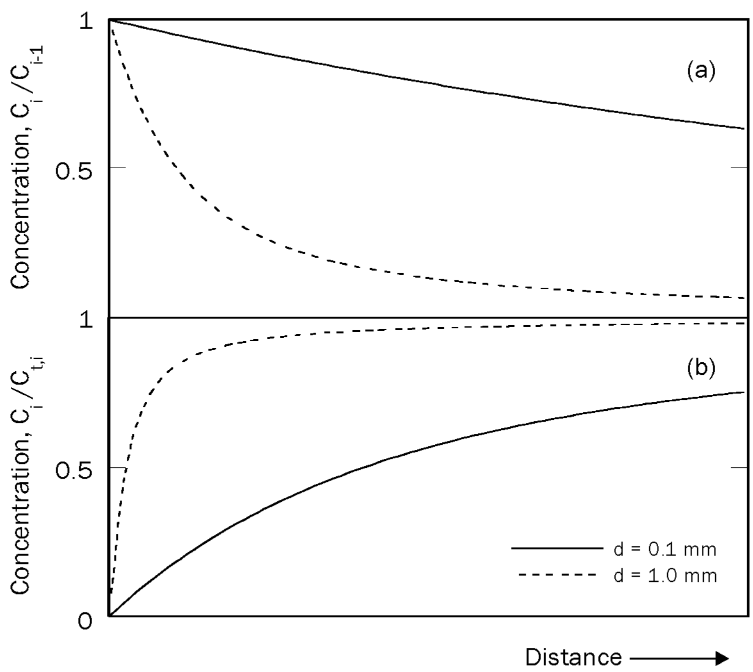


Figure 3.10 Variation of non-equilibrium effects as a function of distance between cross sections for aggradation (a) and for erosion (b).



Note that the non-equilibrium sediment transport phenomenon described by eq. (102) is fundamentally different from the considerations behind the application of eq. (50) in section 3.5. Eq. (50) expresses the way in which fractional sediment transport capacity is calculated from traditional sediment transport equations, which do not incorporate particle size distribution in their computation procedures with enough detail. The resulting calculated capacity, C_t, is an equilibrium capacity, in which it assumes instantaneous exchange of sediments between the bed and the water column. The non-equilibrium equation, eq. (102), operates on C_t to include the time and space lag effects that result from the fact that, in practice, the exchange of sediment particles between bed and water column is not instantaneous. Therefore, both features are implemented independently in GSTARS3 and the user should apply them carefully, with proper engineering judgement.

3.8 Particle Fall Velocity Calculations

Computation of particle fall velocity is necessary for sediment transport capacity calculations. Sediment fall velocities for the sediment particles are computed in different ways, depending on the sediment transport equation used and on particle size. When Toffaleti's equation is used, Rubey's formula (Rubey, 1933) is employed:

$$\omega_s = F\sqrt{dg(G-1)} \tag{103}$$

where

$$F = \left[\frac{2}{3} + \frac{36\nu^2}{gd^3(G-1)}\right]^{1/2} - \left[\frac{36\nu^2}{gd^3(G-1)}\right]^{1/2} \tag{104}$$

for particles with diameter, d, between 0.0625 mm and 1 mm, and where F = 0.79 for particles greater than 1 mm. In the above equations, ω_s = fall velocity of sediments; g = acceleration due to gravity; G = specific gravity of sediments in water; and ν = kinematic viscosity of water. In GSTARS3, the specific gravity of sediments is 2.65 (quartz) and the viscosity of water is computed from the water temperature, T, using the following expression:

$$\nu = \frac{1.792 \times 10^{-6}}{1.0 + 0.0337T + 0.000221T^2} \tag{105}$$

with T in degrees Centigrade and ν in m^2/s.

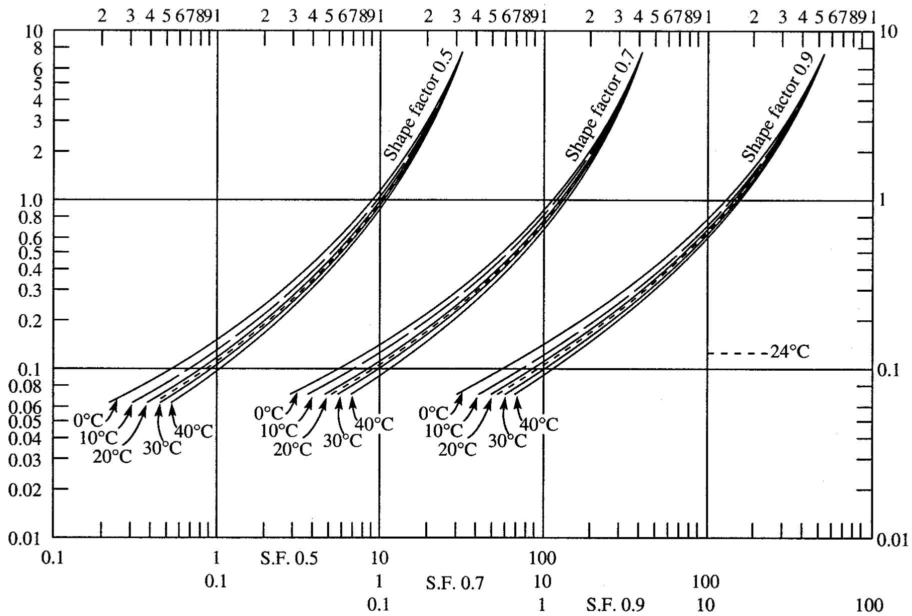
When any of the other sediment transport formulae are used, the values recommended by the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957) are used (figure 3.11). GSTARS3 uses a value for the Corey shape factor of SF = 0.7, where

$$SF = \frac{c}{\sqrt{ab}} \tag{106}$$

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 diameter greater than 10 mm, which are above the range given in figure 3.11, the following formula is used:

$$\omega_s = 1.1\sqrt{(G-1)gd} \tag{107}$$

Figure 3.11 Relation between particle sieve diameter and its fall velocity according to the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957).



For particles in the silt and clay size ranges, that is, with diameters between 1 and 62.5 μm, the sediment fall velocities are computed from the following equations:

unhindered settling:

$$\omega_s = \frac{(G-1)gd^2}{18\nu} \text{ for } C < C_1 \tag{108}$$

flocculation range:

$$\omega_s = MC^N \text{ for } C_1 \le C \le C_2 \tag{109}$$

hindered settling:

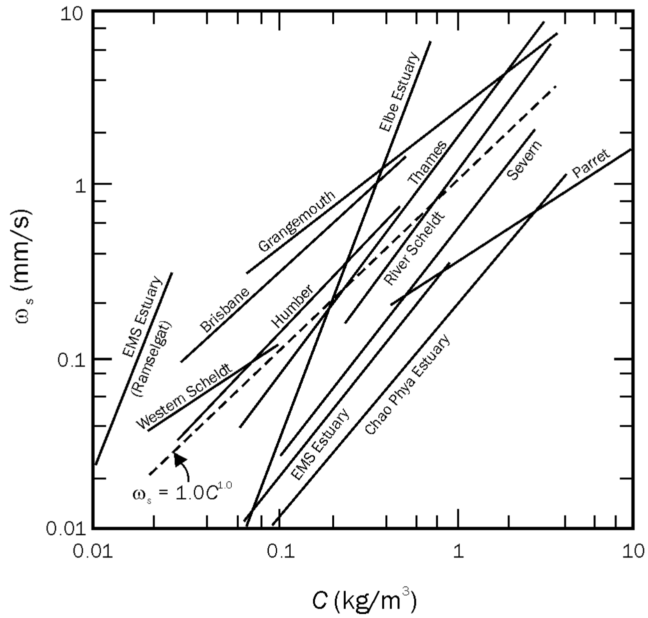
$$\omega_s = \omega_0(1-kC)^l \text{ for } C > C_2 \tag{110}$$

where ω_0 is found by equating eqs.(109) and (110) at $C = C_2$, i.e.,

$$\omega_0 = \frac{MC_2^N}{(1-kC_2)^l} \tag{111}$$

and k, l, M, and N are site specific constants supplied by the user. Figure 3.12 shows typical fall velocities in the flocculation range for a number of different natural conditions. The expression $\omega_s = 1.0C^{1.0}$ seems to represent well the average values (with ω_s in mm/s and C in kg/m^3).

Figure 3.12 Variability of the parameters *M* and *N* of eq. (109) for several well known rivers and estuaries.



CHAPTER

4

Computation of Width Changes

GSTARS3 is able to compute not only channel bed elevation changes, but also channel width changes. This chapter briefly describes the theoretical basis for those calculations and their implementation in the numerical model. Note that this subject is very complex and that its detailed presentation is not in the scope of this manual. The interested reader is strongly encouraged to use the references in the chapter for a more rigorous and complete presentation of the theory.

4.1 Theoretical Basis

Most one-dimensional models treat channel width as a constant value that does not change with changing flow and sediment conditions. These models use the water depth, D, the flow velocity, V, and channel slope, S, as independent variables. The three independent equations that must be satisfied are the conservation of water,

$$Q = BDV \tag{112}$$

where Q = water discharge and B = channel width; a flow resistance equation (Chézy's equation is used for convenience),

$$V = C\left[\frac{BD}{P}S\right]^{1/2} \tag{113}$$

where C = roughness coefficient and P = wetted perimeter; and a sediment transport equation,

$$Q_s = f(D, B, V, S, d, \ldots) \tag{114}$$

where Q_s = sediment transport capacity and d = sediment particle size. However, a fourth independent relationship must be used if the channel width is to be considered as another independent variable. In GSTARS3, the *theory of total stream power minimization* is used as a starting point to obtain the additional independent equation.

The basic theory behind the determination of width and depth adjustments is based on the minimum energy dissipation rate theory developed by Song and Yang (1979a; 1979b; 1982a; 1982b) and Yang and Song (1979; 1986) and this general theory's special case, the minimum stream power theory, used by Chang and Hill (1976; 1977; 1982) and Chang (1979; 1980a; 1980b; 1982a; 1982b; 1983). The minimum energy dissipation rate theory (Yang and Song, 1986) states that when a closed and dissipative system reaches its state of dynamic equilibrium, its energy dissipation rate must be at its minimum value:

$$\Phi = \Phi_W + \Phi_S = \text{a minimum} \tag{115}$$

where Φ, Φ_W, and Φ_S are the total rate of energy dissipation, the rate of energy dissipation due to water movement, and the rate of energy dissipation due to sediment movement, respectively. The minimum value must be consistent with the constraints applied to the system. If the system is not at its dynamic equilibrium condition, its energy dissipation rate is not at its minimum value, but the system will adjust itself in a manner that will reduce its energy dissipation rate to a minimum value and regain equilibrium. Because of changing flow and sediment conditions, a natural river is seldom in its true equilibrium condition. However, a natural river will adjust its channel geometry, slope, pattern, roughness, etc., to minimize its energy dissipation rate subject to the water discharge and sediment load supplied from upstream.

For an alluvial channel or river where the energy dissipation rate for transporting water is much higher than that required to transport sediment, i.e., $\Phi_W \gg \Phi_S$, the theory of minimum energy dissipation rate can be replaced by a simplified theory of minimum stream power (Yang, 1992). For this case, a river will minimize its stream power, γQS, per unit channel length subject to hydrologic, hydraulic, sediment, geometric, geologic, and man-made constraints. In the previous equation, γ is the specific weight of water.

4.2 Computational Procedures

In order to apply the minimization procedure to channel reaches with gradually varied flows, γQS is integrated along the channel:

$$\Phi_T = \int \gamma QS dx \tag{116}$$

where Φ_T is defined as the total stream power. This expression is discretized following Chang (1982a):

$$\Phi_T = \sum_{i=1}^{N} \frac{1}{2}\gamma(Q_i S_i + Q_{i+1} S_{i+1})\Delta x_i \tag{117}$$

where N = number of stations along the reach; Δx_i = reach length, or distance between stations i and $i+1$; and Q_i, S_i = discharge and slope at station i, respectively. Choosing the direction for channel adjustments is made by minimizing the integral represented by eq. (117) for total stream power at different stations. This process is repeated for each time step: if alteration of the channel widths results in lower total stream power than raising or lowering of the channel's bed, then channel adjustments progress in the lateral direction; otherwise, the adjustments are made in the vertical direction.

Figure 4.1 is used to illustrate the process described above. When erosion takes place, channel adjustments can proceed either by deepening or by widening the cross section. Both channel widening and deepening can reduce the total stream power for the reach, but GSTARS3 selects the adjustment that results in the minimum total stream power for the reach. If deposition is predicted by the sediment routing computations, then either the bed is raised or the cross section is narrowed, but the choice must also result in a minimum of the total stream power for the reach. However, in each case the amount of scour and/or deposition is limited by the predicted sediment load, and geological or man-made restrictions are also accommodated by the computational algorithms.

Quantitatively, the amount of channel adjustment during each time step is determined by the sediment continuity equation, i.e., eq. (39) for each stream tube. Channel widening or narrowing can take place only at the stream tubes adjacent to the banks. In this case, the hydraulic radius, R, replaces the wetted perimeter, P, in eq. (39). For stream tubes that are not adjacent to the banks, i.e., interior tubes, bed adjustments can be made only in the vertical direction. The process is briefly schematized in figure 4.2.

In summary, GSTARS3 channel geometry adjustments can occur in the vertical or lateral directions, or in a combination of both. Whether the adjustment will proceed in the vertical or lateral direction at a given time step of computation depends on which direction results in less total stream power in accordance with the theory of minimum total stream power. The requirement of reducing the total stream power during the channel development process constitutes the basis for determining width or depth adjustments in GSTARS3.

Figure 4.1 Total stream power variation as a function of changes in channel width and bed elevation, with constant discharge and downstream stage.

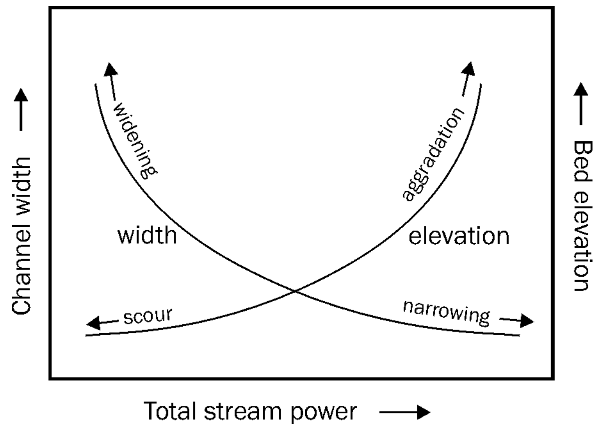
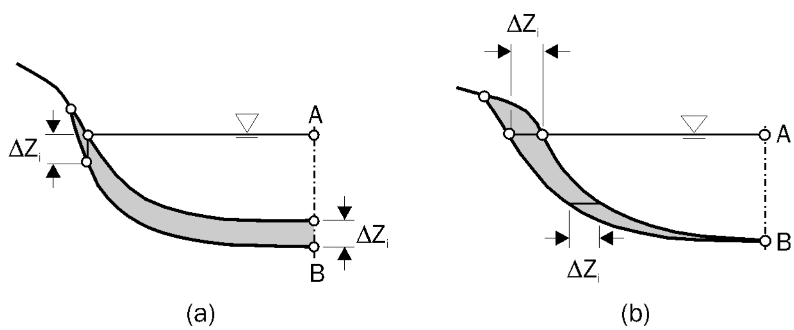


Figure 4.2 Schematic representation of channel changes on exterior stream tubes: (a) bed elevation change due to scour or deposition; (b) width change due to scour or deposition. Line AB denotes the stream tube boundary.



4.3 Channel Side Slope Adjustments

GSTARS3 channel geometry adjustment can take place in both lateral and vertical directions. For an interior stream tube, scour or deposition can take place only on the bed, and the computation of depth change shown in eq. (47) is straightforward. For an exterior stream tube, however, the change can take place on the bed or at the bank.

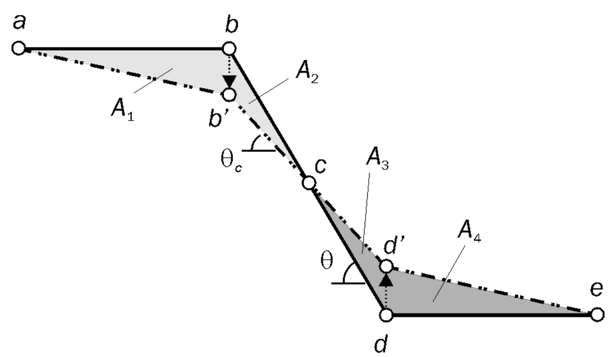
As erosion progresses, the steepness of the bank slope tends to increase. The maximum allowable bank slope depends on the stability of bank materials. When erosion undermines the lower portion of the bank and the slope increases past a critical value, the bank may collapse to a stable slope. The bank 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.

GSTARS3 offers the user the option of checking the angle of repose for violation of a known critical slope. If this option is chosen, the user must then supply the critical angle. The user is also allowed the option of specifying one critical angle above the water surface, and a different critical angle for submerged points. GSTARS3 scans each cross section at the end of each time step to determine if any vertical or horizontal adjustments have caused the banks to become too steep. If any violations occur, the two points adjacent to the segment are adjusted vertically until the slope equals the user-provided critical slope. For the situation shown in figure 4.3, the bank is adjusted from *abde* to *ab'd'e*, so that the calculated angle, θ, is reduced to become equal to the critical angle, θ_c. The adjustments are governed by conservation of mass:

$$A_1 + A_2 = A_3 + A_4 \tag{118}$$

where A_1 = area of triangle *abb'a*; A_2 = area of triangle *bcb'b*; A_3 = area of triangle *cd'dc*; and A_4= area of triangle *d'edd'*.

Figure 4.3 Example of angle of repose adjustment.



CHAPTER

5

RESERVOIR ROUTING

In GSTARS3, special treatments were developed to make the model better suited for modeling flow and sediment transport in lakes, reservoirs, and water impoundments in general. This was necessary because, although flow and sediment transport in lakes and reservoirs are governed by the same physical laws as in rivers and channels, the simplifications and approximations made in earlier versions of the model were mostly based on observations made in riverine situations. Therefore, some modifications and additions had to be made in order to extend and improve the model's ability to handle those cases.

There are many different types of water impoundments, and no model exists that can successfully and indiscriminately be used for all. GSTARS3 is a semi-two-dimensional model, therefore it may not be applicable to situations where fully two- or three-dimensional models are required. GSTARS3 is best in run-of-the-river type of reservoirs, and is particularly suited for long term simulations of large reservoirs, where limitations in data availability, computational resources, time, or financial constraints preclude the use of more sofisticated, multi-dimensional models.

5.1 Reservoir Routing

Sediment routing is accomplished by the same method described in section 2.1 (i.e., the standard step method), but with some modifications. Within the reservoir subreach, the water discharge is computed from a weighted averaged value using the river inflow and the reservoir outflow discharges. The weighting parameter for each cross section is the reservoir's surface area represented by that cross section. For example, for the case pictured in figure 5.1, the reservoir subreach starts in cross section 4 (the reservoir subreach is defined by the cross sections whose thalweg is lower than the reservoir elevation, H_{res}), therefore $Q_3 = Q_{in}$, where Q_i = discharge at cross section i. The discharge Q_4 is given by

$$Q_4 = Q_{in} - a_4(Q_{in} - Q_{out}) \tag{119}$$

where $a_4 = A_4/A_{res}$; A_4 = reservoir's surface area represented by cross section 4; and A_{res} = total surface area of the reservoir. In general,

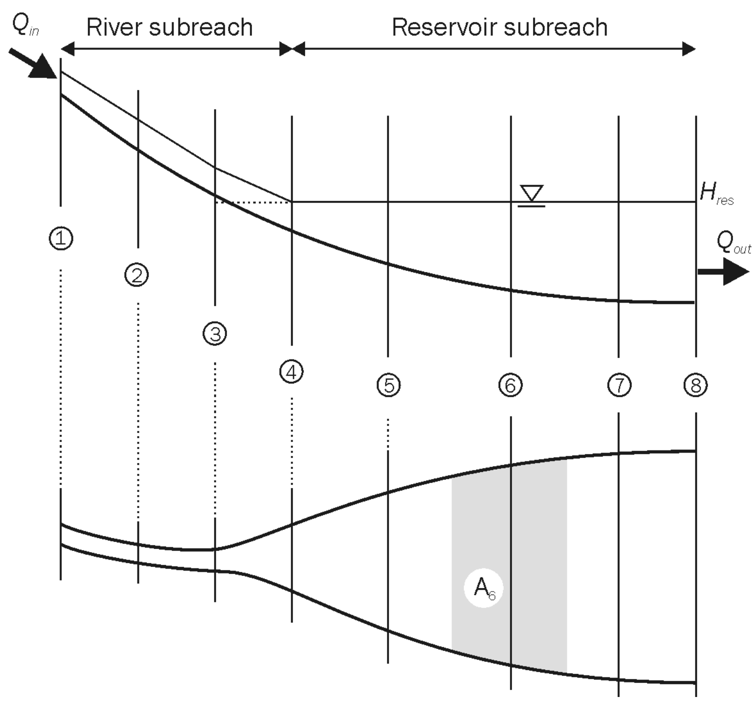
$$Q_j = Q_{in} - (Q_{in} - Q_{out}) \sum_{k=i}^{j} a_k \tag{120}$$

where $a_k = A_k/A_{res}$; A_k = surface area of the reservoir represented by cross section k; i = first cross section belonging to the reservoir subreach (i = 4 in the example of figure 5.1). Of course that, from the definition of a_k,

$$\sum_{k=i}^{N} a_k = 1 \tag{121}$$

where N = cross section at the dam (N = 8 in figure 5.1)

Figure 5.1 Subdivision of a GSTARS3 reach into river and reservoir subreaches for reservoir routing. Top: side view; bottom: top view of the same reservoir. The shaded region depicts the surface area of the reservoir represented by cross section #6.

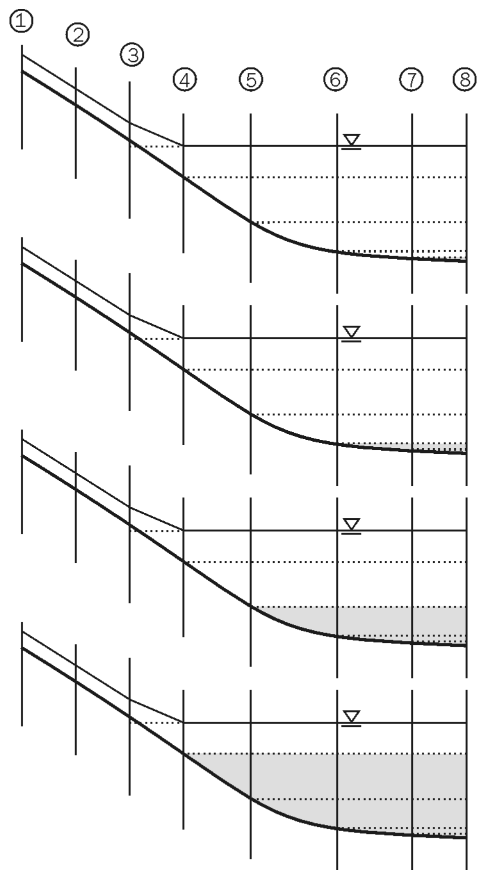


Water levels at the dam are calculated using level-pool routing. Assuming that the reservoir water surface is horizontal,

$$Q_{in} - Q_{out} = \frac{\Delta V}{\Delta t} \tag{122}$$

where ΔV = change in the volume of water in the reservoir during time step Δt. The variation of storage is then used to determine the water level of the reservoir at the dam, H_{res}, using a capacity table. The capacity table is a look-up table that is generated incrementally as pictured in figure 5.2, in a similar fashion to Lewis (1996).

Figure 5.2 Delineation of volumes to build the capacity table used to determine H_{res}.



The reservoir is divided in successive horizontal bands, each band defined by the thalweg of the cross section immediately upstream. Each band corresponds to a volume and a water elevation at the dam. For example, the volume of the first band is $V_{7 \to 8}$ (see top of figure 5.2) and is given by the volume of the frustrum[†] of the cone:

[†]The frustrum is the part of a solid cone or pyramid next to the base that is formed by cutting off the top by a plane parallel to the base.

$$V_{7 \to 8} = \frac{1}{3}\Delta x(A_7 + A_8 + \sqrt{A_7 A_8}) \tag{123}$$

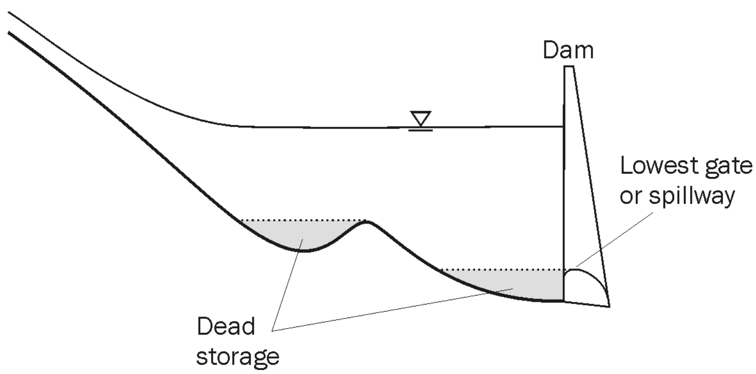
where Δx = distance between cross section 7 and 8; A_7 and A_8 = area of cross sections 7 and 8, respectively, when the water level is equal to the thalweg of section 7. The volume of the fourth band (pictured in the bottom of figure 5.2) is given by $V_{7 \to 8} + V_{6 \to 7} + V_{5 \to 6} + V_{4 \to 5}$. Each volume is calculated from

$$V_{i \to j} = \frac{1}{3}\Delta x_{ij}(A_i + A_j + \sqrt{A_i A_j}) \tag{124}$$

where $V_{i \to j}$ = volume between cross sections i and j; Δx_{ij} = distance between cross sections i and j; and A_i = area of cross section i when the water surface elevation is equal to the thalweg of cross section 4.

When repeated for every station in the reservoir, this procedure defines a capacity table at the elevations of the thalweg of each cross section. In GSTARS3, the value $H_{res} = f(V_{res})$ is computed from that table by interpolation. Dead storage volumes are not included in the table (see figure 5.3).

Figure 5.3 Definition of dead storage regions. GSTARS3 does not include these regions in the capacity table used in level-pool computations.



5.2 Sediment Transport

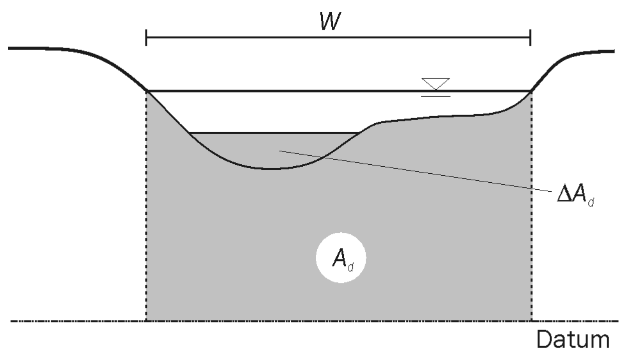
Two new sediment transport equations have been implemented in GSTARS3: the Tsinghua University equation (IRTCES, 1985) and the equation by Ashida and Michiue (1972). These equations have been discussed in section 3.5. Both functions have been tested and used specifically for reservoir sedimentation problems. Other equations that have been developed using river data but that have been applied to reservoir engineering with various degrees of success are the Ackers and White (1973) and the Yang's (1973, 1979, and 1984) equations, among others. Due to the diversity of problems encountered in practice, it is not possible to recommend any specific method as being the best and the most general. As with any other types of problems in sedimentation engineering, it is the responsibility of the user to verify and validate the methods chosen for the particular type of problem at hand.

The default technique used to compute bed changes has been described in section 3.3. It consists in computing the bed elevation change ΔZ and applying it uniformly to all the cross-sectional nodes in the wetted perimeter, resulting in a bed change that resembles that in figure 3.3. However, in cases where deposition dominates and the rates of bed change are slow (i.e., slow deposition), such as in many lakes and reservoirs, deposits are formed by filling the lowest part of the channel first, producing flat cross section profiles, as pictured in figure 5.4. In GSTARS3 the process is called "reservoir deposition". In this case, the cross-sectional area change, ΔA_d, is computed from ΔZ — which is computed from eq. (40) — using

$$\Delta A_d = W \Delta Z \tag{125}$$

where W is the cross section top width in the case of one stream tube, or the stream tube top width in the case of computations using multiple stream tubes.

Figure 5.4 Reservoir deposition for a cross section. Compare to figure 3.3.



CHAPTER

6

DATA REQUIREMENTS

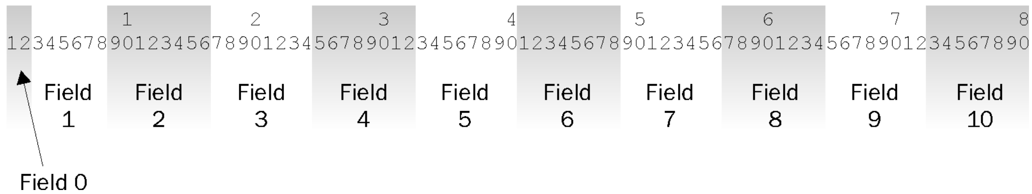
Application of the GSTARS3 computer model requires the use of appropriate data. From a conceptual point of view, GSTARS3 provides the governing equations and their solution, and the user's data provides geometric and hydrologic boundary information. Together, data *and* computer program are what is called a *model*, in the sense that they represent an approximation to a concrete and very specific physical reality. The degree of approximation depends both on the physical and numerical representation implemented in the computer program, and on the accuracy and completeness of the data.

The data requirements of GSTARS3 are described in this chapter. The data has to be processed into ASCII data files that the computer program can understand. A plain ASCII text editor should be used to type in the data in a specific format (as it was done for earlier version of the GSTARS programs). In this chapter it is shown how to set-up that data in an ASCII file that can be used to run the model from a DOS command line window. The reader should go over this chapter carefully before using the GSTARS3 computer program.

6.1 Input Data Format

In GSTARS3 the data is organized in the same way as it was in previous versions of the GSTARS models. Data is tabulated in ASCII files. The file is organized in sequential records. A record is a line of up to 80 characters in length that is divided into fields of fixed width (see figure 6.1). Fields are numbered from left to right, starting in the left-most character. Field 0 is 2 characters long and is used to specify the record name (all record names are 2 characters long). Fields 1 to 10 are used to input data to GSTARS3. Field 1 is 6 characters long; fields 2 to 10 are 8 characters long.

Figure 6.1 Organization of a data record into different fields.



Each record name is unique and is used to input specific data to the program. A comprehensive list of all the records used by GSTARS3 is given in appendix A. Not all records are used (for example, some are mutually exclusive) but they have to be in an appropriate sequence. That sequence is presented in appendix A. The example input files included in the distribution of GSTARS3 should also be studied for that effect. The data requirements presented in this chapter follow the order that should be used when preparing data input for GSTARS3.

6.2 Hydraulic Data

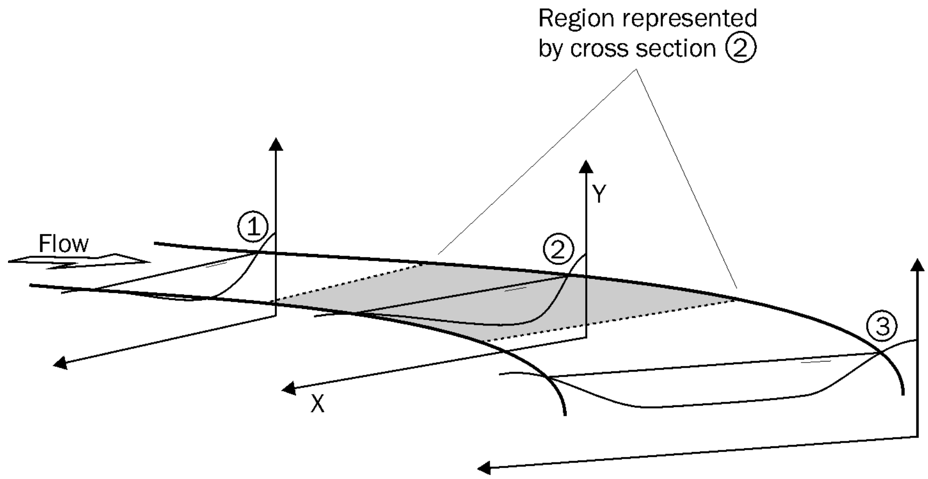
As described in the preceding chapters, GSTARS3 decouples the hydraulics from the sediment routing computations. As a result, the program can be considered as composed by two modules: the first module performs the backwater computations, the second module performs the sediment routing. This modularity is reflected in the way the input data file is designed. The GSTARS3 input file can be divided in four parts: the hydraulics data, the sediment data, the printout control, and the stream power minimization data. The hydraulic and printout parts are always required. The other two parts are optional. The stream power minimization data can only be present if the sediment data is included.

In this section, the hydraulics data requirements are presented. Channel geometry data requirements are presented first, which include cross section geometry, channel roughness, and loss coefficients. Hydrologic data, i.e., water discharges and stages, are presented next.

6.2.1 Channel Geometry, Roughness, and Loss Coefficient Data

The first step to model a river system using GSTARS3 involves the approximation of the channel's bed and banks in a semi-two-dimensional manner. The river reach to be modeled must be described by a finite number of discretized cross sections. Cross section geometry is described by X-Y coordinate pairs, i.e., by coordinate pairs with lateral location and bed elevation. Bed elevations (Y) must be taken using a common datum for the entire reach and must always be positive. Lateral locations (X) must be given using a reference point for each cross section, and the coordinate pairs must be entered in order of increasing X coordinate, i.e., starting from the left-hand side of the cross section and marching towards the right-hand side (looking downstream), as pictured in figure 6.2.

Figure 6.2 Schematic representation of the discretization of a reach by three cross sections.

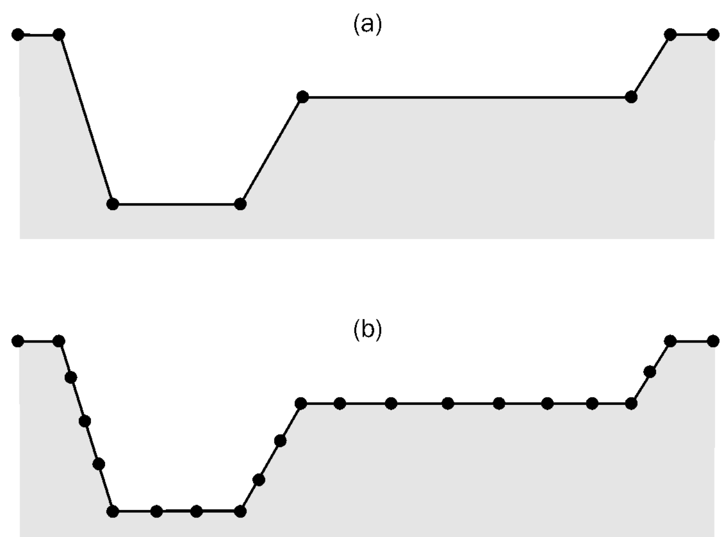


Each cross section, or station, is identified by a value that represents a distance from a reference point located downstream. The distance between stations, which must be a horizontal distance measured along a streamline, is computed by GSTARS3 as the difference between cross section identification numbers. Stations are entered sequentially, starting from the upstream-most cross section and proceeding downstream.

The number and positions of the cross sections are arbitrary. However, it is recommended that they be chosen to best represent the geometry of the study channel reach. Accurate data of channel cross section is essential to ensure that the model works properly. In GSTARS3, each cross section represents a portion of the channel upstream and downstream from its actual location, as shown in figure 6.2. Therefore, the location of each cross section should be chosen to best reflect that approximation. More cross sections are required where there are significant changes in channel geometry and/or hydraulic characteristics. A larger number of cross sections will approximate the channel reach geometry with more accuracy than a smaller number will. Ideally, the user should use as many cross sections as practicable. In the case where too few measured cross sections are available, they may have to be interpolated, especially at abrupt transitions. Some guidelines to choose the cross section locations are given in section 2.3.1.

As mentioned previously, each cross section is discretized by a set of points defined by the bed elevation and cross-section location. The cross sections should be perpendicular to the direction of the flow and extend all the way from margin to margin of the river, that is, they should extend completely across the channel between high ground of both banks. Although two points are enough to define a region of the cross section with constant side slope, the algorithms implemented in GSTARS3 will work better if more points are given. This is illustrated in figure 6.3, in which a section discretized by a minimal set of points is shown together with a "better" discretization of the same cross-sectional geometry. The higher density of points in discretization (b) allows for the points to be closer to stream tube boundaries. In the course of calculations of the positions of stream tube boundaries, a high density of points will ensure that the boundaries remain near discretization points. This allows GSTARS3 to handle the morphological changes better when variations of deposition and/or scour along the wetted perimeter are expected. However, it is much less important for the case of a single stream tube. Users should experiment with adding points to the discretized cross sections until the results become independent of the discretization. Note that too many points also add a significant computational overhead and may stretch the run times considerably.

Figure 6.3 Example of a cross section. (a) minimum shape-preserving discretization for the cross section; (b) same cross section discretized with additional points.



The GSTARS3 computer program uses dynamic memory allocation. That means that the computer memory necessary to carry out a given simulation is a function of the data available for the run in question. This allows for runs with smaller data sets to run on less advanced computers, while very large data sets may require computers with larger memory devices. The data specified using the record NS is used in memory allocation computations. In particular, the parameter *NPTS* is used to define data placeholders for the cross section coordinate points. Parameter *NPTS* should be as small as possible, yet it should be large enough to contain the cross section with the largest number of coordinate points. Furthermore, the number of cross section points may change during a GSTARS3 run. If that happens, make sure that the parameter *NPTS* is large enough to allow for points to be added to the cross section. See appendix A for more detailed information on how the NS record is used in GSTARS3 data files.

Each cross section can be divided into several regions, or channel divisions, of constant roughness. For example, a compound channel with two flood plains might have three divisions, corresponding to the left flood plain, the main channel, and the right flood plain. Each one of these channel divisions would have its own value of the roughness coefficient. In GSTARS3, up to nine channel divisions may be defined, therefore up to nine different roughness coefficient values may be entered for each cross section. Manning, Chézy, or Darcy-Weisbach equations can be selected, with corresponding roughness coefficients are entered from left to right across the section. The total conveyance for each cross section, K_T, is computed as the sum of the conveyance for each subsection of constant roughness. For example, using the Manning's roughness n we have

$$K_T = \sum_{j=1}^{N} \frac{1.49 A_j R_j^{2/3}}{n_j} = \sum_{j=1}^{N} K_j \tag{126}$$

where the subscript j refers to each individual subsection of the wetted perimeter with a given Manning's n_j, and N is the number of those segments (to a maximum of 9).

The organization of a cross section in data records is shown in figure 6.4. Each cross section is defined by a set of four records: ST, ND, XS (more than one XS record may be used), and RH. Records ST, ND, XS, and RH should be provided in that order for each measured cross section along the study reach. A detailed description of each of these records is given in appendix A.

Figure 6.4 Organization of cross section data in records.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

ST133100      39       0       0       0       0     0.0
ND     3   199.0   319.0  1209.0
XS4468.0   111.0  4465.5   128.0  4463.7   164.0  4462.8   183.0  4464.1   199.0
XS4464.0   205.0  4454.8   220.0  4452.1   227.0  4450.4   240.0  4451.0   260.0
XS4450.8   276.0  4450.2   285.0  4461.8   302.0  4463.0   310.0  4463.5   319.0
XS4463.7   374.0  4463.5   451.0  4463.4   516.0  4463.4   587.0  4463.4   654.0
XS4463.2   710.0  4461.9   752.0  4461.6   808.0  4461.7   860.0  4461.7   901.0
XS4460.5   929.0  4462.2   970.0  4463.0  1013.0  4461.5  1031.0  4461.2  1072.0
XS4460.0  1116.0  4462.1  1138.0  4461.5  1147.0  4458.7  1170.0  4462.0  1184.0
XS4461.5  1189.0  4463.9  1197.0  4467.8  1206.0  4467.9  1209.0
RH 0.080   0.024   0.080
```

Record ST contains specific information about the corresponding cross section. It contains the location and number of points needed to define each cross section. The ST record is also used to specify whether the cross section is a control section and may contain factors which are used to adjust both the elevation and offset of each section, where necessary. The last field on the ST record contains the local energy loss coefficient. The local energy loss coefficients account for the hydraulic impacts of bends, natural and man-made structures, etc., at or upstream from the cross section. The default value for the local energy loss is zero. Internally, GSTARS3 sets an additional coefficient of loss to 0.1 for contractions and to 0.3 for expansions.

Record ND is used to define the number of channel divisions at a given cross section and their corresponding lateral locations. Record XS is used to enter the channel geometry of a given station using *x*-*y* (or *y*-*x*) coordinate pairs. The RH record defines the roughness coefficient of each channel division identified on the preceding ND record of the cross section.

GSTARS3 can use the Manning, Darcy-Weisbach, or Chézy equations for energy slope and conveyance computations. The desired equation must be selected using one RE record, which must be present after the channel geometry data. If the RE record is not included in the data set, the program will default to Manning's equation. The RE record is also used to specify the equation employed to compute the local friction slope.

6.2.2 Discharge and Stage Data

The hydraulic data necessary for a numerical simulation are water stages and corresponding surface elevation at certain points (boundary conditions). In GSTARS3, the inflow discharge hydrograph entering the study reach, i.e., at the station farthest upstream, must be given for the period of the analysis. As with any steady state model, the hydrograph must be approximated by bursts of constant discharge and finite duration.

For subcritical open channel flow, the water stage hydrograph must be given for the station farthest downstream. In GSTARS3, the exception is for reservoir operations, where the discharge rather than the stage is prescribed at the dam. As described in section 5.1, the discharge information is used to determine the water stage at the reservoir. In all other cases, the stage for the downstream-most cross section must be given. A supercritical downstream boundary condition should not be used.

Discharge hydrographs are given in tables with the discretized values in multiples of a fixed time increment, i.e., of the time step. Corresponding water surface elevations are given either in tabular format or as stage-discharge rating curves. The type of input for the water discharges is chosen by defining the value of *IOPTQ* in record QQ, and the type of input for the corresponding stages is chosen by defining the value of *IOPTSTQ* in record SS. The possible options are summarized in table 6.1. The data is then entered using records IT, QQ, SS, DD, SQ, TL, TQ, RC, NC, DR, HR, and RQ. Depending on the option chosen, some of these records may be omitted. Detailed descriptions of these records are given in appendix A.

Table 6.1 Records required for each combination of QQ and SS record selections. The numbers in parentheses correspond to the sections where each case is described.

REQUIRED RECORDS	QQ	
SS	TABLE OF DISCHARGES	DISCRETIZED DISCHARGES
RATING CURVE	NC, RC, TQ (Sec. 6.2.2.2)	NC, RC, DD (Sec. 6.2.2.1)
STAGE DISCHARGE TABLE	TL, SQ (Sec. 6.2.2.3)	
DISCHARGE AT DAM	DR, HR (Sec. 6.2.2.4)	DD, RQ, HR (Sec. 6.2.2.5)

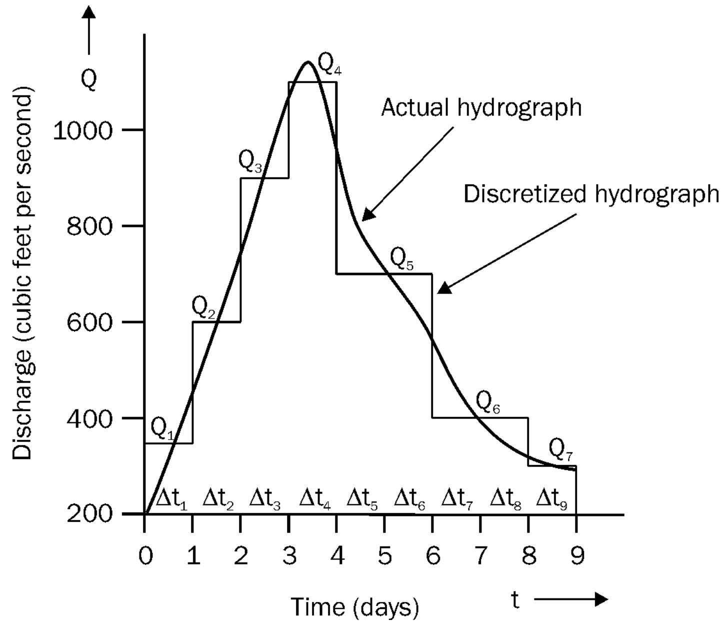
6.2.2.1 Discharge Hydrograph with a Stage-Discharge Rating Curve

In this case, the water discharges for the reach are given in the form of a hydrograph, and the corresponding water stages are given as a rating curve, i.e., as a function of the discharge. This option is selected by using the RATING CURVE option in record SS and the DISCRETIZED DISCHARGES option in record QQ. The discretized hydrograph is entered using DD records, and the water stage is defined by a rating curve using records NC and RC.

The discretization of the hydrograph is a process that transforms a continuous curve into discrete numerical values with a certain discharge and time duration. The continuous curve is then replaced by a stair-stepping curve with constant discharge bursts with a duration that, in GSTARS3, must be a whole multiple of the time step, Δt. The process is briefly illustrated in figure 6.5. First, a time interval must be chosen for the time step, Δt. It must be small enough so that all the important features of the hydrograph may be preserved without significant distortion. Using Δt, the hydrograph is broken into intervals of constant discharge. The duration of each of these intervals is expressed as whole multiples of Δt.

As an example of this procedure, a hypothetical hydrograph is given as a continuous, smooth line in figure 6.5. A time step Δt = 1 day is chosen to discretize the hydrograph. The hydrograph is then replaced by the stair-stepping curve representing the following discharge bursts: one time step of Q_1, one time step of Q_2, one time step of Q_3, one time step of Q_4, two time steps of Q_5, two time steps of Q_6, and one time step of Q_7 discharges. A total of 7 discharges are used, but 9 time steps must be carried out by the simulation. These values will be entered in DD records, as shown below. Note that a smaller time step could have been used. This would have resulted in a more accurate representation of the hydrograph, but more time steps would have to be computed by the program, resulting in longer computational times.

Figure 6.5 Discretization of input discharge hydrograph. Note that $\Delta t_1 = \Delta t_2 = \ldots = \Delta t_9 = \Delta t = 1$ day in this example.



Usually, the discretization process involves a compromise between accuracy and computational burden, depending also on the availability of data and on the user's experience. Nevertheless, the discretized hydrograph is required to preserve total water and sediment volumes. Furthermore, it is also necessary to preserve the shape and peak discharge of the event. A compromise must be reached to obtain the optimum duration of the bursts (time step Δt) without requiring an unnecessarily large number of time steps. It is recommended that the duration of the time step should be at least long enough to allow the flow to travel across the largest interval between any two adjacent cross sections. However, in most cases, simulations suffer from using time steps that are too large, i.e., the solutions may be unstable and/ or inaccurate.

In this option, the water stage at selected locations must be given as a rating curve, i.e., as a functional expression of the discharge. In GSTARS3, the relationship between stage and discharge is assumed to be in the form

$$\text{Stage (ft)} = C_1 \times Q^{C_2} + C_3 \qquad (127)$$

where Q is given in ft^3/s. The values of the constants C_1, C_2, and C_3 are coefficients supplied by the user on the RC record. For example, in the case above a stage-discharge rating curve could be defined at station 23 of the reach. If this relationship is defined as

$$\text{Stage} = 0.41 Q^{0.25} + 1000 \qquad (128)$$

then the input data records would be as follows:

```
         1         2         3         4
123456789012345678901234567890123456789012345

IT    9.       1.       1.
QQ       DISCRETIZED DISCHARGES
SS       RATING CURVE
DD     1     350.
DD     1     600.
DD     1     900.
DD     1    1100.
DD     2     700.
DD     2     400.
DD     1     300.
NC     1
RC    23     0.41    0.25     1000.
```

Note that the sum of all the time steps defined in the first column of the DD records (*NDAYS* in field 1 of DD records) must be equal to the total number of time steps for the run (*ITIMAX* in field 1 of the IT record), which, in this case, is 9 time steps for 9 days.

6.2.2.2 Table of Discharges with a Rating Curve at The Control Section

This type of input is a particular form of the input described above. It may be useful when discharges are known from periodic records, at fixed time intervals, in the form of a table. This option is selected by using the RATING CURVE option in record SS and the TABLE OF DISCHARGES option in record QQ. The table is entered using TQ records, and the water stage is defined by a rating curve using records NC and RC.

As an example, consider the following table of daily discharges which could have been obtained from a gaging station at the upstream end of the study reach:

Days	Discharge (ft^3/s)
0	200
1	450
2	700
3	1,020
4	1,000
5	700
6	525
7	400
8	325

With the same stage-discharge rating curve in the example of the previous section, the input data records would be:

```
         1         2         3         4         5         6         7
1234567890123456789012345678901234567890123456789012345678901234567890123

IT    9.      1.      1.
QQ      TABLE OF DISCHARGES
SS      RATING CURVE
TQ  200.    450.    700.   1020.   1000.    700.    525.    400.    325.
NC     1
RC    23    0.41   0.25    1000.
```

Additional TQ records may be supplied for longer simulations.

6.2.2.3 Stage-Discharge Table at a Control Section

In this case, the information for the control station is given in a table with discharges and corresponding water stages. This option is selected by using the STAGE DISCHARGE TABLE option in record SS and the TABLE OF DISCHARGES option in record QQ. The table is entered using TL and SQ records. As an example, consider the information given in the table below, which could have been obtained from a gaging station at the control section located at section 35:

Days	Discharge (ft^3/s)	Stage	Days	Discharge (ft^3/s)	Stage
0	200	1002.6	5	700	1003.3
1	450	1003.1	6	525	1003.2
2	700	1003.3	7	400	1003.0
3	1,020	1003.6	8	325	1002.9
4	1,000	1003.6			

For daily time steps, the input data records for this example would be:

```
         1         2         3         4
123456789012345678901234567890123456789012345

IT    9.      1.      1.
QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE
TL    35
SQ  200.  1002.6
SQ  450.  1003.1
SQ  700.  1003.3
SQ 1020.  1003.6
SQ 1000.  1003.6
SQ  700.  1003.3
SQ  525.  1003.2
SQ  400.  1003.0
SQ  325.  1002.9
```

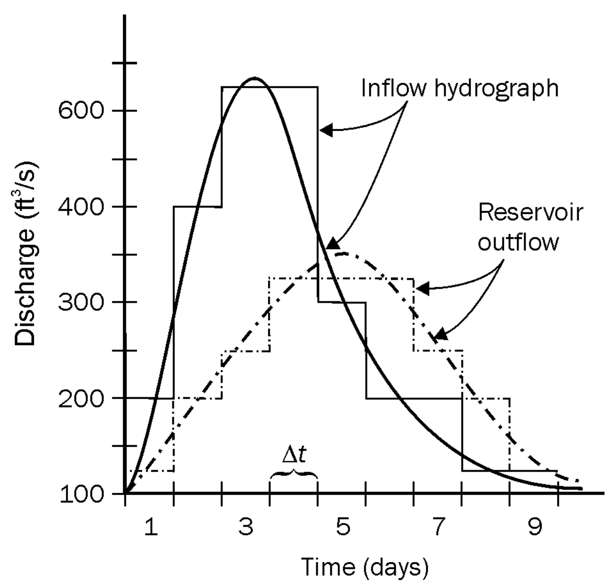
6.2.2.4 Reservoir Routing with Table of Discharges

Usually, in reservoir routing the outflow through the dam differs from the river inflow to the reservoir. In this case, the discharge at the dam is given, from which level-pool routing is used to compute the stage there. Backwater computations can thus proceed upstream, starting at the dam. The dam is always located at the last cross section, i.e., at the downstream-most cross section of the reach.

To illustrate the use of reservoir routing calculations in GSTARS3 using one table of discharges, consider the hydrographs in figure 6.6. The river discharge (inflow to the reservoir) is given as a solid line, and the outflow through the dam is given in a dotted line. A uniform time step Δt = 1 day is used. A possible discretization of the hydrographs, also shown in the same figure, is the following:

Days	Inflow Discharge	Outflow Discharge
1	200	25
2	400	200
3	625	250
4	625	325
5	300	325
6	200	325
7	200	250
8	25	200
9	25	25

Figure 6.6 Idealized inflow and outflow hydrographs for reservoir routing calculations, with the corresponding discretized stepped hydrographs.



Then, using HR and DR records, the input data would have the following format:

```
         1         2         3         4
123456789012345678901234567890123456789012345

IT      9       1.        1.
QQ       TABLE OF DISCHARGES
SS       DISCHARGE AT DAM
HR      5    1350.     1300.     1400.
DR      1     200.       25.
DR      1     400.      200.
DR      1     625.      250.
DR      1     625.      325.
DR      1     300.      325.
DR      1     200.      325.
DR      1     200.      250.
DR      1      25.      200.
DR      1      25.       25.
```

The HR record is used to define the water elevation at the reservoir and to specify how often level-pool routing computations are to be performed. In the example above, a new reservoir capacity table is computed every 5th computation time step. The HR record is also used to define the minimum and the maximum water surface elevations at the dam. See appendix A for more information on HR and DR records. HR and DR records should be used when the TABLE OF DISCHARGES option is used in record QQ and the DISCHARGE AT DAM is used in the SS record.

6.2.2.5 Reservoir Routing with Discretized Discharges

This option allows the input of the inflow and outflow discharges using two diferent tables (instead of one, as in the previous section). This option is activated by selecting the DISCRETIZED DISCHARGES option in record QQ and DISCHARGE AT DAM in record SS. Using the same data as in section 6.2.2.4, the formatted input data would look like this:

```
         1         2         3         4
123456789012345678901234567890123456789012345

IT      9       1.        1.
QQ       DISCRETIZED DISCHARGES
SS       DISCHARGE AT DAM
HR      5    1350.     1300.     1400.
DD      1     200.
DD      1     400.
DD      2     625.
DD      1     300.
DD      2     200.
DD      2      25.
RQ      1      25.
RQ      1     200.
RQ      1     250.
RQ      3     325.
RQ      1     250.
RQ      1     200.
RQ      1      25.
```

Records DD are used to specify the inflow hydrograph, while records RQ are used to specify the discharge at the dam. Note that the *NDAY* values in the DD and RQ records should add up to 9, i.e., to the total number of time steps specified in record IT.

6.3 Sediment Data

The information presented in the last section is enough to have GSTARS3 performing backwater computations in a channel with fixed bed. If, however, sediment routing is required, sediment data must be given to the model. Sediment data includes bed material size distributions for the reach of study and the sediment inflow hydrograph entering the reach, including its particle size distribution. The input data requirements (and corresponding records) for sediment routing computations are presented in this section.

The sediment transport computations are activated by inclusion of the SE record in the input data file. The SE record is used to select the equation for computing sediment transport capacities. In GSTARS3, sediment transport capacities can be determined by any of the methods in table 6.2. Desired sediment transport equations can be selected by the variable *ISED* in the SE record. These methods were chosen because of their accuracy and associated short computational times. Many of the sediment transport equations available for routing computations are applicable only to sand sizes (0.0625 to 2.0 mm). The Yang gravel equation is recommended for sediments up to 10 mm gravel, although successful applications to coarser materials can be found in the literature. The Meyer-Peter and Müller or Parker methods are often used by engineers for materials coarser than 10 mm. The methods by Krone (1962) and Ariathurai and Krone (1976) are used to compute cohesive sediment (clay and silt) transport. When clay and/or silt size fractions are present, GSTARS3 automatically activates the cohesive sediment transport methods for those fractions, while still using one of the above methods for size fractions larger than 62.5 μm. The only exception is the Tsinghua University's equation which, when chosen, is used for all size classes present in the river (or reservoir) bed.

Table 6.2 Sediment transport methods for non-cohesive sediments available in GSTARS3 and corresponding values of the *ISED* variable in record SE.

ISED	Method	*ISED*	Method
1	Meyer-Peter and Müller (1948)	9	Yang et al. (1996)
2	Laursen (1958)	10	Revised Ackers and White
3	Toffaleti (1969)		(HR Wallingford, 1990)
4	Engelund and Hansen (1972)	11	DuBuois (1879)
5	Ackers and White (1973)	12	Modified Laursen (Madden,
6	Yang (1973) + Yang (1984)		1993)
7	Yang (1979) + Yang (1984)	13	Ashida and Michiue (1972)
8	Parker (1990)	14	Tsinghua Univ. (IRTCES, 1985)

In GSTARS3 it is possible to use a particular sediment transport equation for a broad range of sediment particle sizes. In particular, it is possible to avoid using the Krone/Ariathurai methods for silt and clay sizes. By default, the Krone/Ariathurai methods are automatically used for sediment particle sizes smaller than 62.5 μm. When the Krone/Ariathurai methods are not used (section 6.3.4 explains how to deactivate them when silt and clay particle sizes are present in the input data), the transport of all the sediment size fractions is accomplished using the traditional sediment capacity concept, that is, the sediment transport capacity equations of section 3.5 are used for the finer size fractions. However, due to algebraic limitations, not all equations can be used for the very small particle sizes. Table 6.3 shows the limits of applicability (as far as sediment particle size is concerned) accepted in GSTARS3 for each of the sediment transport equations. Sediment particles with sizes falling outside of the specified ranges will be imovable, i.e., the sediment transport capacity for those fractions is zero. Note that only the Tsinghua University's equation will compute sediment transport capacity for all size fractions, irrespective of particle size.

Table 6.3 Limits of applicability of the sediment transport equations present in GSTARS3. These limits are valid only when the Krone/Ariathurai methods for cohesive sediment transport are deactivated.

ISED	Method	Finest limit	Coarsest limit (mm)
1	Meyer-Peter and Müller	Sand (62.5 μm)	1,000
2	Laursen	Clay	100
3	Toffaleti	Sand (62.5 μm)	10
4	Engelund and Hansen	Clay	10
5	Ackers and White	Clay	100
6	Yang 1973 + 1984	Clay	100
7	Yang 1979 + 1984	Clay	100
8	Parker	Sand (62.5 μm)	1,000
9	Yang 1996	Clay	100
10	Revised Ackers and White	Clay	100
11	DuBoys	Clay	1,000
12	Laursen-Madden	Clay	100
13	Ashida and Michiue	Clay	100
14	Tsinghua University	All size classes	

The selection of the appropriate sediment transport function remains an unsolved problem. Differences in the assumptions used to derive the equations, study of published data, and practical reasoning and experience are factors that can help in this process. There are tremendous uncertainties involved in estimating sediment discharge under different flow and sediment conditions and under different hydrologic, geologic, and climatic constraints. It is very difficult to recommend a particular equation or method to be used under all circumstances. The following guidelines are based on those given by Yang (1996) and were adapted for inclusion in the present manual:

1 Use as much field and measured data as possible, within the time, budget, and manpower limits of each particular study.
2 Examine as many formulae as possible, based on assumptions used in their derivation and range of data used to determine its coefficients, and select those consistent with the data and measurements obtained in step 1.
3 If more than one formula survived step 2, compute sediment transport rates with these formulae and select those that best agree with any field measurements taken in step 1.
4 In the absence of measured sediment loads for comparison, the following guidelines could be considered:
    - Use Meyer-Peter and Müller's formula when the bed material is coarser than 5 mm.
    - Use Toffaleti's formula for large sand-bed rivers.
    - Use Yang's (1973) formula for sand transport in laboratory flumes and natural rivers; use Yang's (1979) formula for sand transport when the critical unit stream power at incipient motion can be neglected.
    - Use Parker's (1990) or Yang's (1984) gravel formulae for bed load or gravel transport;
    - Use Yang's (1996) modified formula for high-concentration flows when the wash load or concentration of fine material is high.
    - Use Ackers and White's or Engelund and Hansen's formulae for subcritical flow condition in the lower flow regime.
    - Use Laursen's formula for laboratory flumes and shallow rivers with fine sand or coarse silt.

GSTARS3 users may also consider using Yang and Huang’s (2001) analyses, included in appendix D, as a reference in the selection of sediment transport formulae.

6.3.1 Sediment Inflow Data

The inflow sediment hydrograph must be given for the section farthest upstream from the study reach. In GSTARS3, this can be given in the form of either discretized sediment discharges on QS records or a sediment rating curve using record QR. It can also be indirectly obtained by using an equilibrium condition at the upstream-most station, in which sediment inflow is set to the sediment transport capacity of the cross section. In the first case, the sediment rating curve has to be discretized following a procedure similar to that described in section 6.2.2.1 for the water discharge hydrograph. The data is entered using QS records, which follow the same format as the DD records described above.

Alternatively, a sediment rating curve, if known, may be given using a QR record. This record allows the user to specify a sediment discharge that is a function of the water discharge in the form

$$Q_s = aQ^b \qquad (129)$$

where Q_s = incoming sediment discharge (in ton/day); Q = water discharge (ft^3/s); and a and b are coefficients to be supplied in the QR record (a, $b > 0$). For example, if it is known that the incoming sediment discharge is a function of the water discharge such that

$$Q_s = 0.4Q^{1.2} \qquad (130)$$

the input QR record would take the following format:

```
         1         2         3         4
123456789012345678901234567890123456789012345

QR   0.4      1.2
```

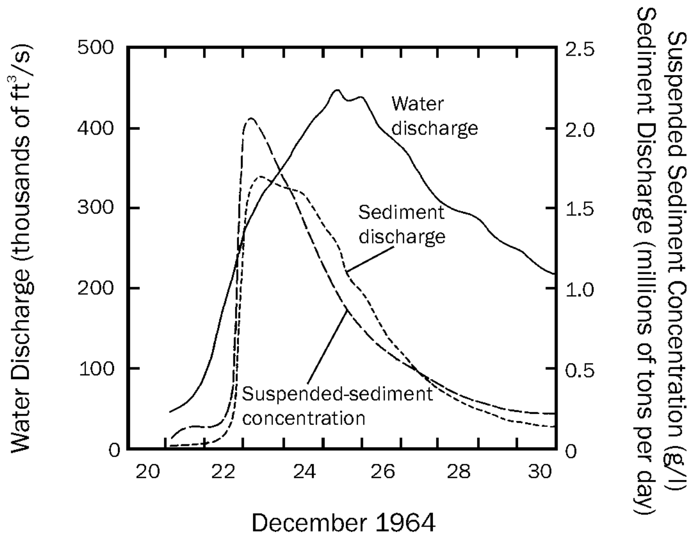
An alternative way to specify the sediment inflow and its distribution is to use an equilibrium first station. In this case, the definition of equilibrium is that the cross section geometry and bed gradation distribution do not change during the simulation run. The inflow sediment transport rate and its distribution can thus be calculated directly from the sediment transport equation selected in the SE record. In GSTARS3, this method can only be applied in the cases that do not involve cohesive sediment transport, because the transport of this type of sediments is not governed by transport capacity concepts. Recor QR is used to specify equilibrium sediment input in the following manner:

```
         1         2         3         4
123456789012345678901234567890123456789012345

QR       EQUILIBRIUM
```

Caution should be exercised when using a relationship similar to eq. (129). In most practical cases, eq. (129) represents only an approximation, and often a very poor one. Figure 6.7 shows an example of water and sediment discharge curves measured at the same location and at the same time. In this example, the peak of the water discharge rating curve lags the peak of the sediment discharge rating curve by over two days. During that time, the trends of the two hydrographs are opposite (increasing water discharge and decreasing sediment load). Sometimes, it is the sediment rating curve that lags the water discharge rating curve. This well known phenomenon is explained in many textbooks on the subject. However, GSTARS3 provides the facility to use eq. (129) for those cases in which its use may be warranted.

Figure 6.7 Suspended sediment concentration, sediment discharge, and water discharge, Willamette River at Portland, Oregon, December 21-30, 1964. (After Waananen et al., 1971.)



By default, the size gradation distribution of the incoming sediment is set equal to the gradation given for the cross section farthest upstream (the input of sediment gradation curves is discussed in section 6.3.3). However, the user may specify different gradation distributions using IQ and IS records. The gradations must be known as a function of the water discharge, and their input must be given in tabular format. For example, consider the following hypothetical size gradation curves, each one defined for a given discharge:

Size fraction no.	Q = 1,000 ft^3/s	Q = 5,000 ft^3/s	Q = 12,000 ft^3/s
1 (fine sand)	50%	60%	60%
2 (medium sand)	50	30	25
3 (coarse sand)	0	10	15

Using IQ and IS records, that information would be specified in the following way:

```
          1         2         3         4
123456789012345678901234567890123456789012345

IQ      3     1000      5000     12000
IS fsand      0.50      0.60      0.60
IS msand      0.50      0.30      0.25
IS csand      0.00      0.10      0.15
```

GSTARS3 interpolates the gradations for water discharges falling in between the specified discharges, but does not extrapolate for water discharges outside that range (e.g., if the discharge is 13,000 ft^3/s, the distribution specified for Q = 12,000 ft^3/s is used).

GSTARS3 solves the sediment continuity equation, eq. (26), to route sediments through a channel reach. Eq. (26) is discretized following the methods presented in section 3.3, and computations proceed from upstream to downstream. The incoming sediment discharge is specified at the first cross section of the reach (the section located at the upstream end of the reach), therefore a special treatment is necessary there. The reach length for that section is taken to be half the distance between station 1 and station 2, that is, $\Delta x_{i-1} = 0$ in eq. (39). The incoming sediment is used to represent $Q_{s,i\text{-}1}$, and the solution is the obtained in the usual way. Note that the bed composition of station 1 will, in general, change with time, therefore the distribution of the incoming sediment should be specified by the use of IQ/IS sets of records (or by using the equilibrium method described earlier for the first station). If the distribution of the incoming sediment is not specified, it is assumed that the distribution of the incoming sediment is identical to that of the bed at station 1.

Note that the last cross section also requires special treatment. For that boundary, GSTARS3 uses all the hydraulic and sediment transport quantities necessary to compute the appropriate rates of scour and deposition on a half-sized control volume. Only upstream information is used. Ideally, the first and last cross sections should be located at places where the channel changes are mild or nonexistent. These terminal sections should not be the sections of primary interest to the particular study.

6.3.2 Temperature Data

Water temperature data, necessary for kinematic viscosity and for water density computations, is given in tabulated form using TM records. The water temperature of the reach must be given for each time step of the run.

6.3.3 Sediment Gradation Data

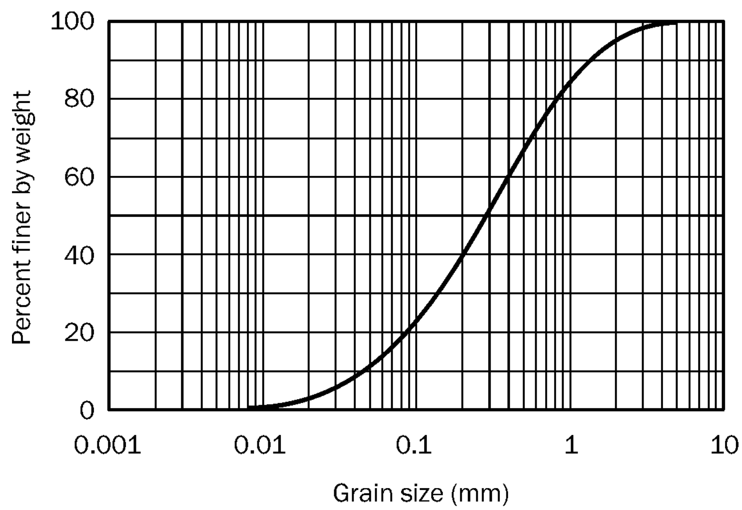
Sediment mixtures are characterized by gradation curves. A common way of depicting bed gradation distributions is by a graph that shows, for each grain size, the percentage of bed sediments with a smaller size, such as picture in figure 6.8. In GSTARS3, that information must be given for the bed composition of all the cross sections, and for the grain size distribution of the incoming sediment discharges.

First, the size classes must be defined by using SF and SG records. The SF record defines the number of size fractions (a maximum of 10 size fractions may be defined), and the SG record identifies the different sediment size groups. Each size class is defined by entering the lower and upper bound of that class in a SG record. For example, for the hypothetical size gradation curve shown in figure 6.8 (see also figure 6.9), the following set of SF/SG records could be used:

```
          1         2         3         4
123456789012345678901234567890123456789012345

SF     5
SG 0.008     0.04
SG  0.04      0.2
SG   0.2      0.6
SG   0.6      2.0
SG   2.0      5.0
```

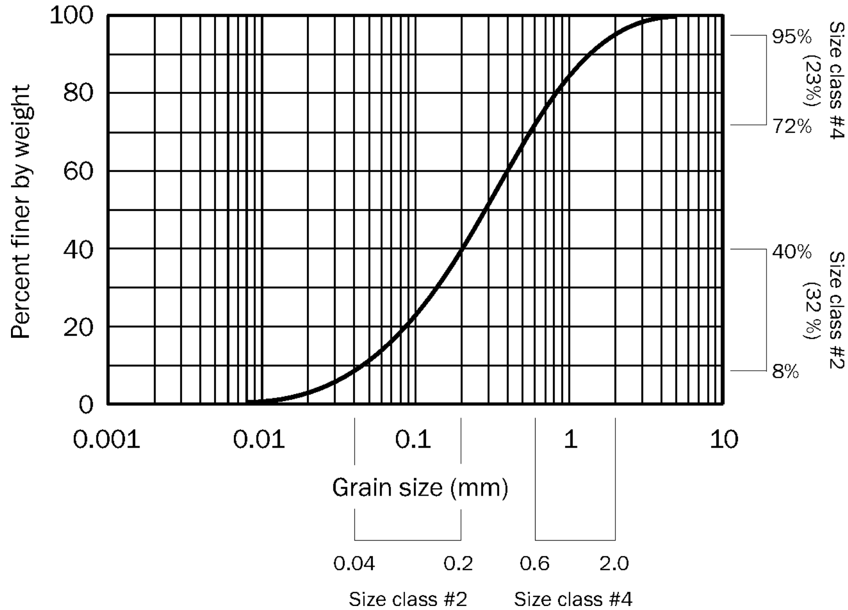
Figure 6.8 Hypothetical size gradation curve.



Note that the divisions defined in the SG records (specified in mm) are quite arbitrary. Note also that the SF and SG records can be used to specify different values for the dry specific weight, γ_m:

$$\gamma_m = \gamma G(1 - p_0) \tag{131}$$

Figure 6.9 Schematic representation on how to extract data from gradation curves for GSTARS3 input. Shown are the second and fourth size classes from a split into five size classes (see text). The gradation curve is the same of figure 6.8.



where γ = specific weight of water at 4 °C; G = specific gravity (G = 2.65 in GSTARS3); and p_0 = porosity of the sediment. GSTARS3 uses the default value of $\gamma_m = 99.2$ lb/ft^3, for a porosity of 40 percent, but that can be changed in records SF and/or SG. For example, to change the default value of γ_m to 90.0 lb/ft^3, the following records might be used:

```
          1         2         3         4
123456789012345678901234567890123456789012345

SF      5      90.0
SG 0.008       0.04
SG  0.04        0.2
SG   0.2        0.6
SG   0.6        2.0
SG   2.0        5.0
```

The SG records can also be used to selectively change γ_m for specific size fractions. For example, the following set of records would change γ_m for the specified size classes to 41.0, 50.0, and 74.0 lb/ft^3, leaving the remaining size classes to use the values defined in record SF:

```
         1         2         3         4
123456789012345678901234567890123456789012345

SF     5    90.0
SG 0.008    0.04    41.0
SG  0.04     0.2    50.0
SG   0.2     0.6    74.0
SG   0.6     2.0
SG   2.0     5.0
```

When different dry specific weights are used for different size fractions, eq. (131) is used to compute the porosity of the bed sediments. First, a composite dry specific weight for the bed, γ_m^*, is computed following Colby (1963):

$$\gamma_m^* = \frac{1}{\sum_{i=1}^{N} \frac{p_i}{\gamma_{mi}}} \tag{132}$$

where p_i = the percentage of sediments of size fraction i present in the bed ($0 \le p_i \le 1$); γ_{mi} = dry specific weight of sediments of size fraction i; and N = total number of size fractions. The porosity of the bed is then found using γ_m^* and eq. (131).

Gradation information is specified by converting the bed gradation curves into histograms containing the percentage of sediments in each interval. The process is schematized in figure 6.9. The data can be specified using either SD records, or sets of NB and BG records. These records are used to enter the bed material size fractions that fall within each of the size groups defined by SG records. Using the hypothetical gradation curve of figure 6.8, the SD records would take the form

```
         1         2         3         4
123456789012345678901234567890123456789012345

SD  0.08    0.32    0.32    0.23    0.05
```

One SD record must be specified for each cross section. SC records are similar to SD records, but they use cumulative values rather than the individual size classes. For example, the same data of the example above would be entered as

```
         1         2         3         4
123456789012345678901234567890123456789012345

SC  0.08    0.40    0.72    0.95     1.0
```

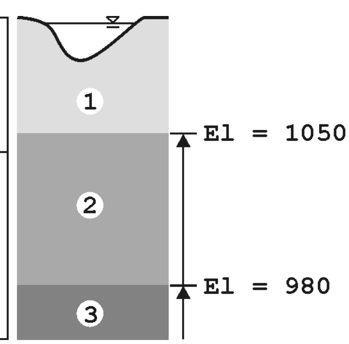
Alternatively, sets of NB and BG records can be used to specify size distributions at particular locations. These locations do not need to coincide with the defined cross-section locations. GSTARS3 will interpolate bed gradations for the defined cross sections using the information from the NB and BG records. In this case, a minimum of one NB/BG set of records must be used. By using this option, one single set of NB and BG records could be used to define a whole reach (see the record descriptions in appendix A for more detail).

It is possible to used layered beds with different particle distributions in each layer. In those cases, multiple SD records must be specified for each cross section, i.e., one SD record for each cross section and for each bed layer. Additionally, the bottom elevation of each layer must also be given. As an example, lets consider the case displayed in figure 6.10: the river bed is in layer 1, under which there is a layer of coarser material (layer 2) and finally a layer of finer material (layer 3). Using that data and SD records, the formatted data for the particular cross section of figure 6.10 would be

```
          1         2         3         4
12345678901234567890123456789012345678901234 5
NL      3
...
SD  0.08      0.32      0.32      0.23      0.05
EL          1050.0
SD   0.0      0.10      0.15      0.40      0.35
EL           980.0
SD  0.40      0.30      0.25       0.5       0.0
...
```

Figure 6.10 Example of layered river bed.

		Percent in size class (%)					Bottom elevation (ft)
		1	2	3	4	5	
Layer #	1	8	32	32	23	5	1050
	2	0	10	15	40	35	980
	3	40	30	25	5	0	-



The same information can be entered using NB/BG/EL sets of records. If the bed sample presented in figure 6.10 was collected at a river location of 13500 ft (the coordinate system used must be the same as the one used to describe the location of the discretized cross sections using records ST/ND/XS/RH), the data could be entered in the following manner:

```
          1         2         3         4
123456789012345678901234567890123456789012345

NL     3
...
NB13500.
BG  0.08     0.32     0.32     0.23     0.05
EL        1050.0
BG   0.0     0.10     0.15     0.40     0.35
EL         980.0
BG  0.40     0.30     0.25      0.5      0.0
...
```

Note that record NL specifies the number of bed layers and only appears once, before any SD or NB records. Every cross section has to have the same number of layers specified in record NL. The example above shows the data for one cross section. All other cross sections must have the data entered in the same way, starting on cross section 1 (upstream-most) and proceeding downstream in successive order. Note also that the lowest layer (last entered data) does not have a bottom elevation: the layer thickness is assumed to be infinite.

Bed layer distribution information can also be specified using records SC, or NB/BG sets of records. See appendix A for more detail about how to prepare formatted data for GSTARS3 using these records.

6.3.3.1 Remarks

The questions that remain are:

1 how to define the intervals for each size class; and

2 how many size classes are needed for each particular study.

Sediment particle size classes should be defined reflecting the well known fact that finer particles are more important in the sediment transport process than coarser particles. Therefore, it is reasonable to expect that more classes are necessary in the finer range, and fewer classes can be used in the coarser range of the distribution. This is, in effect, what is reflected in the scale used by the American Geophysical Union and presented in table 6.4. Although the nomenclature and size class definitions in the table are quite arbitrary, its theoretical background is based on physical principles and approximations that are convenient follow. Therefore, a similar process can be devised for defining size classes for use in GSTARS3. Of course that the classes defined in table 6.4 can be used in GSTARS3, but it will become clear that there are advantages in not always doing it.

The recommended procedure consists in dividing the range of particle sizes such that they have the same magnitude in the logarithmic space. The process of creating the size classes can be summarized in the following steps:

Table 6.4 Sediment grading scale (Lane, 1947).

Size range in class (mm)		Class nomenclature
4,096–2,048	$(2^{12}-2^{11})$	Very large boulders
2,048–1,024	$(2^{11}-2^{10})$	Large boulders
1,024–512	$(2^{10}-2^{9})$	Medium boulders
512–256	$(2^{9}-2^{8})$	Small boulders
256–128	$(2^{8}-2^{7})$	Large cobbles
128–64	$(2^{7}-2^{6})$	Small cobbles
64–32	$(2^{6}-2^{5})$	Very coarse gravel
32–16	$(2^{5}-2^{4})$	Coarse gravel
16–8	$(2^{4}-2^{3})$	Medium gravel
8–4	$(2^{3}-2^{2})$	Fine gravel
4–2	$(2^{2}-2^{1})$	Very fine gravel
2–1	$(2^{1}-2^{0})$	Very coarse sand
1–0.5	$(2^{0}-2^{-1})$	Coarse sand
0.5–0.25	$(2^{-1}-2^{-2})$	Medium sand
0.25–0.125	$(2^{-2}-2^{-3})$	Fine sand
0.125–0.062	$(2^{-3}-2^{-4})$	Very fine sand
0.062–0.031	$(2^{-4}-2^{-5})$	Coarse silt
0.031–0.016	$(2^{-5}-2^{-6})$	Medium silt
0.016–0.008	$(2^{-6}-2^{-7})$	Fine silt
0.008–0.004	$(2^{-7}-2^{-8})$	Very fine silt
0.004–0.002	$(2^{-8}-2^{-9})$	Coarse clay
0.002–0.001	$(2^{-9}-2^{-10})$	Medium clay
0.001–0.0005	$(2^{-10}-2^{-11})$	Fine clay
0.0005–0.00025	$(2^{-11}-2^{-12})$	Very fine clay
< 0.00025	$(< 2^{-12})$	Colloids

1. determine the upper and lower bounds of the particle size ranges to be worked with. If d_{max} and d_{min} are the greatest and the smallest particle diameters encompassing the particle range, find the values of a and b such that

$$d_{min} = 2^a \text{ and } d_{max} = 2^b$$

2. let N be the desired number of size classes for a particular application ($N \le 10$). Select the lower and upper bound diameters for each interval i in the following way:

$$d_{min,\,i} = 2^{a + (i-1)\frac{b-a}{N}}, \quad i = 1, \ldots, N \tag{133}$$

and

$$d_{max,\,i} = 2^{a + i\frac{b-a}{N}}, \quad i = 1, \ldots, N \tag{134}$$

As an example, consider the grain size distribution presented in figure 6.8. The range of particle sizes is

$$d_{min} = 0.008 \cong 2^{-6.8} \Rightarrow a = -6.8$$

and

$$d_{max} = 5.0 \cong 2^{2.3} \Rightarrow b = 2.3$$

For five size classes ($N = 5$) one gets:

i	$d_{min,i}$ (mm)	$d_{max,i}$ (mm)	$d_{mean,i}$ (mm)
1	0.008	0.031	0.016
2	0.031	0.112	0.059
3	0.112	0.395	0.210
4	0.395	1.39	0.742
5	1.39	5.0	2.64

where

$$d_{mean,\,i} = \sqrt{d_{min,\,i} \times d_{max,\,i}} \qquad (135)$$

is the mean grain size of size class *i*.

The remaining issue is then to determine what value of *N* to choose. For that purpose we carried an analysis using two sediment grading curves and two sediment transport equations, trying to answer the following question: what is the lowest value of *N* that characterizes adequately the predicted sediment in transport? In other words, there must be a value of $N = N_0$ beyond which there is no gain in further refinement of the size classes, and we wish to find what that value is.

The criterion to find the optimal N_0 is based on the characteristics of the mixture of the sediment particles in transport. For the purposes in this manual, it is enough to characterize the gradation of the transported sediments by the d_{50} and the geometric standard deviation of the mixture (σ_g), and by the amount of sediment in transport. The geometric standard deviation of the mixture is defined as

$$\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \qquad (136)$$

The amount of the sediment in transport is the quantity of sediment predicted by one of the sediment transport equations presented in section 3.5.

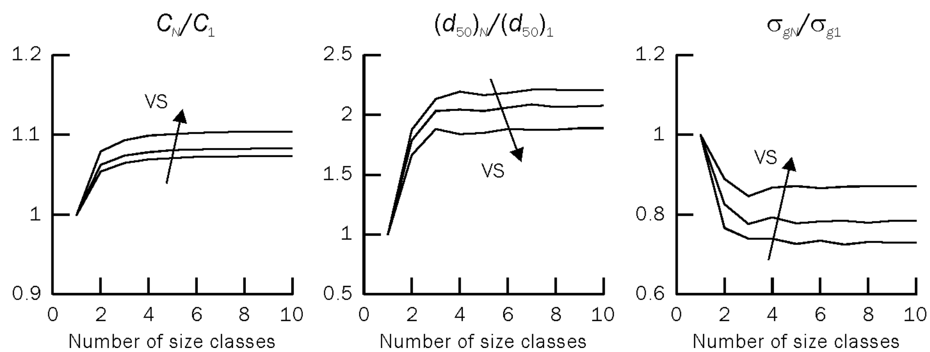
The first analysis was carried out using the Yang (1973) unit stream power equation of section 3.5.7. A bed gradation was synthesized using a log-normal distribution:

$$f(d) = \frac{1}{\sigma_z d\sqrt{2\pi}} \exp\left\{-\frac{(\ln d - \mu_z)^2}{\sigma_z^2}\right\} \quad (137)$$

where μ_z and σ_z are the mean value and the standard deviation of $z = \ln d$ (d is the grain diameter), cut at the 1% probabilities at the extremes. In this analysis, the gradation used had $\mu_z = -1.04$ and $\sigma_z = 0.7$, falling in the sand range (62.5 μm to 2.0 mm). Sediment transport capacities were computed for various values of the unit stream power and using increasing number of particle size fractions. The ranges of each size fraction were determined using the procedure described above in this section.

The results are shown in figure 6.11. They show the different quantities normalized by the value obtained with $N = 1$, i.e., by using a single class encompassing the entire gamut of particle sizes. It can be seen that the predicted quantities stabilize at values of $N = 4$ or $N = 5$. Further refinement into more size classes is not followed by a corresponding change in the predicted quantities.

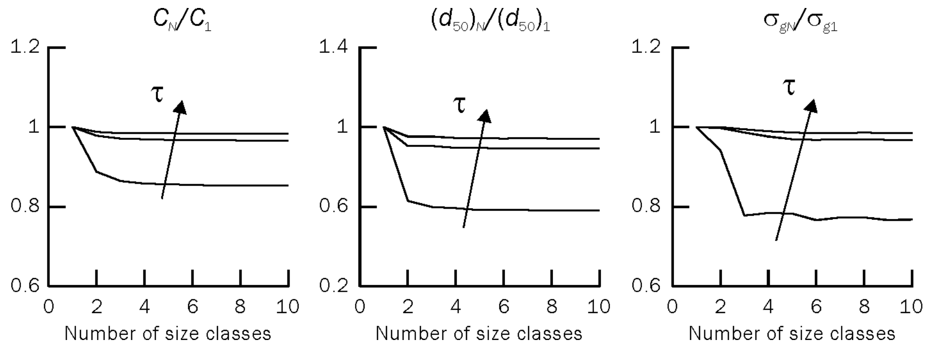
Figure 6.11 Normalized sediment concentration, mean diameter, and standard deviation of the transported sediment mixture using Yang (1973) sand transport equation. The arrows show the direction of increasing values of the unit stream power, *VS*.



This simple study was repeated using a similarly synthesized bed distribution in the range of sand and gravel (1 to 64 mm), with $\mu_z = 2.08$ and $\sigma_z = 0.7$. The Meyer-Peter and Müller (1948) equation was used. The results, shown in figure 6.12, confirm the above findings, i.e., that 4 or 5 size classes are enough to fully characterize the mixture of the sediments in transport.

Ultimately, it is up to the user to determine how many size classes (and how to define them) are needed for the particular study at hand, but the above guidelines should provide a good starting point for most applications.

Figure 6.12 Normalized sediment concentration, mean diameter, and standard deviation of the transported sediment mixture using Meyer-Peter and Müller (1948) transport equation. The arrow shows the direction of increasing values of the bed shear stress, τ.



6.3.4 Cohesive Sediment Transport Parameters

The parameters necessary to model cohesive sediment transport are schematically represented in figure 6.13. Because these parameters are highly case dependent, and because they vary within orders of magnitude, GSTARS3 does not assume default values for these quantities. When modeling cohesive sediment transport, the user should rely on field data as much as possible.

In figure 6.13, *STDEP* = shear threshold for deposition of clay and silt; *STPERO* = shear threshold for particle erosion of clay and silt; *STMERO* = shear threshold for mass erosion of clay and silt; *ERMASS* = slope of the erosion rate curve for mass erosion; and *ERSTME* = Erosion rate of clay and silt when the bed shear stress is equal to *STMERO*. Finally, a last parameter is needed, *ERLIM*, which is the threshold value for the percentage of clay in the bed composition above which the erosion rates of gravels, sands, and silts are limited to the erosion rate of clay, as described in section 3.6.2. Values of *ERLIM* have been found to have a large range of variation $(7\% \le ERLIM \le 80\%)$. These parameters are formatted using CS or C0 records, as described in appendix A.

The parameters for fall velocities for flocculation and hindered settling are specified using record CH. The quantities needed are schematically represented in figure 6.14 (see also section 3.6.1 for further details). Parameters *CS1*, *CS2*, *CSCOEF1*, *CSCOEF2*, *CSCOEF3*, and *CSCOEF4* are entered using a single record. Note that parameters *CS1* and *CS2* are reference concentrations, and they are always given in mg/l, irrespective of the selected system of units.

Finally, note that the Krone/Ariathurai methods to compute cohesive sediment transport can be deactivated by setting *STDEP* < 0 in record CS. Transport of fines (i.e., of particles with diameter smaller than 62.5 μm) will take place using the traditional sediment carriyng capacity concept used for the larger particle sizes. The transport capacity is computed using the equation selected in record SE.

Figure 6.13 Schematic representation of the parameters necessary to model the transport of cohesive sediments.

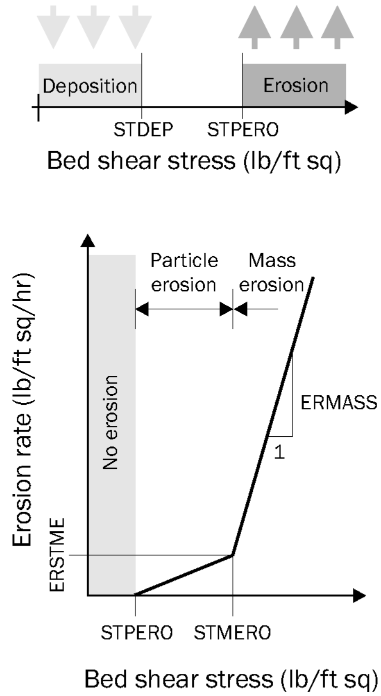
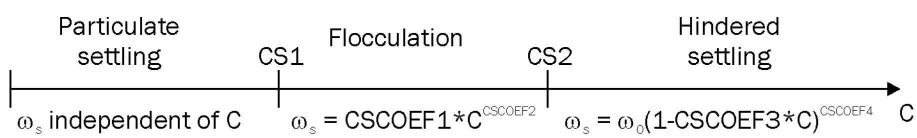


Figure 6.14 Representation of the parameters necessary to describe the fall velocity of cohesive sediments, ω_s, in water.



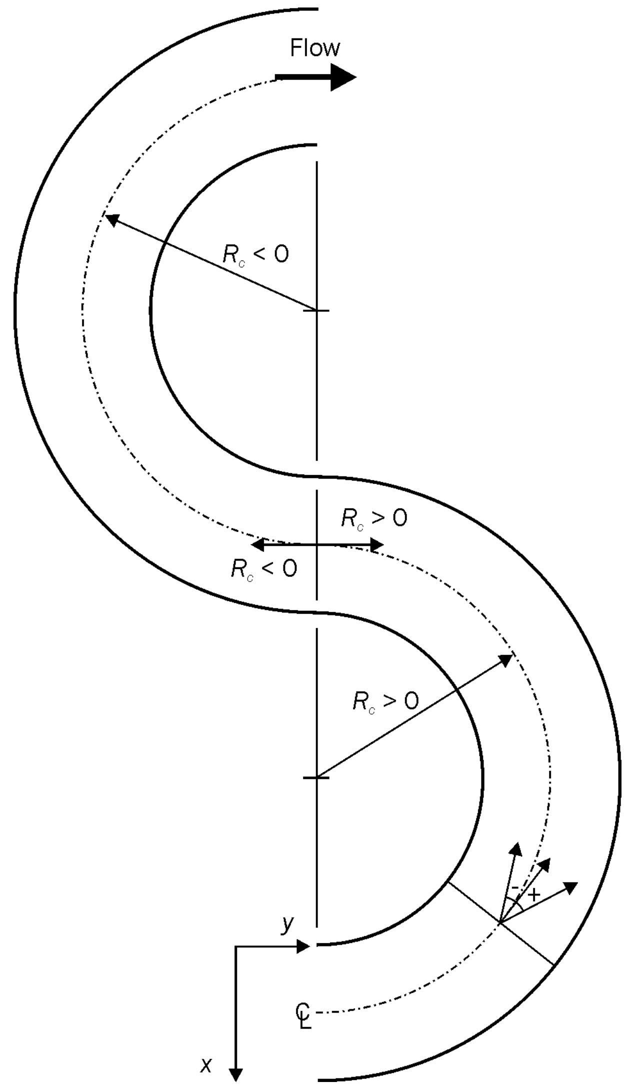
6.3.5 Transfer of Sediment Across Stream Tube Boundaries

The option to compute transfer of sediments across stream tubes boundaries can be activated using record CV. CV is used to activate two different sets of computations: one for transfer due to stream curvature, the other for transfer due to transverse bed slope. The theoretical and implementation details of these computations are explained in section 3.2. The data needed is the radius of curvature, R_c, as shown in figure 6.15.

Careful attention must be paid to the coordinate system used, because that defines the sign of the radius of curvature. In the convention adopted in figure 6.15, the *x*-direction points from left to right bank, looking downstream, and the *y*-direction points along the channel's centerline. The *z*-direction is the vertical, pointing upwards. With this arrangement, R_c is positive when it points along the positive *x*-direction and negative otherwise.

The radii of curvature are entered using CV records. If $R_c = 0$, then transfer due to secondary flows is deactivated and only transverse bed slope computations are carried out. If $R_c \neq 0$, both computations are activated. By omitting the CV recors GSTARS3 assumes there is no transfer of sediment across stream tube boundaries.

Figure 6.15 Schematic top view of a two-loop meander. Note the reference system used (at inlet of meander) and the convention used to define positive and negative curvature radii.



6.3.6 Erosion and Deposition Limits

Sometimes, the presence of natural or man-made features puts constraints to how a river or water course may change. For example, in a sandy river bed where bedrock is present at a certain elevation, below the sandy layer, erosion may be limited to that sandy layer. The bedrock will constitute an effective control, preventing erosion from taking place below its elevation. In GSTARS3, this type of vertical control is specified using LM records.

To effectively use LM records, knowledge of man-made restrictions to deposition and/or scour and geological boring data is required. For example, consider the following hypothetical situation: a channel with bed elevation at 1000 ft is discretized by 5 sections. A nonerodible bedrock layer at elevation 920 ft is known to exist under the first three sections, but not thereafter. One LM record is necessary for each cross section, and the data is entered from to the upstream-most cross section and proceeding in the downstream direction. The LM records for this hypothetical situation would be:

```
         1         2         3         4
123456789012345678901234567890123456789012345

LM  920.   9999.
LM  920.   9999.
LM  920.   9999.
LM    0.   9999.
LM    0.   9999.
```

Notice that zero is the lowest bed elevation allowed in GSTARS3. All computations should be defined such that all vertical bed points have a positive datum at all times of the run. In practice, the computations will never proceed below the datum line (much like if an artificial unerodible layer exists at elevation zero). Since no vertical restrictions exist to deposition, the vertical limits of the example above are simply set to a very high value.

6.4 Output Control

GSTARS3 output is accomplished through column-formatted ASCII files that can be accessed via a plain ASCII text editor or imported into spreadsheets, such as Microsoft's Excel. There are two types of output: hydraulic/sediment parameters and geometry data. The hydraulic/sediment parameters are organized in files containing flow velocities, Froude numbers, energy grade line, particle size distributions, etc., for the computational cross sections in the reach. The geometry data is comprised by tables of thalweg elevation and water surface elevation versus longitudinal distance, and by cross-sectional geometries.

Hydraulic/sediment parameter output is controlled in record PR, including the interval at which the output is desired. There are five possible choices in the control of output using parameter *IPRLVL* of record PR:

IPRLVL	Type of output
-1	No output is required.
0	Level 0 output: print water surface profile and sediment routing tables.
1	Level 1 output: in addition to level 0 output, normal and critical depth tables are generated.
2	Level 2 output: in addition to level 1 output, stream tube geometry and conveyances are generated.
3	Level 3 output: in addition to level 2 output, sediment transport capacities are written to the .SED file.

The output of the several quantities is stored in files with extensions .OUT, .SED, and .DBG. The files are well labeled and are straightforward to understand

Geometry data output is controlled using records PX for the cross sections, and PW for water surface profiles. Output is carried out during the model run at time step intervals specified in these records. Output is stored in files of extension .XPL for the cross-sectional information, and in files of extension .WPL for the water surface profiles.

When records PX and/or PW are used, the first output to the respective external data files is a straight dump of the data *before* the first time step is carried out. In the .WPL output file, the first table is built with the water surface elevation set to zero, simply because the water routing computations have not yet been performed. This approach was chosen because it facilitates automatic importing into spreadsheets, and because it is useful for checking the accuracy and consistency of the data used in the input to the model.

More information about GSTARS3 data output files is presented in section 6.7 below.

6.5 Stream Power Minimization Procedure Data

The total stream power minimization data constitutes the last part of the data described in this chapter. Their inclusion in the input data file is optional. They are necessary only if total stream power minimization computations are requested from GSTARS3.

Minimization computations are activated by the inclusion MR records in the input data file following the printout control records described in the previous section. MR records are also used to specify the range of allowable width and depth variation at different cross sections along a study reach (see the detailed description of this record in appendix A). One MR record is necessary for each section in the study reach. MR records must be given in order, starting from the farthest upstream station and proceeding downstream. If the minimization computations are activated, total stream power computations are performed at the end of each time step.

MR record usage is similar to the usage of LM records, presented above in section 6.3.6. However, additionally to vertical limits, MR records also contain lateral erosion limits. Using the same example as in section 6.3.6, (a channel discretized by 5 cross sections with bedrock at 920 ft for the first three cross sections), consider now that the channel is 100 ft wide and contains a lateral constraint (rock formation) at the right-hand side (looking downstream) of station 3, located at 112 ft; another lateral constraint is located at the left side of station 5 (man-made gaging station) at location 0 ft. No other constraints are known at that reach. The MR records for this hypothetical situation would be:

```
         1         2         3         4
123456789012345678901234567890123456789012345

MR-9999.   9999.    920.   9999.
MR-9999.   9999.    920.   9999.
MR-9999.    112.    920.   9999.
MR-9999.   9999.      0.   9999.
MR    0.   9999.      0.   9999.
```

Note that if both LM and MR sets of records are used, the values in the MR records superseed those in records LM.

Stream power minimization computations are very demanding of computer processing power. They involve considerably more calculations than runs that do not employ stream power minimization. As a result, a GSTARS3 run of a data file using MR records can have much longer run times than that of an equivalent data file that does not include MR records. The user is cautioned about this possibility. A possible way of estimating run times is by runnig only a few time steps before committing to a full-fledged simulation. Of course, the final outcome will depend not only on the computing power of the workstation at hand, but also on the amount and type of data being used for each particular run of the GSTARS3 model.

6.6 Tributary Inflow Data

The information necessary to model the effects of a tributary flow are the tributary's water discharge, the inflow sediment and its composition (needed only if sediment transport computations are active), and how sediment mixing takes place among the stream tubes. This information is set-up in separate files. There must be one file for each tributary. The file names for each tributary are passed to GSTARS3 using LI records. For each tributary, use one LI record located after the RH record corresponding to the cross section located immediately downstream from the tributary.

Tributary inflow information is set-up using DD, MX, QS, IQ, and IS records. A typical file with lateral inflow data will look like this:

```
         1         2         3         4
123456789012345678901234567890123456789012345

* Example of lateral input
* data file.

* Tributary discharge:
DD    50      0.0
DD    50     50.0

* Sediment mixing:
MX  0.10    0.30    0.50

* Sediment discharge:
QS    50      0.0
QS    50     10.0

* Sediment composition:
IQ     2    0.10   100.0
IS          0.50    0.40
IS          0.40    0.40
IS          0.10    0.20
```

All data is tabulated in the same format as described in section 6.1. Water discharge is specified using records DD. Do not use any other records for this purpose (the lateral input file does not have the same input facilities as the main data file discussed in the previous sections). The example above will only work for a 100 time step run (two DD records with 50 time steps each), but the principle can be easily extended to any number of time steps.

If sediment transport is requested, the DD records must be followed by an appropriate sequence of MX, QS, IQ, and IS records, in this order. The MX record is used to specify the proportions of sediment entering each stream tube. In the example above, 10% will go into the left stream tube, 30% to the middle, and 50% to the right stream tube, assuming that three stream tubes are used in the run. Incoming sediment loads are specified using QS records and sediment size distribution is defined using records IQ and IS. These records have been defined in the previous sections. No other records are allowed in the lateral input data file, except comment records (CM, *, and blank lines).

It is difficult to give general guidelines regarding the distribution of the tributary sediment loads among multiple stream tubes. This distribution is directly related to transverse dispersion at the tributary junction: large dispersion rates imply a more uniform lateral distribution of the sediments, while at lower dispersion rates the sediment distribution is more biased towards the side of the channel where the tributary meets the main flow. Multiple factors influence transverse dispersion, such as flow discharge, flow curvature, the presence of secondary flows and their strength, geometric properties of the channel bed, bed roughness, angle of incidence of the tributary flow on the main stem, etc. In practice, the most common approach is, perhaps, to adjust the distribution ratios during the model calibration stage using measured data. A possible procedure is to perform a series of GSTARS3 runs, starting by using uniform mixing across the sream tubes (i.e., equal values of all the variables in MX records), and then gradually increasing the bias towards the side of the cross section where the tributary discharge occurs. Model parameters to match to measured data are bed geometry and backwater profile upstream from the tributary sections (in subcritical flow).

6.7 Using GSTARS3 in Command Line Mode

After preparing the input data file using a plain ASCII text editor (using blank spaces, not tabs), GSTARS3 can be used from the command line interface (DOS window — see your system's user's manual for more information regarding your particular computer) like any conventional DOS program. At the prompt simply type

```
C:\> GSTARS3.EXE FILENAME.DAT
```

where FILENAME.DAT is the file containing the necessary model input data (the filename can be any name chosen by the user that is compatible with the operating system in use and that does not exceed 80 characters in length). As usual, make sure that the executables exist in the system PATH variable. If GSTARS3 is launched without an input file name, the program prompts the user to enter it. The presentation screen was designed for a standard console window (25 lines by 80 columns), but, aesthetic considerations aside, it will work on any size console window. For consistency, the input data file should have an extension .DAT (or .dat), but the program will work with any other extension. Depending on the output requested using the PR, PW, and PX records, several different output files may be generated by GSTARS3 each time the program is executed. The complete set of output files will have the same base file name, which is that part to the left of the period. Each output file containing specific information will have a unique file extension, as outlined below. Make sure that existing files do not contain any of the following file extensions, because they will be overwritten by the GSTARS3 program.

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

sample.out: the .OUT file is the main output file containing the results from the model run. This file contains information about the input data set, as well as hydraulic and sediment transport information. The output level in this file is determined by record PR.

sample.xpl: The .XPL file contains the cross section data points, which can be imported to any generic spreadsheet program. This file is generated only if requested by the PX record.

sample.wpl: The .WPL file contains the water surface profile data points. A water surface profile plot is created for each requested time step. Similarly to the .XPL file, information in this file may be viewed/plotted using a generic spreadsheet program. This file is generated only if requested by the PW record.

sample.dbg: The .DBG file contains information about the model run which can be helpful in finding errors or anomalies in the model run. This information includes all comment records included in the input data set as well as additional information about the hydraulics and sediment calculations performed by the model. The output level in this file is also determined by record PR.

sample.sed: The .SED file contains sediment carrying capacities for each stream tube at each section for the requested time steps. It also contains actual sediment in transport and bed sorting information for the time step. It is generated if level 3 output is selected on the PR record.

As mentioned above, thalweg and stage output is done to the .WPL file in a tabular format appropriate for use with any general purpose spreadsheet program. Its only purpose is to facilitate plotting of the channel's longitudinal bed and stage profiles. The same information is also supplied in the .OUT file. The first lines of the file contain the date and time stamp of the run, as well as the title of the study, entered using TT records in the input data file (in the .DAT file). The remainder of the file contains the output of the program for the time steps specified in record PW (in the .DAT file).

For each time step of output, a three-column table is printed containing *NSTA* + 1 rows (*NSTA* is the number of stations used in the study). The first row contains (from left to right) the number of stations used in the study, the discharge for that time step, and the time step number. The remaining rows contain (from left to right) the station coordinate, thalweg, and stage for the time step. Note that the first set in the file corresponds to time step zero, i.e., to the conditions defined before the run starts. Therefore, the discharge and stages are not defined (they are printed to the file as zero values).

Cross-sectional geometry is output to file .XPL, also in a tabular format appropriate for use in a spreadsheet program. The data in this file shows cross section evolution in time. Output is made at given time steps, as specified in record PX (in the input .DAT file). Similarly to the .WPL file, the first lines of the file contain the date/time stamp of the run and the title of the study. Cross sectional geometry for the entire reach is dumped to the file at each desired time step. For each time step of the output, the data is structured in the following manner:

- the first line contains the number of stations used in the study (*NSTA*);

- data is grouped by station, starting at the station farthest upstream and ending at the station farthest downstream;
- for each station, the first row of data contains three entries: location of station (as defined in record ST, in the input .DAT file), the number of coordinate pairs used for that station (*NPTS*); and the time step. The remaining rows contain *NPTS* pairs of coordinates, with bed elevation in the first column and lateral coordinate in the second column.

The first set in the file corresponds to time step zero, i.e., to the initial conditions.

Due to the nature of the algorithms used in GSTARS3, the number of coordinate points used to describe each cross section may vary with time. The lateral location of coordinate points may also change, especially if minimization computations are performed. Care must be exercised by the user when preparing the data for plotting using a generic spreadsheet program.

6.8 Compatibility with Earlier Versions

Most GSTARS 2.1 data files will run successfully in GSTARS3 with few or no changes. The exceptions are:

- Cohesive sediment transport now requires the additional record CH for fall velocity computations. Equivalent runs between GSTARS 2.1 and 3.0 can still be carried out by setting the parameters *CS1* and *CS2* to very high numbers (say, to 100,000 mg/l or higher).
- Record C1 has two new entries. See appendix A for further details.
- Erosion and deposition limits are now set in an independent set of records (records LM) instead of being associated with the streampower minimization records (record MR). However, GSTARS 2.1 input data files containing MR records are fully compatible with GSTARS3.

Finally, note that many of the code and algorithms of GSTARS3 were rewritten in order to improve performance and accuracy. As a result, a GSTARS3 run using input data files from earlier versions may, in general, produce different results from those of earlier versions.

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APPENDIX A

List of input data records used by GSTARS3.

Alphabetic list of the input data records used in GSTARS3

The detailed descriptions of the records are given in the following pages. The records are presented in the same order in which they should appear in the GSTARS3 input file.

Record CM

COMMENT

Optional

Comment lines are lines containing informative text usually employed to document the input data files. The input data file can have any number of comment lines anywhere in the file. Any line beginning with the uppercase characters CM will be ignored. Any input record that has an asterisk (‘*') or a blank character as the first character will also be ignored. Comment lines using CM or an asterisk are echoed to the .DBG output file, but the lines with a blank character in the first column are not.

Field	Variable	Value	Description
0	*ID*	CM	Record identification.
		*	Record identification.
		Blank	Record identification.
1–10			Any ASCII string.

TT

Record TT

TITLE OF STUDY

Required

The TT record is used to define a title, i.e., a short text that may be used to identify the study or the datafile. Up to three TT records can be used (they must be present, but they may be left blank). The text typed in fields 1 to 10, including blank spaces, will be echoed to the output files generated by GSTARS3. TT records beyond the third are ignored.

Field	Variable	Value	Description
0	*ID*	TT	Record identification.
1–10	*TITLE*		ASCII text to be echoed in the GSTARS3 output files.

Record MT

METRIC UNITS OPTION

Optional

Although the foot (ft) and the pound (lb) are the primary units of length and mass used throughout this manual, GSTARS3 can also use the International System (SI) of units. This is accomplished by including record MT in the input file. Record MT is used to set-up GSTARS3 to use the SI units in its input and output files. If this record is used, follow the table below to specify the appropriate units for all of the fields in each record:

If manual reads:	Use SI unit:
feet (ft)	meter (m)
cubic foot per second (ft^3/s)	cubic meter per second (m^3/s)
ton per day (ton/day)	tonne per day, i.e., metric ton per day (tonne/day)
pound per cubic foot (lb/ft^3)	kilogram per cubic meter (kg/m^3)
pound per square foot (lb/ft^2) (stress)	Pascal (Pa)
pound per square foot per hour ($lb/ft^2/hr$)	Pascal per hour (Pa/hr)

Table of conversion factors used in GSTARS3

1 ft = 0.3048 m	1 m = 3.281 ft
1 ft^2 = 0.0929 m^2	1 m^2 = 10.76 ft^2
1 ft^3 = 0.02832 m^3	1 m^3 = 35.31 ft^3
1 ft^3/s = 0.02832 m^3/s	1 m^3/s = 35.31 ft^3/s
1 lb = 0.4536 kg	1 kg = 2.205 lb
1 ton = 2,000 lb = 907.2 kg = 0.9072 tonne	1 tonne = 1,000 kg = 2,205 lb = 1.102 ton
1 lb/ft^3 = 16.02 kg/m^3	1 kg/m^3 = 0.06243 lb/ft^3
1 lb/ft^2 = 47.88 Pa (stress)	1 Pa = 0.02089 lb/ft^2 (stress)

The units of the following parameters remain unchanged: in record TM, the water temperature units remain as defined; in record SG, the values of *DRL* and *DRU* are always given in mm, but the dry specific weight must be specified in kg/m^3; in record CS, the unit of ERMASS becomes $s^2/m/h$; in record SE, the value of *OMEGA* is always given in metric units conforming to the values of table 3.3; in record CH, the values of *CS1* and *CS2* are always specified in mg/l, and *CSCOEF3* is always specified in l/mg.

Field	Variable	Value	Description
0	*ID*	MT	Record identification.

NS

Record NS

Number of Stations

Required

The NS record defines the number of cross sections, or stations, to be used by the program, and the maximum number of discretization points defining the cross sections. GSTARS3 uses dynamic memory allocation, therefore there are no imposed limits on these values.

Field	Variable	Value	Description
0	*ID*	NS	Record identification.
1	*NSTA*	+	Number of cross sections defined in the study.
2	*NPTS*	+ (≥ 3), or blank	Maximum number of discretization points for each cross section (default is 50).

Record YX

ALTERNATE COORDINATE ORDER

Optional

The YX record allows the option of using cross-section coordinate input data pairs with the bed elevation (y value) followed by the lateral location (x value) on the XS record. The default is lateral location followed by bed elevation (see record XS).

Field	Variable	Value	Description
0	*ID*	YX	Record identification.

ST

Record ST

STATION (CROSS SECTION) PROPERTIES

Required

The ST record is used to define a number of cross section properties: its location, number of coordinate points used to define its geometry, type of section (whether it is a control or not), constant modifications to coordinate data, local energy loss coefficient, and transmissivity properties (transmissivity is relevant only for the case when sediment transport is activated, otherwise it has no effect on the backwater computations). The stations are entered in order, in the downstream direction, starting at the farthest upstream cross section. Each station is identified by a set of several records: ST, ND, XS, and RH.

Field	Variable	Value	Description
0	*ID*	ST	Record identification.
1	*STA*	+	Location of the station, i.e., its coordinate measured from a reference station located downstream (ft).
2	*NPOINTS*	+	Total number of points, i.e., coordinate pairs, used in records XS to define the geometry of the cross section.
3	*ISWITCH*	0 or blank	The current station is not a control section; therefore, no boundary condition is imposed there.
		1	The current station is a control section; therefore, the water surface elevation is a known function of the discharge (boundary condition) at this station.
4	*ITYP*	0 or blank	If *ISWITCH* is equal to 0.
		1	If *ISWITCH* = 1. This information is redundant, but it is kept here to allow for future developments of GSTARS3 without compromising backward datafile compatibility.
5	*BEC*	0 or blank	No action is taken by GSTARS3.
		+/-	The constant elevation, BEC, will be added to the given bed elevations across the channel at the present station.
6	*XSWF*	0 or blank	No action is taken by GSTARS3.
		+	The scaling factor *XSWF* is applied to the lateral location of the data points that define the cross section at this station.
7	*CLOSS*	+	Local energy loss coefficient to account for bends or natural and man-made structures upstream or at this cross section.

Field	Variable	Value	Description
8	*TRSMSV*	0 or blank	Cross section is not a transmissive cross section.
		1	Cross section is transmissive with no mixing across stream tubes.
		2	Cross section is transmissive with full mixing across stream tubes.

ND

Record ND

NUMBER OF SUBCHANNELS

Required

The ND record is used to define areas of same roughness in the cross section. Its most common use is to define main channel and flood plain locations. The roughness coefficient values corresponding to each channel division are given on the RH record. The subchannels are confined within the lateral locations specified in this record. The first subchannel is defined by the first coordinate pair entered in the XS record and by the first lateral location defined in the ND record. A maximum of 9 channel divisions can be defined. Note that if $XSWF \neq 0$ in record ST, the values of DL will also be multiplied by that factor.

Field	Variable	Value	Description
0	*ID*	ND	Record identification.
1	*NDIVI*	+	Number of channel divisions at the present station.
2–10	*DL*	+/-	Locations of the channel division boundaries. These locations are defined as a distance from a reference point in the cross section. They must be given in order, starting at the point farthest left in the cross section (looking downstream).

Example: if the cross section consists of only one channel, i.e., if the roughness coefficient is the same along the cross section, then *NDIVI* = 1 and DL must be equal to or greater than the last *CROSLOC* value on the XS record(s) defining the cross section. This would be the case if a river consists of main channel only, with no flood plains.

If a river has, say, a main channel, a left, and a right flood plain, then *NDIVI* = 3 which would be followed by 3 locations for the channel division boundaries. The value corresponding to the end point of the left flood plain (looking downstream) would be entered first. The left flood plain would be bounded by this point and by the first *CROSLOC* value of the station's XS record. The point corresponding to the end of the main channel/start of the right flood plain would be entered as the next *DL* value. The main channel would be defined as the perimeter bounded by the first two *DL* values. Finally, a number equal to, or greater than, the last *CROSLOC* value on the XS record would be entered as the last *DL* value to define the right flood plain.

Record XS

CROSS SECTION GEOMETRY

Required

The XS record is used to define the cross section 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 must be given starting from the left side of the channel, looking downstream, and progress towards the right-hand side. The maximum number of coordinate points per cross section is defined by variable *NPTS* in record NS.

Field	Variable	Value	Description
0	*ID*	XS	Record identification.
1,3,5,7,9†	*CROSLOC*	+/-	Lateral coordinate, measured from a reference point, of the data points that define the cross-sectional geometry at the current station (ft).
2,4,6,8,10†	*BOTTOM*	+	Vertical coordinate (bottom elevation) of the data points that define the cross-sectional geometry at the current station (ft).

† **Note:** Input of cross section coordinate data does not require that the pair values fill all available fields. However, fields must be skipped in pairs, i.e., if field 5 (*CROSLOC*) is skipped, then field 6 (the corresponding *BOTTOM*) must also be skipped. The number of XS records per station is not a consideration, but the number of coordinate pairs entered in each station must equal the corresponding *NPOINTS* value in record ST. In addition, if a YX record is included in the input file, the cross section geometry must be input using bottom elevation, lateral location pairs instead of the lateral location and bottom elevation pairs as shown above.

RH

Record RH

ROUGHNESS COEFFICIENTS

Required

Record RH is used to specify the roughness coefficient for each of the channel divisions defined in record ND for each station. The friction factors, or resistance coefficients, used must correspond to the particular roughness equation selected (see RE record description). By default, GSTARS3 uses Manning's equation.

Field	Variable	Value	Description
0	*ID*	RH	Record identification.
1–9	*RN*	+	Friction factor for each of the channel divisions defined in record ND. Values must be entered using the same order as in record ND, i.e., from the left to the right side of the cross section (looking downstream).

Record LI

LATERAL INFLOW OF SEDIMENT AND/OR WATER

Optional

This record is used to indicate that a particular section has a lateral inflow of sediment and/or water. The information regarding the lateral inflows is stored in a separate external file whose name is given to GSTARS3 using record LI. There should be one external data file for each lateral inflow. One record LI should appear at each cross section with lateral inflow.

Field	Variable	Value	Description
0	*ID*	LI	Record identification.
1–5	*FNAME*	string	An alphanumeric text string of up to 40 characters, including extension, with the name of the file containing the data corresponding to the lateral inflow for the section.

MX

Record MX

Sediment Mixing Across Stream Tubes at Lateral Inflow Points

Optional (Required if lateral inflows are specified using LI record(s))

Record MX is used to specify the distribution of sediment across stream tubes at lateral inflow points. The data is entered in tabular format, specifying the percentage of the total incoming sediment (from the lateral inflow only; the sediment coming from the upstream computational reach will not be affected by the data in this record) falling into stream tube. If no sediment transport computations are performed, this record will be ignored.

Field	Variable	Value	Description
0	*ID*	MX	Record identification.
1–5	*PSIST*	+	The percentage of sediment staying in the corresponding stream tube. A maximum number of *NSTUBE* values must be entered, and the sum of all *PSIST* values should be 1.

Example: A river reach is being simulated using three stream tubes. If the incoming sediment is coming from the left bank and no mixing is allowed (i.e., no mixing across stream tubes), the following record could be used:

```
         1         2         3         4
123456789012345678901234567890123456789012345
MX   1.0       0.0       0.0
```

If the incoming sediment is entering from the right bank and if 20% of it is allowed to move into the middle stream tube, the following record may be used:

```
         1         2         3         4
123456789012345678901234567890123456789012345
MX   0.0      0.20      0.80
```

If five stream tubes are used and the lateral inflow gets fully mixed:

```
         1         2         3         4
123456789012345678901234567890123456789012345
MX  0.20      0.20      0.20      0.20      0.20
```

Record RE

ROUGHNESS EQUATION AND FRICTION LOSS CALCULATION

Optional

The RE record is used to select the calculation method for friction loss calculations and the roughness equation. These parameters are used in the backwater computations. The Manning, Darcy-Weisbach, and Chézy equations are available. If present, record RE must be placed after the last cross-sectional set of records, i.e., after the [ST, ND, XS, RH] set for the last cross section. If no RE record is found, the program will default to the Manning equation.

Field	Variable	Value	Description
0	*ID*	RE	Record identification.
1	*IOPTFR*	1 or blank	Compute friction loss using the average slope of the adjacent reaches (default).
		2	Friction loss is computed using the geometric mean slope of the adjacent reaches.
		3	Friction loss is computed using average conveyances.
		4	Friction loss is computed using the harmonic mean slope of the adjacent reaches.
2	*EQROUGH*	MANNING	Use Manning equation; use Manning's roughness coefficients in record RH (default).
		DARCY	Use Darcy-Weisbach equation; use Darcy's friction factors in record RH.
		CHEZY	Use Chézy equation; use Chézy's resistance coefficients in record RH.

NT

Record NT

NUMBER OF STREAM TUBES

Optional

The number of stream tubes used in sediment-routing computations is defaulted to three. The NT record defines an alternate number of stream tubes to be used in computations. The number of calculations performed in GSTARS3 is proportional to the number of stream tubes used, therefore more stream tubes also means longer computation times. In general, three stream tubes provide enough detail across a channel, but up to five stream tubes can be used in GSTARS3. If the NT record is not used, *NSTUBE* is set to 3.

Field	Variable	Value	Description
0	*ID*	NT	Record identification.
1	*NSTUBE*	1–5	Number of stream tubes to be used in the computations.

Record IT

NUMBER OF ITERATIONS

Required

This record is used to define the desired number of time steps for the run. There are two time stepping procedures in GSTARS3: the water-routing and the sediment-routing procedures. Time steps can be defined for each of these procedures. The number of water routing time steps is defined by *ITIMAX*, and its duration is defined by *DTIME* (all time steps have the same duration in time). The number of sediment-routing time steps is defined by *NITRQS*, and their duration is *DTIME/NITRQS*. The number of sediment-routing time steps is a multiple of *ITIMAX*; i.e., several sediment routing time steps can be performed during each water-routing time step. During each of the sediment time steps, the hydraulic parameters are kept constant.

Field	Variable	Value	Description
0	*ID*	IT	Record identification.
1	*ITIMAX*	+	The number of time steps to be performed, pertaining to the water-routing calculations.
2	*NITRQS*	+	The number of sediment-routing time steps to be carried out during each hydraulic time step.
3	*DTIME*	+	Duration of time step for the backwater computations.
4	*TSUNITS*	0, DAY	Time step unit is a day. This is the default value.
		HOUR	Time step unit is the hour.
		MIN	Time step unit is the minute.
		SEC	Time step unit is the second.

QQ

Record QQ

TYPE OF DISCHARGE INPUT

Required

This record is used to specify the type of input format chosen for the water discharge information. There are two options: the discharge values can be given as a table (discharge per time step) or as discretized discharges in time blocks of different durations.

Field	Variable	Value	Description
0	*ID*	QQ	Record identification.
1	–	–	Leave blank.
2	*IOPTQ*	TABLE OF DISCHARGES†	Enter the discharges in tabular form. Discharges must be given for each time step. This is the default.
		DISCRETIZED DISCHARGES‡	Enter the discharges as time blocks with specified duration.

† TA or 0 in field 2 is also acceptable to select the table of discharges option.

‡ DI or DD in field 2 is also acceptable to select the discretized discharges option.

Record SS

TYPE OF STAGE INPUT

Required

Record SS is used to define the type of stage input format at the control section(s). There are three options: a rating curve defining a stage-discharge relationship, a table with a list of stage-discharge values, or a table of discharges at the dam outlet.

Field	Variable	Value	Description
0	*ID*	SS	Record identification.
1	–	–	Leave blank.
2–3	*IOPTQ*	RATING CURVE	Use a rating curve, as described in the RC record.
		STAGE DISCHARGE TABLE	Use a list of stage values with corresponding discharges (see description of SQ record).
		DISCHARGE AT DAM	Use a table of discharges instead of stage values at the outflow boundary.

TQ

Record TQ

TABLE OF DISCHARGES

Optional

This record is used when the TABLE OF DISCHARGES option (QQ record) is used in conjunction with the RATING CURVE option (SS record). The TQ record is used to enter a table with the water discharge for each time step. One value of the water discharge must be entered for each time step; i.e., *ITIMAX* values of the water discharge must be given (see IT record). When the TQ record is used, a stage-discharge relationship must be defined using the RC record.

Field	Variable	Value	Description
0	*ID*	TQ	Record identification.
1–10	*QQ*	+	Value of the water discharge for each time step. The number of water discharge values must be equal to the value of *ITIMAX* entered in the IT record (ft^3/s).

Record DD

DISCRETIZED DISCHARGES

Optional

This record is used when the option DISCRETIZED DISCHARGES is used in record QQ. The values of the discharges are entered in time blocks with duration multiple of the time step. The values are entered in a two-column table with the duration of the discharge in field 1 and its value in field 2. The sum of all the values in field 1 must correspond to the total duration of the run; i.e., it must equal the number of time steps for the run (value *ITIMAX* in record IT).

Field	Variable	Value	Description
0	*ID*	DD	Record identification.
1	*NDAY*	+	Number of time steps corresponding to the duration of the discharge defined in field 2.
2	*QI*	+	Value of the water discharge. Note that, for the duration of *NDAY*DTIME*, the system is considered in steady state with the constant discharge given in *QI* (ft^3/s).

NC

Record NC

NUMBER OF RATING CURVES

Optional

The NC record is used to input the number of rating curves used for the reach being modeled. This record must be entered immediately before the RC records with the rating curve information.

Field	Variable	Value	Description
0	*ID*	NC	Record identification.
1	*NCURVES*	+	Number of rating curves defined in the reach.

Record RC

RATING CURVE

Optional

Each RC record contains all the information pertinent to a particular rating curve. Each rating curve is a stage-discharge relationship defined in the form

$$Stage\ (\text{ft}) = C1\ \ (discharge\ [\text{ft}^3/\text{s}])^{C2} + C3$$

The RC record, which is used when the options RATING CURVE is selected in the SS record, contains the number of the station where the rating curve applies, as well as the values of the coefficients *C*1, *C*2, and *C*3. The total number of rating curves used is defined in the NC record.

Field	Variable	Value	Description
0	*ID*	RC	Record identification.
1	*ISTA*	+	Number of the station where the rating curve applies. Note that the cross section numbering starts at the station farthest upstream and proceeds downstream.
2	*C*1	+/-	Value of the coefficient *C*1.
3	*C*2	+/-	Value of the coefficient *C*2.
4	*C*3	+/-	Value of the coefficient *C*3.

TL

Record TL

CROSS SECTION IDENTIFICATION RECORD FOR THE STAGE-DISCHARGE TABLE

Optional

This record is used when SQ records are used to define pairs of stage-discharge values. Record TL is used to identify the station number for which the SQ records apply. The cross sections are numbered starting from the section furthest upstream (station 1) and proceeding downstream. The last station (farthest downstream) is numbered *NSTA* (see record NS).

Field	Variable	Value	Description
0	*ID*	TL	Record identification.
1	*ITABLE*	+	Number of the station for which the values given in record SQ apply.

Record SQ

STAGE-DISCHARGE TABLE

Optional

The SQ record is used when option TABLE OF DISCHARGES in record QQ is used in conjunction with option STAGE DISCHARGE TABLE in record SS. In this case, SQ records are used to build a table defining water discharges and corresponding stages at the downstream-most end of the reach for each time step. The stage-discharge pairs are entered in each row of the table in the proper time sequence. The same pair can be used for multiple consecutive time steps, but the summation of all *TSCOUNT* values must equal the variable *ITIMAX* defined in the IT record.

Field	Variable	Value	Description
0	*ID*	SQ	Record identification.
1	*QQ*	+	Value of water discharge (ft^3/s).
2	*STAGE*	+	Value of corresponding water elevation (ft).
3	*TSCOUNT*	0, 1	Use discharge and stage values for a single time step (default).
		+	Use discharge and stage values for multiple time steps.

HR

Record HR

INITIAL STAGE AT RESERVOIR

Optional (Required for reservoir routing)

This record is used when option DISCHARGE AT DAM is specified in record SS. It is used to define the initial water stage at the dam for reservoir routing computations. Variable *HFREQ* is used to define the frequency at which the reservoir's capacity table is regenerated by GSTARS3., i.e., the number of time steps between updates of the capacity table.

Field	Variable	Value	Description
0	*ID*	HR	Record identification.
1	*HFREQ*	0, blank	Compute the reservoir's capacity table at the first time step only (use this option when there are no sediment routing computations).
		+	Number of time steps between updates of the reservoir's capacity table. *HFREQ* = 1 means that the capacity table is updated at every time step. *HFREQ* > *ITIMAX* (see record IT) means the same as *HFREQ* = 0.
2	*RSTAGE*	+	Stage at the dam for time step 1 (ft).
3	*RSTGMIN*	+	Minimum value of the stage at the dam (ft). During the course of the reservoir routing computations, the stage at the dam will never fall below this level.
4	*RSTGMAX*	+	Maximum value of the stage at the dam (ft). During the course of the reservoir routing computations, the stage at the dam will never rise above this level. Must be $\geq$ *RSTGMIN*.

Record DR

Table of Discharges for Reservoir Routing

Optional

This record defines a table of river and reservoir discharges for reservoir routing. It is used when the TABLE OF DISCHARGES is used in record QQ and option DISCHARGE AT DAM is used in record SS. The values of the river and dam discharges must be entered in the proper time sequence. The same pair of discharges can be used for multiple consecutive time steps, but the summation of all *NDAY* values must be equal to the variable *ITIMAX* defined in record IT.

Field	Variable	Value	Description
0	*ID*	DR	Record Identification.
1	*NDAY*	0, 1, or blank	Use discharge values for one single time step (default).
2		+	Use the discharge values for multiple time steps.
3	*QRIVER*	+	Value of inflow water discharge (river discharge) (ft^3/s).
4	*QDAM*	+	Value of outflow water discharge (discharge at the dam) (ft^3/s).

RQ

Record RQ

DISCRETIZED DISCHARGES AT A DAM

Optional

Record RQ is when the DISCRETIZED DISCHARGES is used in record QQ and option DISCHARGE AT DAM is used in record SS. It works in similar manner to record DD, but it is used to enter the water discharge at the dam. Values are entered in a two-column table with the duration of the discharge in column 1 (in multiples of the time step) and a corresponding value of the discharge in column 2. All value pairs must be entered in the proper chronological order. The sum of all the *NDAY* values must be equal to the number of time steps in the run (variable *ITIMAX* in record IT).

Field	Variable	Value	Description
0	*ID*	RQ	Record Identification.
1	*NDAY*	0, 1, or blank	Use discharge values for one single time step (default).
		+	Use the discharge values for multiple time steps.
2	*QDAM*	+	Value of water discharge at the dam (ft^3/s).

Record SE

SEDIMENT TRANSPORT EQUATION

Required for Sediment Transport

The SE record selects the sediment transport equation used to compute sediment carrying capacities for size fractions greater than 0.0625 mm. This record also allows the control of the active layer thickness.

Field	Variable	Value	Description
0	*ID*	SE	Record identification.
1	*ISED*	+	Variable to choose the sediment transport equation used to compute sediment carrying capacity. The options are:
		1	Meyer-Peter and Müller's method.
		2	Laursen's method.
		3	Toffaleti's method.
		4	Engelund and Hansen's method.
		5	Ackers and White's 1973 method.
		6	Yang's 1973 sand with 1984 gravel methods.
		7	Yang's 1979 sand with 1984 gravel methods.
		8	Parker's method.
		9	Yang's 1996 modified method. (Requires additional wash load parameter input. See SP record.)
		10	Ackers and White's method with the revised (1990) coefficients.
		11	DuBoys' method.
		12	Modified Laursen's method (by Madden).
		13	Ashida and Michiue's method.
		14	Tsinghua University method (requires additional parameter input in field 3).
2	*NALT*	0 or blank	Use the default active layer thickness of 14**D(LSF)*, where *D(LSF)* is the geometric mean sediment size of the largest size fraction available (with at least 1%) at a specific cross section for a particular time step.
		+	A user-specified positive multiplication factor for defining the thickness of active layer given as *TAL = NALT * D(LSF)*.

SE

Field	Variable	Value	Description
3	*RFILL*	blank, ≤ 0	Use standard bed change computations (default).
		> 0	Use fill from the bottom for reservoir deposition computations.
4	*OMEGA*†	0	Default value of the factor for Tsinghua University's equation (default is 300).
		+	User defined value for the Tsinghua University's equation, following the nomenclature in table 3.3.

† Variable *OMEGA* must be specified only if the value of variable *ISED* is set to 14. If ISED $\neq$ 14, specifying a value for *OMEGA* has no effect in the GSTARS3 computations.

Record SP

High Concentration Transport Parameters

Optional (Required with Yang's 1996 modified formula)

The SP record allows the user to input the additional parameter values needed by Yang's 1996 modified formula. This record must be included in the input file if the *ISED* value on the SE input record is set to select Yang's 1996 modified formula. The SP record immediately follows the SE input record.

Field	Variable	Value	Description
0	*ID*	SP	Record identification.
1	*PWASHLD*	+	Percentage of wash load $(0 \le PWASHLD \le 1)$.

NE

Record NE

NON-EQUILIBRIUM SEDIMENT TRANSPORT

Optional

The NE record is used to input the parameters necessary for non-equilibrium sediment transport calculations. The non-equilibrium calculations are activated if this record is present in the input file.

Field	Variable	Value	Description
0	*ID*	NE	Record identification.
1	*ALPHAD*	0, blank	Use the default value for the recovery factor for deposition (default is 0.25).
		+	User specified value for the recovery factor for deposition.
2	*ALPHAS*	0, blank	Use the default value for the recovery factor for scour (default is 1.0).
		+	User specified value for the recovery factor for scour.

Record N0

VARIABLE NON-EQUILIBRIUM SEDIMENT TRANSPORT PARAMETERS

Optional

The N0 record is used to input the parameters necessary for non-equilibrium sediment transport calculations when the non-equilibrium recovery factors vary along a certain reach. The non-equilibrium calculations are activated if this record is present in the input file. Any number of N0 records can be used, but not to exceed the number of cross sections defined. The records must be given from downstream to upstream, i.e., the records must be specified in the order of increasing *NESTA*. N0 records can be used instead of NE records, but not simultaneously.

Each record defines the recovery factors for deposition and scour at a particular location. The given location does not need to coincide with an actual station defined by a ST record. Stations located in between N0 record locations will have interpolated values of the recovery factors. Stations located outside N0 record ranges will not be extrapolated, i.e., stations located downstream from the first N0 record will have the recovery factors defined by the first N0 record; the stations located upstream from the last N0 record will have the same distribution as the last N0 record.

Field	Variable	Value	Description
0	*ID*	N0	Record identification.
2	*NESTA*	+	The location where the recovery factors are defined (ft).
1	*ALPHAD*	+	Recovery factor for deposition at the current location (no default value).
2	*ALPHAS*	+	Recovery factor for scour at the current location (no default value).

C1

Record C1

COEFFICIENTS FOR THE DISCRETIZATION OF EXNER'S EQUATION

Optional

This record is used to define the coefficients used to approximate the change in the volume of bed sediments due to deposition or scour, ΔA_d, which is used in the numerical solution of Exner's equation, that is, of the sediment routing equation. ΔA_d is discretized using

$$(\Delta A_d)_i = (aT_{i-1} + bT_i + cT_{i+1})\Delta Z_i$$

where T = top width; i = cross section index (i - 1 is upstream, i + 1 is downstream); ΔZ = change in bed elevation; and a, b, and c are coefficients that must satisfy $a + b + c = 1$. The values of a, b, and c are entered using this record. If the record is absent from the input data file, GSTARS3 uses the values $a = c = 0.25$ and $b = 0.5$. If the record is present, then all the coefficients must be specified. For the first cross section (i = 1) the value of P_{i-1} is not defined, therefore a = 0. The user must specify separately the values for b and c for this particular station, with the requirement that $b + c = 1$. Similarly, P_{i+1} is not defined for the last cross section, therefore c = 0 and coefficients a and b must verify $a + b = 1$.

Field	Variable	Value	Description
0	*ID*	C1	Record identification.
1	*C1WP*	+	Value of the coefficient a in the equations above (default is 0.25).
2	*C2WP*	+	Value of the coefficient b in the equations above (default is 0.5).
3	*C3WP*	+	Value of the coefficient c in the equations above (default is 0.25).
4	*C1WPD*	+	Value of the coefficient a for the last cross section (default is 0.25).
5	*C2WPD*	+	Value of the coefficient b for the last cross section (default is 0.75).
6	*C1WPU*	+	Value of the coefficient b for the cross section i = 1 (default is 0.75).
7	*C2WPU*	+	Value of the coefficient c for the cross section i = 1 (default is 0.25).

Record C2

Coefficients for Computing Sediment Transport Capacity

Optional

The hydraulic parameters used for the computation of sediment transport capacities are values of the cross-sectional area, depth, velocity, and friction slope. These representative values are computed from a weighted average in the following manner:

$\Theta R_i = a\Theta_{i-1} + b\Theta_i + c\Theta_{i+1}$ for interior sections ($i < NSTA$)

$\Theta R_i = a^*\Theta_{NSTA-1} + b^*\Theta_{NSTA}$ for the downstream most section ($i = NSTA$)

$\Theta R_i = b^{**}\Theta_1 + c^{**}\Theta_2$ for the upstream most section ($i = 1$)

where Θ represents the hydraulic property of interest (cross-sectional area, depth, velocity, or friction slope); i = cross section index (i-1 is upstream, i+1 is downstream); a, b, and c are coefficients that must satisfy $a + b + c = 1$; a^* and b^* are coefficients that must satisfy $a^* + b^* = 1$; and b^{**} and c^{**} are coefficients that must satisfy $b^{**} + c^{**} = 1$. The values of a, b, c, a^*, b^*, b^{**}, and c^{**} are entered using this record. If the record is absent from the input data file, GSTARS3 uses the values $a = c = 0$, $b = 1$, $a^* = 0$, and $b^* = 1$. If the record is present, then all the coefficients must be specified.

Field	Variable	Value	Description
0	*ID*	C2	Record identification.
1	*C1Q*	+	Value of the coefficient a in the equation above (default is 0).
2	*C2Q*	+	Value of the coefficient b in the equation above (default is 1).
3	*C3Q*	+	Value of the coefficient c in the equation above (default is 0).
4	*C1QD*	+	Value of the coefficient a^* in the equation above (default is 0).
5	*C2QD*	+	Value of the coefficient b^* in the equation above (default is 1).
6	*C1QU*	+	Value of the coefficient b^{**} in the equation above (default is 1).
7	*C2QU*	+	Value of the coefficient c^{**} in the equation above (default is 0).

QS

Record QS

SEDIMENT DISCHARGE

Required for Sediment Transport (May be eliminated if QR record is used)

Sediment transport modeling requires specifying the sediment entering the reach being studied. In GSTARS3, the sediment discharge hydrograph must be approximated by a series of bursts having a constant value and a certain duration. The resulting discretized hydrograph is entered in tabular format in QS records. The table has two columns: one for the duration of the constant discharge burst (as a multiple of the time step *DTIME* defined in record IT), another for the value of the sediment discharge. The values are entered sequentially.

Note that record QR can be used instead of record QS, but these two records are mutually exclusive.

Field	Variable	Value	Description
0	*ID*	QS	Record identification.
1	*NDAY*	+	Number of time steps for the specified sediment discharge. Note that the sum of all *NDAY* values must equal the value of *ITIMAX* specified in record IT.
2	*QSI*	+	Sediment discharge entering the study reach for the specified period of time (tons/day, US units of 2,000 lb/day).

Record QR

SEDIMENT DISCHARGE RATING CURVE

Optional

The QR record defines the sediment discharge entering the study reach at the cross section farthest upstream as a function of the water discharge. The assumed relationship between the water discharge and the sediment discharge is of the form:

$$\textit{Sediment discharge}\ [\text{ton/day}] = AQRC \cdot (\textit{Water discharge}\ [\text{ft}^3/\text{s}])^{BQRC}$$

Record QR can also be used to specify the sediment discharge to be equal to the sediment transport capacity of the first cross section of the reach. In this case, the first cross section will not suffer aggradation or scour. This boundary condition should be used only when there is no cohesive sediments in the study reach. In that case, coefficients *AQRC* and *BQRC* should not be specified, Instead, enter the word EQUILIBRIUM anywhere in fields 1 through 10.

Only one QR record is permitted. The QR record can be used instead of record QS, but not at the same time; i.e., the records QR and QS are mutually exclusive.

Field	Variable	Value	Description
0	*ID*	QR	Record identification.
1	*AQRC*	+	Value of the coefficient *AQRC* (no default).
2	*BQRC*	+	Value of the exponent *BQRC* (no default).
1–10	*EQRC*	EQUILIBRIUM	Used to specify an inflow sediment rating curve from the capacity potential of the first cross section. Used instead of variables *AQRC* and *BQRC*. Use all upper-case letters.

TM

Record TM

Water Temperature

Required for Sediment Transport

Record TM is used to enter the water temperature of the study reach for each time step. The temperatures are entered in a two-field record, with the values of the temperature in field 2 and the number of time steps for which the temperature is valid in field 1. Field 3 may be used to specify the temperature units used (Centigrade or Fahrenheit). The summation of *NDAY* from all the TM records must equal the value of *ITIMAX* defined in the IT record.

Field	Variable	Value	Description
0	*ID*	TM	Record identification.
1	*NDAY*	+	Number of time steps for which the given water temperature (*TEMP*) applies to the study reach.
2	*TEMP*	+	Water temperature of the study reach.
3	*TEMPU*	0, F	Temperature is given in degrees Fahrenheit (default).
		C	Temperature is given in degrees Centigrade.

Record SF

NUMBER OF SEDIMENT SIZE FRACTIONS

Required for Sediment Transport

This record is used to specify the dry specific weight of sediments and the number of sediment size fractions used in the study. A maximum of 10 size fractions is allowed in GSTARS3.

Field	Variable	Value	Description
0	*ID*	SF	Record identification.
1	*NF*	+	Number of size fractions defined for the current study $(1 \le NF \le 10)$.
2	*BDINPUT*	0, blank†	Use a dry specific weight default value of 99.26 lb/ft^3.
		+†	Specify a dry specific weight value (lb/ft^3).

† Porosity is calculated from the specified dry specific weight and specific gravity values.

SG

Record SG

SEDIMENT SIZE GROUPS

Required for Sediment Transport

The sediment size groups for the study are defined using SG records. The dry specific weight for individual size groups can also be defined in these records. The number of SG records must equal the value of NF defined in record SF (one SG record is required for each size fraction), and the records must be ordered with increasing sediment sizes.

The lower bound for sand sizes is 0.0625 mm. If a lower mean particle size is given, the cohesive sediment transport methods will automatically be activated, and a CS record is required. For each size group, GSTARS3 computes the geometric mean grain size as $D_{mean} = \sqrt{DRU \times DRL}$.

Field	Variable	Value	Description
0	*ID*	SG	Record identification.
1	*DRL*	+	Lower bound of the particle size for this group (mm).
2	*DRU*	+	Upper bound of the particle size for this group (mm).
3	*BDINPK*	0, blank	Use the default dry specific weight (99.26 lb/ft^3) or the dry specific weight specified in record SF.
		+	Dry specific weight for this size fraction (lb/ft^3). This value will override the value of *BDINPUT* given in record SF.

Record NL

NUMBER OF BED LAYERS

Optional (Required for multiple bed layers)

The NL record is used to specify the number of layers used to describe the bed. In GSTARS3, a maximum of 10 bed layers can be used. Each layer has its own particle size distribution. If record NL is omitted, GSTARS3 assumes that there is only one bed layer. The same number of bed layers must be used for the entire reach being simulated, but the particle size distribution can vary longitudinally within the same bed layer.

Field	Variable	Value	Description
0	*ID*	NL	Record identification.
1	*NLAYER*	+	Number of bed layers $(1 \le NLAYER \le 10)$.

SD

Record SD

SEDIMENT SIZE DISTRIBUTION

Required for Sediment Transport

SD records are used to specify the bed material composition for each station in the study reach. At each station, the bed composition is defined as the bed material size fractions falling within each one of the size fractions defined in SG records. One SD record must be entered for each cross section of the study reach and for each bed layer. Information for each station is entered beginning with the particle size distribution of the top layer and proceeding downwards. The bottom elevation of each layer is given using EL records immediately below each SD record, except for the last layer (bottom layer), which is assumed to have infinite depth. The sets of *NLAYER (see record NL)* SD and EL records must be entered starting at the upstream-most station and proceeding downstream. Note that records SC or a combination of NB and BG records may be used instead of SD records.

Field	Variable	Value	Description
0	*ID*	SD	Record identification.
1–10	*P*	+	Percentage of bed material falling within each of the size groups defined in SG records. The values of *P* must be entered in order, from the smallest to the largest size fractions defined for the study. A total of *NF* values must be entered in each record (*NF* is defined in record SF). The sum of all *P* values must be equal to 1. $(0 \le P \le 1)$

Record EL

BOTTOM ELEVATION OF EACH BED LAYER

Optional (Required for multiple bed layers)

Records EL are used to enter the bottom elevation of each layer of a stratified bed. The last layer is assumed to be infinite, therefore there is no need to use an EL record there. The EL record must appear immediately after the SD record (or SC record, or BG record) to which it applies.

Field	Variable	Value	Description
0	*ID*	EL	Record identification.
1	–	–	Leave blank.
2	*ELEV*	+	Bottom elevation of each layer (ft).

SC

Record SC

CUMULATIVE SEDIMENT SIZE DISTRIBUTION

Optional

Record SC can be used instead of record SD to specify the bed composition of each station in the study reach. It differs from records SD in which the cumulative distribution is used, rather that the percentage falling within each of the defined particle size classes. There must be one SC record per bed layer and per cross section. For each cross section, one SC record is required for each bed layer, immediately followed by an EL record (except for the last layer). Layers must be specified from top to bottom. There must be one set of SD and El records for each cross section, and cross section data must be given starting at the upstream-most cross section and proceeding downstream.

Field	Variable	Value	Description
0	*ID*	SC	Record identification.
1–10	*PCM*	+	Cumulative distribution for each of the size groups defined in SG records. The values of *PCM* must be entered in order, from the smallest to the largest size fractions defined for the study. A total of *NF* values must be entered in each record (*NF* is defined in record SF). Note that $0 \le PCM \le 1$ and that $PCM_i \ge PCM_j$, where *i* and *j* are consecutive size classes, with $d_i > d_j$ (d_i = particle diameter of class *i*). Note also that $PCM_{NF} = 1.0$.

Record NB

SEDIMENT SIZE DISTRIBUTION LOCATION

Optional

Record NB is used in conjunction with record BG to specify the bed material size fractions for a specific location. Each NB record requires one BG record for each bed layer (followed by an EL record), and a maximum of *NSTA* (record NS) sets of NB/BG/EL records is allowed. The NB/BG/EL records may be used instead of SD or SC records. See description of BG record for more details.

The NB record specifies the location where the bed gradation is known. This location does not have to coincide with an actual computational cross section, as defined in records [ST,ND,XS,RE]. However, the location must be given as a distance from the downstream reference location used for variable *STA* (record ST). The [NB,BG,EL] sets of records must be ordered, starting with the location having the lowest *BGSTA* value and ending with the location having the highest *BGSTA* value.

Field	Variable	Value	Description
0	*ID*	NB	Record identification.
1	*BGSTA*	+	The location where the bed gradation is given (ft).

BG

Record BG

SEDIMENT SIZE DISTRIBUTION FOR SPECIFIC LOCATION

Optional (Required if record NB is present)

Record BG is used to input the bed material size fractions falling within each size group defined by SG records. An EL record must follow each BG record, except for the bottom bed layer. The location where the BG data is defined is given in the associated NB record. GSTARS3 uses [NB,BG,EL] records to determine the bed material size fractions at each computational cross section by interpolation. The records must be given from downstream to upstream; i.e., the records must be specified in the order of increasing *BGSTA*.

The bed material size fractions of the computational cross sections located between two *BGSTA* locations are determined from a linear interpolation of the corresponding values specified in BG records. However, GSTARS3 does not extrapolate values: the stations located downstream from the first [NB,BG,EL] set will have the same distribution as the first BG record; the stations located upstream from the last [NB,BG,EL] set will have the same distribution as the last BG record.

Field	Variable	Value	Description
0	*ID*	BG	Record identification.
1–10	*P*		Percentage of bed material falling within each one of the size groups defined in SG records. The values of *P* must be entered in order, from the smallest to the largest size fractions defined for the study. A total of *NF* values must be entered in each record (*NF* is defined in record SF). The sum of all *P* values must be equal to 1. $(0 \le P \le 1)$

Record CS

Transport Parameters for Cohesive Sediments

Optional (Required if sediment size fractions in the silt/clay range are included in the SG record)

The CS record is used for cohesive sediment (clay and silt) transport modeling. If a sediment size group (defined in the SG record) has a geometric mean grain size lower than 0.0625 mm, the cohesive sediment transport methods will be selected for those size groups. The equation specified in record SE will be used for the remaining size groups.

If silt and/or clay group sizes are not present, this record must not be given. This record must not be given when silt and/or clay group sizes are present, but Tsinghua University equation is used (*ISED* = 14 in record SE). Otherwise, the record should be inserted immediately after the last SD (or BG) record. No default values are available for any of the variables in this record.

When *STDEP* is set to a negative value, the silt and clay routines based on shear stress are deactivated. In this circumstance, the carrying capacity of these fractions is computed using the sediment transport equation defined by variable *ISED* (in record SE), and fields 2 through 6 of record CS will be ignored.

Field	Variable	Value	Description
0	*ID*	CS	Record identification.
1	*STDEP*	+	Shear threshold for deposition of clay and silt (lb/ft^2).
		< 0	Cohesive sediment transport routines are deactivated.
2	*STPERO*	+	Shear threshold for particle erosion of clay and silt (lb/ft^2).
3	*STMERO*	+	Shear threshold for mass erosion of clay and silt (lb/ft^2).
4	*ERMASS*	+	Slope of the erosion rate curve for mass erosion (1/hr).
5	*ERSTME*	+	Erosion rate of clay and silt when the bed shear stress is equal to *STMERO* ($lb/ft^2/hr$).
6	*ERLIM*	+	Threshold value for the percentage of clay in the bed composition above which the erosion rates of gravels, sands, and silts are limited to the erosion rate of clay $(0 < ERLIM \leq 1)$.

C0

Record C0

VARIABLE PARAMETERS FOR COHESIVE SEDIMENT TRANSPORT

Optional (Required if sediment size fractions in the silt/clay range are included in the SG record)

The C0 record is used for cohesive sediment transport modeling. If a sediment size group (defined in the SG record) has a geometric mean grain size lower than 62.5 μm, the clay/silt transport methods will be selected for those size groups. The equation specified in record SE will be used for the remaining size groups, except when Tsinghua University equation is used (*ISED* = 14 in record SE), in which case no C0 record is allowed. This record can be used instead of record CS, but not simultaneously.

Each record defines the cohesive transport parameters at a particular location. The given location does not need to coincide with an actual station defined by a ST record. Stations located in between C0 record locations will have interpolated values of the parameters. Stations located outside C0 record ranges will not be extrapolated, i.e., stations located downstream from the first C0 record will have the parameters defined by the first C0 record; the stations located upstream from the last C0 record will have the same parameters as the last C0 record.

Any number of C0 records can be used, to a maximum of *NMXSTA* records (*NMXSTA* is the variable that defines the maximum number of cross sections allowed in a particular release of GSTARS3). The records must be given from downstream to upstream, i.e., the records must be specified in the order of increasing *NESTA*.

Field	Variable	Value	Description
0	*ID*	C0	Record identification.
1	*NESTA*	+	The location where the parameters are defined (ft).
2	*STDEP*	+	Shear threshold for deposition of clay and silt (lb/ft^2).
3	*STPERO*	+	Shear threshold for particle erosion of clay and silt (lb/ft^2).
4	*STMERO*	+	Shear threshold for mass erosion of clay and silt (lb/ft^2).
5	*ERMASS*	+	Slope of the erosion rate curve for mass erosion (1/hr).

Field	Variable	Value	Description
6	*ERSTME*	+	Erosion rate of clay and silt when the bed shear stress is equal to *STMERO* ($lb/ft^2/hr$).
7	*ERLIM*	+	Threshold value for the percentage of clay in the bed composition above which the erosion rates of gravels, sands, and silts are limited to the erosion rate of clay $(0 < ERLIM \leq 1)$.

Record CH

PARAMETERS FOR FALL VELOCITY OF COHESIVE SEDIMENTS

Optional (Required if sediment size fractions in the silt/clay range are included in the SG record

The parameters entered using this record are used in the calculation of fall velocities of cohesive sediment particles. They are the concentration limits for flocculation and hindered settling, and the parameters *M*, *N*, *k*, and *l* of eqs. (109) and (110) (see section 3.8 for more details). The CH record is required if a sediment size group (defined in the SG record) has a geometric mean grain size lower than 62.5 μm, except when Tsinghua University equation is used (*ISED* = 14 in record SE). The CH record must appear immediately after the CS or C0 records. However, do not use the CH record if *STDEP* < 0 in record CS.

Field	Variable	Value	Description
0	*ID*	CH	Record identification.
1	*CS1*	0, +	Concentration lower limit for flocculation (default is 300.0 mg/l).
2	*CS2*	0, +	Lower limit of the concentration for hindered settling (default is 6000 mg/l).
3	*CSCOEF1*	0, +	Coefficient *M* of equation (109) (default is 3.281×10^{-6} ft s^{-1} mg^{-N} l^{N}).
4	*CSCOEF2*	+/-	Coefficient *N* of equation (109) (default is 1.0).
5	*CSCOEF3*	+/-	Coefficient *k* of equation (110) (default is 1.0 l/mg).
6	*CSCOEF4*	+/-	Coefficient *l* of equation (110) (default is 5.0).

Note: entering a negative value in fields 4 through 6 activates the default values. Entering a zero or negative value (or leaving blank) in fields 1 through 3 activates the default values.

Record CF

SEDIMENT SIZE DISTRIBUTION FOR TRANSPORT CAPACITY CALCULATIONS

Optional

The CF record defines the C_{factor} coefficient for fractional sediment transport capacity computations:

$$FBB_k = C_{factor}FB_k + (1 - C_{factor})FS_k$$

where FB_k = percentage of bed material belonging to size fraction k; FS_k = percentage of incoming sediment belonging to size fraction k; and FBB_k = percentage used to compute the transport capacity of size fraction k.

This parameter may be useful to model situations in which the distribution of the sediment incoming to a reach may be different from the distribution of the sediment present in the bed. This record should be placed after record CH (or after the place where record CH would be, if present).

Field	Variable	Value	Description
0	*ID*	CF	Record identification.
1	*CFACTOR*	+	Value of C_{factor}. Must have a value between 0 and 1. If C_{factor} = 1 (default), only material present in the bed will have non-zero carrying capacity.

IQ

Record IQ

INPUT SEDIMENT DISTRIBUTION

Optional

This record is used to vary the size distribution of the input sediment discharge. It is used in conjunction with IS records to construct a table of size distribution as a function of water discharge entering the channel. Record IQ is used to define the water discharges for which sediment size distributions are defined. For values of the discharge between the values defined in record IQ, the sediment size distribution is interpolated from the corresponding size distributions defined in the corresponding fields of IS record(s). See description of IS record.

Field	Variable	Value	Description
0	*ID*	IQ	Record identification.
1	*NDISCH*	1–9	Number of columns in the table, i.e., number of entries for which water discharge is defined. A maximum of nine water discharge entries is allowed.
2–10	*QIC*	+	Water discharge values which will define interpolation segments of the incoming sediment size distribution. A maximum of nine values is permitted. Each value entered must be larger than its predecessor (ft^3/s).

Record IS

INPUT SEDIMENT DISTRIBUTION BY SIZE FRACTION

Optional (Required if record IQ is present)

This record is used in conjunction with record IQ to construct a table of input sediment size distribution as a function of water discharge:

	QIC_1	QIC_2	...	QIC_{NDISCH}
Size fraction 1	$PISED_{1,1}$	$PISED_{2,1}$	...	$PISED_{NDISCH,1}$
Size fraction 2	$PISED_{1,2}$	$PISED_{2,2}$	...	$PISED_{NDISCH,2}$
...	...	...	...	...
Size fraction *NF*	$PISED_{1,NF}$	$PISED_{2,NF}$	...	$PISED_{NDISCH,NF}$

The values QIC_i are the water discharges for which the size distributions of the incoming sediment are known. Using IS records, the percentage of material, $PISED_{i,j}$, for each size fraction defined in the SF and SG records is entered in columns corresponding to each value of QIC_i defined on the IQ record. The size distributions are given in each column in order from the finest to the coarsest size fractions. The number of IS records must equal the number of SG records (i.e., must be equal to *NF*, which is the number of size fractions defined in record SF). The size distributions are interpolated for discharges between the specified *QIC* values. For values of the discharge outside the table, no extrapolation is done; i.e., if $Q < QIC_1$ the size distribution for QIC_1 is used; if $Q > QIC_{NDISCH}$ the size distribution for QIC_{NDISCH} is used.

Field	Variable	Value	Description
0	*ID*	IS	Record identification.
1	*COMNT*	string	A comment, i.e., an alphanumeric ASCII string of up to six characters.
2–10	*PISED*	+	The percentage of the incoming sediment corresponding to the given size fraction and discharge $(0 \le PISED \le 1)$.

Example: If three size fractions are specified, for example silt, sand, and gravel (*NF* = 3), and the corresponding distributions are known for three discharges, 100, 1,000, and 10,000 ft^3/s (*NDISCH* = 3), then the following records could be used:

IS

```
         1         2         3         4
123456789012345678901234567890123456789012345

IQ     3    100.   1000.  10000.
IS silt     0.50    0.60    0.90
IS sand     0.40    0.25    0.07
IS gravl    0.10    0.15    0.03
```

Record CV

TRANSPORT OF SEDIMENT ACROSS STREAM TUBE BOUNDARIES

Optional

Record CV is used to define the parameters necessary to perform the computations to determine the amount of sediment exchange across stream tube boundaries. If CV records are omitted, no sediment exchange will take place between stream tubes. Records CV must follow records IS (or the place where records IS would be, if present).

Field	Variable	Value	Description
0	*ID*	CV	Record identification.
1-10†	*RCURV*	0	Radius of curvature of the channel at each cross section (ft). If $RCURV = 0$, only transfer due to transverse bed slope is considered by the GSTARS3 computations.
		+/-	Additionally to transverse bed slope effects, secondary flows due to stream curvature are also considered when calculating the transfer of sediments across stream tube boundaries.

† **Note:** Not all fields must be filled. Fields may be skipped at will, but a total of *NSTA* (see record NS) values must be given. Multiple CV records may be used.

AR

Record AR

ANGLE OF REPOSE

Optional

The input record AR allows users the option to input bank slope criteria both above and below the calculated water surface. Each time step, the bank slopes will be flattened to the specified angle of repose limits. Mass is conserved in this adjustment.

Field	Variable	Value	Description
0	*ID*	AR	Record identification.
1	*ANGLE1*	90†	Default angle of repose at and above the water surface.
		+	The value of the angle, specified in degrees from horizontal, limits the bank slope at and above the water surface.
2	*ANGLE2*	90†	Default angle of repose below the water surface.
		+	The value of the angle, specified in degrees from horizontal, limits the bank slope below the water surface.

† **Note**: a negative angle of repose specified for either *ANGLE1* or *ANGLE2* will deactivate the computations and the program will behave as if a 90 degree angle was entered. However, the overall computational time of the run will be reduced.

Record LM

SCOUR AND DEPOSITION LIMITS

Optional

LM records are used to define constraints to bed deposition and/or erosion. They allow to define bed elevations above which cannot be any deposition, or below which there will be no scour. These limits correspond to geological and/or man-made restrictions to the sedimentation processes. There must be one LM record for each cross section. LM records are entered starting at the upstream-most cross section and proceeding in the downstream direction. LM records are optional: their absence from the GSTARS3 input datafile indicates that there are no erosion or deposition limits.

Field	Variable	Value	Description
0	*ID*	LM	Record identification.
1	*CBLI*	+/-	Limit for scour: no scour is allowed below this elevation. (ft)
2	*CBHI*	+/-	Limit for deposition: no deposition is allowed above this elevation. (ft)

If *CBLI* has a negative value, GSTARS3 automatically interprets it as zero, which is the lowest bed elevation permissible during the computations. If *CBHI* has a zero or negative value, GSTARS3 interprets it as a very high value, indicating that there is no vertical limit to deposition.

PR

Record PR

PRINTOUT CONTROL

Required

GSTARS3 output is given in ASCII files with different extensions. Usually, the output of relevant quantities is required at the end of the computer run. The PR record is used to define the level of output generated and its interval, i.e., the amount of information required and the number of time steps elapsing between successive writings to the output files during the run.

Field	Variable	Value	Description
0	*ID*	PR	Record identification.
1	*IPRLVL*	-1	No output is required.
		0	Level 0 output: print only water surface profile and sediment routing tables (default).
		1	Level 1 output: in addition to level 0 output, normal and critical depth tables are generated.
		2	Level 2 output: in addition to level 1 output, stream tube geometry and conveyances are generated.
		3	Level 3 output: in addition to level 2 output, sediment transport capacities are written to the .SED file.
2	*INTPR*	+	Number of time steps between output. If *INTPR* = 1, output takes place at each time step. If *INTPR* > *ITMAX* (record IT), no output is generated.

Record PX

CHANNEL CROSS SECTION PLOTTING

Optional

This record is used to generate cross section data for plotting at certain time intervals during the run. Cross section geometry is written in an external ASCII file with extension .XPL containing the title of the study followed by tables of coordinate pairs. Each table contains bottom elevation and lateral location of the points describing each cross section of the reach. The data can be easily imported into almost any spreadsheet program for graphing purposes. Cross-sectional geometry is printed at specified time step intervals. The first set of cross sections represent the initial conditions at the reach; i.e., they are the cross sections before the run has started (at time step 0).

Field	Variable	Value	Description
0	*ID*	PX	Record identification.
1	*INTPL1*	0	No cross section plots are generated.
		> 0	Cross section plots are generated for all of the stations in the study reach, at time intervals with duration equal to *INTPL1* time steps. If *INTPL1* = 1, output is generated at every time step. If *INTPL1* > *ITIMAX*, no output is generated (except for time step 0).

PW

Record PW

WATER SURFACE PROFILE PLOTTING

Optional

The PW record is used to generate longitudinal profiles with the thalweg and the water surface of the study reach at certain time intervals during the run. The data are written in an external ASCII file with extension .WPL containing the title of the study followed by tables with three entries: station location, bottom elevation, and free surface elevation. Each table contains information for a particular time step of the run, and the information is generated at a specified interval. The first table represents the reach at time step 0, i.e., before the run has started. The data can be easily imported into almost any spreadsheet program for graphing purposes.

Field	Variable	Value	Description
0	*ID*	PW	Record identification.
1	*INTPL2*	0	No profiles are generated.
		> 0	Longitudinal profiles of thalweg and water surface elevation are generated at time intervals with duration equal to *INTPL2* time steps. If *INTPL2* = 1, output is generated at every time step. If *INTPL2* > *ITIMAX*, no output is generated (except for time step 0).

Record MR

STREAM POWER MINIMIZATION

Optional

When the MR record is used, GSTARS3 automatically activates the total stream power minimization routines. Record MR is also used to define bed elevation and width limits for each station in the reach. These limits correspond to restrictions, geological or man-made, to deposition and/or scour. The MR records must be omitted if minimization is not requested. For each time iteration, the total stream power minimization computations are used in the program's logic to decide whether to make scour or deposition adjustments in the lateral or vertical directions. One MR record has to be specified for each station. MR records must be entered in sequential order, starting at the station farthest upstream and proceeding downstream.

Field	Variable	Value	Description
0	*ID*	MR	Record identification.
1	*XLFTI*	+/-	Lateral location beyond which no cross section widening is allowed. This location corresponds to the left-hand side restriction, looking downstream, and is valid for a particular station (ft).
		-9999.	No left-hand side boundary.
2	*XRGHTI*	+/-	Lateral location beyond which no cross section widening is allowed. This location corresponds to the right-hand side restriction, looking downstream, and is valid for a particular station (ft).
		9999.	No right-hand side boundary.
3	*CBLI*	+	Limit for scour in the vertical direction. No scour is allowed below this bottom elevation (ft).
		0	No restrictions for scour in the vertical direction.
4	*CBHI*	+	Limit for deposition in the vertical direction. No deposition is allowed above this bottom elevation (ft).
		9999.	No restrictions for deposition in the vertical direction.

Note: when record LM is used in conjunction with record MR, the values of *CBLI* and *CBHI* set in MR records supersede those set in LM records. In other words, if records MR are used, LM records are ignored.

END

Record END

END OF INPUT DATA

Required

The END record is required at the end of each input data file to terminate the data input operations.

Field	Variable	Value	Description
0	*ID*	END	Record identification.

APPENDIX B

Example applications of GSTARS3.

Table of contents for Appendix B

NOTE: The sets of examples presented in this appendix are conceptual problems. They are presented here to show the user how to set-up input data files for GSTARS3. Although some of the examples are part of actual field studies carried out using GSTARS3 or earlier versions, they should not be used for any other purpose without appropriate verification and validation of the input data and of the computed results.

GSTARS3 is in a stage of constant evolution and is subject to change without notice. Because of that, and because of the time lag between the writing of this manual and its actual typesetting and publication, there may be some differences between the release version of GSTARS3 and the version that was used to run the examples. As a result, there may be slight differences between the printed output presented in this appendix and the actual output generated by GSTARS3.

EXAMPLE 1

WATER SURFACE CALCULATIONS

This example shows a GSTARS3 data file set-up for water surface profile calculations without sediment transport. For that purpose, the test problem 4 in MacDonald et al. (1997) is used. This example was chosen because it contains mixed flow regimes: the flow is subcritical at the channel's inlet, turns supercritical one third down the channel, and becomes subcritical again at the downstream end, involving two regime transitions (including one hydraulic jump).

The channel is 3281 ft (1000 m) in length and has a Manning's roughness coefficient of 0.02. It has a trapezoidal cross section with side slopes of 1:1 and a bottom width of 32.8 ft (10 m). A discharge of 706.2 ft^3/s (20 m^3/s) is specified at the inlet. The bed slope varies along the channel's length, as seen in figure 1.1. In figure 1.1 the critical water depth level is also plotted to help determine the regions of sub- and supercritical flow.

The data file (given in the next section) was prepared using a table of discharges and a rating curve to specify the known water stage at the channel's outlet. Note that in this case no sediment transport takes place, therefore no stream tube hydraulics is necessary (the program is set to use one stream tube). Print options are set to 2 in record PR and 0 in record PX (no cross section plots are requested).

1.1 Input data file

The files shown in this and the next sections are part of the main GSTARS3 distribution package. They can be found under directory Example1.

```
TT    Example problem for GSTARS3: mixed flow regime, hydraulics only.
TT        Set-up based on Test Problem 4 of MacDonald et al. (1997).
TT                   File set-up by F. Simoes, Dec. 2000.
```

```
*******************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  ------------------------------------------------------------            ***
***  Problem Description: problem #4 of MacDonald et al. (1997).             ***
***  Data Filename: Ex1.data                                                 ***
***  Shape: trapezoidal channel, top width = 32.81 + 2y (ft).                ***
***  Side Slopes: 1:1                                                        ***
***  Channel Length: 3280.8 ft (1000 m).                                     ***
***  Channel Slope (s): 0.001                                                ***
***  Number of Stations: 21 equally spaced at 164 ft (50 m).                 ***
***  Testing: mixed flow regimes with hydraulic jump.                        ***
***  ------------------------------------------------------------            ***
*******************************************************************************

NS    21

*** Station  1
ST3280.8       9       1       1
ND     1 32.8084
XS 0.000 45.9318 16.4042 29.5276 32.8084 13.1234 41.0105 13.1234 49.2126 13.1234
XS57.415 13.1234 65.6168 13.1234
XS82.021 29.5276 98.4252 45.9318
RH 0.020
*** Station  2
ST3116.8       9
ND     1 32.8084
XS 0.000 45.6336 16.4042 29.2294 32.8084 12.8252 41.0105 12.8252 49.2126 12.8252
XS57.415 12.8252 65.6168 12.8252
XS82.021 29.2294 98.4252 45.6336
RH 0.020
*** Station  3
ST2952.8       9
ND     1 32.8084
XS 0.000 45.2824 16.4042 28.8782 32.8084 12.4740 41.0105 12.4740 49.2126 12.4740
XS57.415 12.4740 65.6168 12.4740
XS82.021 28.8782 98.4252 45.2824
RH 0.020
*** Station  4
ST2788.7       9
ND     1 32.8084
XS 0.000 44.8662 16.4042 28.4620 32.8084 12.0578 41.0105 12.0578 49.2126 12.0578
XS57.415 12.0578 65.6168 12.0578
XS82.021 28.4620 98.4252 44.8662
RH 0.020
*** Station  5
ST2624.7       9
ND     1 32.8084
XS 0.000 44.3703 16.4042 27.9661 32.8084 11.5619 41.0105 11.5619 49.2126 11.5619
XS57.415 11.5619 65.6168 11.5619
XS82.021 27.9661 98.4252 44.3703
RH 0.020
*** Station  6
ST2460.6       9
ND     1 32.8084
XS 0.000 43.7764 16.4042 27.3722 32.8084 10.9680 41.0105 10.9680 49.2126 10.9680
XS57.415 10.9680 65.6168 10.9680
```

```
XS82.021 27.3722 98.4252 43.7764
RH 0.020
*** Station  7
ST2296.6       9
ND     1 32.8084
XS 0.000 43.0617 16.4042 26.6575 32.8084 10.2533 41.0105 10.2533 49.2126 10.2533
XS57.415 10.2533 65.6168 10.2533
XS82.021 26.6575 98.4252 43.0617
RH 0.020
*** Station  8
ST2132.5       9
ND     1 32.8084
XS 0.000 42.1991 16.4042 25.7949 32.8084  9.3907 41.0105  9.3907 49.2126  9.3907
XS57.415  9.3907 65.6168  9.3907
XS82.021 25.7949 98.4252 42.1991
RH 0.020
*** Station  9
ST1968.5       9
ND     1 32.8084
XS 0.000 41.1757 16.4042 24.7715 32.8084  8.3673 41.0105  8.3673 49.2126  8.3673
XS57.415  8.3673 65.6168  8.3673
XS82.021 24.7715 98.4252 41.1757
RH 0.020
*** Station 10
ST1804.5       9
ND     1 32.8084
XS 0.000 40.0100 16.4042 23.6058 32.8084  7.2016 41.0105  7.2016 49.2126  7.2016
XS57.415  7.2016 65.6168  7.2016
XS82.021 23.6058 98.4252 40.0100
RH 0.020
*** Station 11
ST1640.4       9
ND     1 32.8084
XS 0.000 38.7386 16.4042 22.3344 32.8084  5.9302 41.0105  5.9302 49.2126  5.9302
XS57.415  5.9302 65.6168  5.9302
XS82.021 22.3344 98.4252 38.7386
RH 0.020
*** Station 12
ST1476.4       9
ND     1 32.8084
XS 0.000 37.3976 16.4042 20.9934 32.8084  4.5892 41.0105  4.5892 49.2126  4.5892
XS57.415  4.5892 65.6168  4.5892
XS82.021 20.9934 98.4252 37.3976
RH 0.020
*** Station 13
ST1312.3       9
ND     1 32.8084
XS 0.000 36.0144 16.4042 19.6102 32.8084  3.2060 41.0105  3.2060 49.2126  3.2060
XS57.415  3.2060 65.6168  3.2060
XS82.021 19.6102 98.4252 36.0144
RH 0.020
*** Station 14
ST1148.3       9
ND     1 32.8084
XS 0.000 35.2253 16.4042 18.8211 32.8084  2.4169 41.0105  2.4169 49.2126  2.4169
XS57.415  2.4169 65.6168  2.4169
XS82.021 18.8211 98.4252 35.2253
RH 0.020
*** Station 15
ST 984.3       9
ND     1 32.8084
```

```
XS 0.000 34.9243 16.4042 18.5201 32.8084  2.1159 41.0105  2.1159 49.2126  2.1159
XS57.415  2.1159 65.6168  2.1159
XS82.021 18.5201 98.4252 34.9243
RH 0.020
*** Station 16
ST 820.2       9
ND     1 32.8084
XS 0.000 34.6943 16.4042 18.2901 32.8084  1.8859 41.0105  1.8859 49.2126  1.8859
XS57.415  1.8859 65.6168  1.8859
XS82.021 18.2901 98.4252 34.6943
RH 0.020
*** Station 17
ST 656.2       9
ND     1 32.8084
XS 0.000 34.4871 16.4042 18.0829 32.8084  1.6787 41.0105  1.6787 49.2126  1.6787
XS57.415  1.6787 65.6168  1.6787
XS82.021 18.0829 98.4252 34.4871
RH 0.020
*** Station 18
ST 492.1       9
ND     1 32.8084
XS 0.000 34.2908 16.4042 17.8866 32.8084  1.4824 41.0105  1.4824 49.2126  1.4824
XS57.415  1.4824 65.6168  1.4824
XS82.021 17.8866 98.4252 34.2908
RH 0.020
*** Station 19
ST 328.1       9
ND     1 32.8084
XS 0.000 34.1006 16.4042 17.6964 32.8084  1.2922 41.0105  1.2922 49.2126  1.2922
XS57.415  1.2922 65.6168  1.2922
XS82.021 17.6964 98.4252 34.1006
RH 0.020
*** Station 20
ST 164.0       9
ND     1 32.8084
XS 0.000 33.9146 16.4042 17.5104 32.8084  1.1062 41.0105  1.1062 49.2126  1.1062
XS57.415  1.1062 65.6168  1.1062
XS82.021 17.5104 98.4252 33.9146
RH 0.020
*** Station 21
ST   0.0       9       1       1
ND     1 32.8084
XS 0.000 33.7316 16.4042 17.3274 32.8084  0.9232 41.0105  0.9232 49.2126  0.9232
XS57.415  0.9232 65.6168  0.9232
XS82.021 17.3274 98.4252 33.7316
RH 0.020

RE     1MANNING
NT     1
IT     1       1       1 DAY
QQ      TABLE OF DISCHARGES
SS      RATING CURVE
TQ706.29
NC     2
RC     10.022920     1.0     0.0
RC    210.007578     1.0     0.0

PR     2       1
PX     0
PW     1
END
```

1.2 Output data files

1.2.1 Main Output File (.OUT)

```
           GGGGG     SSSSS   TTTTTTTT     A     RRRRRR     SSSSS
          GGGGGGG   SSSSSSS  TTTTTTTT    AAA    RRRRRRR   SSSSSSS
         GG     GG SS     SS    TT      AA AA   RR    RR SS     SS
         GG        SS           TT     AA   AA  RR    RR SS
         GG  GGGGG  SSSSSSS     TT    AA     AA RRRRRRR   SSSSSSS
         GG  GGGGG   SSSSSSS    TT    AAAAAAAAA RRRRRR     SSSSSSS
         GG     GG        SS    TT    AAAAAAAAA RR RR           SS
         GG     GG SS     SS    TT    AA     AA RR  RR   SS     SS
          GGGGGGG   SSSSSSS     TT    AA     AA RR   RR   SSSSSSS
           GGGGG     SSSSS      TT    AA     AA RR    RR   SSSSS
```

```
GSTARS Version 3.0 - Dec 2002                         U.S. Bureau of Reclamation
INPUT FILE:  Ex1.data                                 Technical Service Center
DATE OF RUN:  1 Jul 2003                              Denver, Colorado
TIME OF RUN: 13:37:26
```

```
********************************************************************************
*     Example problem for GSTARS3: mixed flow regime, hydraulics only.      *
*         Set-up based on Test Problem 4 of MacDonald et al. (1997).           *
*                    File set-up by F. Simoes, Dec. 2000.                      *
********************************************************************************
```

```
* * * * * * *   SUMMARY OF INPUT PARAMETERS   * * * * * * *

Number of cross sections:............................    21
Number of stream tubes:..............................     1
Number of time steps:................................     1
Duration of time step (days):........................  1.0000E+00
Formula selected for conveyance calculations:........  MANNING
Formula selected for friction slope:.................  average
Printout control is  2; print interval:..............     1
Do not generate x-sec plots.
Number of time steps for thalweg plots:..............     1
No minimization requested.
```

Sect. #	Location (ft)	ISWITCH	ITYP	Thalweg (ft)	Bed slope	Loss Coef.	NDIVI	NPOINTS
1	3.2808E+03	1	1	1.3123E+01	1.8183E-03	0.00	1	9
2	3.1168E+03	0	0	1.2825E+01	1.8183E-03	0.00	1	9
3	2.9528E+03	0	0	1.2474E+01	2.1415E-03	0.00	1	9
4	2.7887E+03	0	0	1.2058E+01	2.5363E-03	0.00	1	9
5	2.6247E+03	0	0	1.1562E+01	3.0238E-03	0.00	1	9
6	2.4606E+03	0	0	1.0968E+01	3.6191E-03	0.00	1	9
7	2.2966E+03	0	0	1.0253E+01	4.3579E-03	0.00	1	9
8	2.1325E+03	0	0	9.3907E+00	5.2566E-03	0.00	1	9
9	1.9685E+03	0	0	8.3673E+00	6.2402E-03	0.00	1	9
10	1.8045E+03	0	0	7.2016E+00	7.1079E-03	0.00	1	9
11	1.6404E+03	0	0	5.9302E+00	7.7477E-03	0.00	1	9
12	1.4764E+03	0	0	4.5892E+00	8.1768E-03	0.00	1	9

```
  13   1.3123E+03    0       0   3.2060E+00   8.4290E-03  0.00    1       9
  14   1.1483E+03    0       0   2.4169E+00   4.8116E-03  0.00    1       9
  15   9.8430E+02    0       0   2.1159E+00   1.8354E-03  0.00    1       9
  16   8.2020E+02    0       0   1.8859E+00   1.4016E-03  0.00    1       9
  17   6.5620E+02    0       0   1.6787E+00   1.2634E-03  0.00    1       9
  18   4.9210E+02    0       0   1.4824E+00   1.1962E-03  0.00    1       9
  19   3.2810E+02    0       0   1.2922E+00   1.1598E-03  0.00    1       9
  20   1.6400E+02    0       0   1.1062E+00   1.1335E-03  0.00    1       9
  21   0.0000E+00    1       1   9.2320E-01   1.1159E-03  0.00    1       9
-----------------------------------------------------------------------------


********************************************************************************
********************************************************************************
    TIME STEP NO.     1 AFTER  1.0000E+00 DAYS; DISCHARGE IS  7.0629E+02 CFS
********************************************************************************
********************************************************************************


                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  7.0629E+02 C.F.S.      *
                 *********************************************

STA.  STATION   WATER SURFACE   FLOW AREA  FLOW VELCTY  ENERGY GRADE    FROUDE
  #     (ft)     ELEVATION(ft)    (ft^2)      (ft/s)     LINE ELEV(ft)   NUMBER
********************************************************************************
  1  3.2808E+03  1.62049E+01  1.10595E+02  6.38629E+00  1.68730E+01  6.86202E-01
  2  3.1168E+03  1.57964E+01  1.06309E+02  6.64374E+00  1.65182E+01  7.25413E-01
  3  2.9528E+03  1.53325E+01  1.01953E+02  6.92758E+00  1.61159E+01  7.69450E-01
  4  2.7887E+03  1.47941E+01  9.72594E+01  7.26192E+00  1.56532E+01  8.22387E-01
  5  2.6247E+03  1.42071E+01  9.37832E+01  7.53109E+00  1.51298E+01  8.65826E-01
  6  2.4606E+03  1.34489E+01  8.75496E+01  8.06731E+00  1.45048E+01  9.54494E-01
  7  2.2966E+03  1.26599E+01  8.47484E+01  8.33396E+00  1.37854E+01  1.00000E+00
  8  2.1325E+03  1.16874E+01  8.06264E+01  8.76004E+00  1.29287E+01  1.07313E+00
  9  1.9685E+03  1.05277E+01  7.55478E+01  9.34891E+00  1.19383E+01  1.17748E+00
 10  1.8045E+03  9.29772E+00  7.31639E+01  9.65353E+00  1.08000E+01  1.23269E+00
 11  1.6404E+03  7.97635E+00  7.13175E+01  9.90346E+00  9.55614E+00  1.27860E+00
 12  1.4764E+03  6.60568E+00  7.02236E+01  1.00577E+01  8.23427E+00  1.30722E+00
 13  1.3123E+03  6.22984E+00  1.08351E+02  6.51854E+00  6.92529E+00  7.06256E-01
 14  1.1483E+03  6.14320E+00  1.36139E+02  5.18800E+00  6.58856E+00  5.13241E-01
 15  9.8430E+02  6.00928E+00  1.42894E+02  4.94275E+00  6.41456E+00  4.79866E-01
 16  8.2020E+02  5.88057E+00  1.47016E+02  4.80416E+00  6.26403E+00  4.61323E-01
 17  6.5620E+02  5.75975E+00  1.50548E+02  4.69147E+00  6.12590E+00  4.46416E-01
 18  4.9210E+02  5.64665E+00  1.53963E+02  4.58739E+00  5.99716E+00  4.32788E-01
 19  3.2810E+02  5.54126E+00  1.57459E+02  4.48554E+00  5.87680E+00  4.19580E-01
 20  1.6400E+02  5.44318E+00  1.61099E+02  4.38421E+00  5.76415E+00  4.06568E-01
 21  0.0000E+00  5.35227E+00  1.64927E+02  4.28244E+00  5.65892E+00  3.93630E-01


* * * * * *  GSTARS run completed successfully  * * * * * *
```

1.2.2 Debug File (.DBG)

```
GSTARS Version 3.0 - Dec 2002                         U.S. Bureau of Reclamation
INPUT FILE:  Ex1.data                                 Technical Service Center
DATE OF RUN:  1 Jul 2003                              Denver, Colorado
RUN STARTED: 13:37:26:76

********************************************************************************
```

```
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  ------------------------------------------------------------            ***
***  Problem Description: problem #4 of MacDonald et al. (1997).             ***
***  Data Filename: Ex1.data                                                 ***
***  Shape: trapezoidal channel, top width = 32.81 + 2y (ft).                ***
***  Side Slopes: 1:1                                                        ***
***  Channel Length: 3280.8 ft (1000 m).                                     ***
***  Channel Slope (s): 0.001                                                ***
***  Number of Stations: 21 equally spaced at 164 ft (50 m).                 ***
***  Testing: mixed flow regimes with hydraulic jump.                        ***
***  ------------------------------------------------------------            ***
********************************************************************************
********************************************************************************
*     Example problem for GSTARS3: mixed flow regime, hydraulics only.     *
*         Set-up based on Test Problem 4 of MacDonald et al. (1997).          *
*                    File set-up by F. Simoes, Dec. 2000.                     *
********************************************************************************
*** Station  1
  Cross section coordinate order is X-Y
*** Station  2
*** Station  3
*** Station  4
*** Station  5
*** Station  6
*** Station  7
*** Station  8
*** Station  9
*** Station 10
*** Station 11
*** Station 12
*** Station 13
*** Station 14
*** Station 15
*** Station 16
*** Station 17
*** Station 18
*** Station 19
*** Station 20
*** Station 21

 NO SEDIMENT TRANSPORT REQUESTED


                 ******** Memory allocated for this run ********
                 * Number of cross sections:.............  21 *
                 * Number of points per cross section:....  50 *
                 * Number of particle size fractions:......  0 *
                 * Number of stream tubes:................. 1 *
                 * Memory allocated (MBytes):..... 8.31299E-02 *
                 ***********************************************



********************************************************************************
********************************************************************************
    TIME STEP NO.     1 AFTER  1.0000E+00 DAYS; DISCHARGE IS  7.0629E+02 CFS
********************************************************************************
```

```
*********************************************************************************

                          CRITICAL        CRITICAL
                         DEPTH (ft)     W.S.ELV.(ft)
                        ****************************
                         2.4066E+00     1.55300E+01
                         2.4066E+00     1.52318E+01
                         2.4066E+00     1.48806E+01
                         2.4066E+00     1.44644E+01
                         2.4066E+00     1.39685E+01
                         2.4066E+00     1.33746E+01
                         2.4066E+00     1.26599E+01
                         2.4066E+00     1.17973E+01
                         2.4066E+00     1.07739E+01
                         2.4066E+00     9.60820E+00
                         2.4066E+00     8.33680E+00
                         2.4066E+00     6.99580E+00
                         2.4066E+00     5.61260E+00
                         2.4066E+00     4.82350E+00
                         2.4066E+00     4.52250E+00
                         2.4066E+00     4.29250E+00
                         2.4066E+00     4.08530E+00
                         2.4066E+00     3.88900E+00
                         2.4066E+00     3.69880E+00
                         2.4066E+00     3.51280E+00
                         2.4066E+00     3.32980E+00


                      *************************************
                      *   NORMAL DEPTH PROPERTIES TABLE   *
                      *************************************

  STA.  BOTTOM     BOTTOM      FLOW     NORM FLOW  FROUDE   NORMAL     NORMAL
   ID  ELEVATION   SLOPE       AREA     VELOCITY     NO.    DEPTH     W.S.ELV.
         (ft)                 (ft^2)     (ft/s)              (ft)       (ft)
*********************************************************************************
    1 1.31234E+01  1.818E-03  1.141E+02  6.190E+00  0.657  3.171E+00 1.62946E+01
    2 1.28252E+01  1.818E-03  1.141E+02  6.190E+00  0.657  3.171E+00 1.59964E+01
    3 1.24740E+01  2.141E-03  1.082E+02  6.528E+00  0.708  3.020E+00 1.54936E+01
    4 1.20578E+01  2.536E-03  1.024E+02  6.897E+00  0.765  2.870E+00 1.49282E+01
    5 1.15619E+01  3.024E-03  9.675E+01  7.300E+00  0.829  2.723E+00 1.42849E+01
    6 1.09680E+01  3.619E-03  9.131E+01  7.735E+00  0.900  2.580E+00 1.35481E+01
    7 1.02533E+01  4.358E-03  8.602E+01  8.211E+00  0.979  2.440E+00 1.26935E+01
    8 9.39070E+00  5.257E-03  8.100E+01  8.720E+00  1.066  2.307E+00 1.16974E+01
    9 8.36730E+00  6.240E-03  7.668E+01  9.211E+00  1.153  2.191E+00 1.05582E+01
   10 7.20160E+00  7.108E-03  7.356E+01  9.601E+00  1.224  2.107E+00 9.30851E+00
   11 5.93020E+00  7.748E-03  7.157E+01  9.868E+00  1.273  2.053E+00 7.98326E+00
   12 4.58920E+00  8.177E-03  7.036E+01  1.004E+01  1.304  2.020E+00 6.60929E+00
   13 3.20600E+00  8.429E-03  6.968E+01  1.014E+01  1.322  2.002E+00 5.20773E+00
   14 2.41690E+00  4.812E-03  8.333E+01  8.476E+00  1.024  2.369E+00 4.78568E+00
   15 2.11590E+00  1.835E-03  1.137E+02  6.209E+00  0.660  3.162E+00 5.27818E+00
   16 1.88590E+00  1.402E-03  1.242E+02  5.686E+00  0.583  3.428E+00 5.31391E+00
   17 1.67870E+00  1.263E-03  1.285E+02  5.496E+00  0.556  3.536E+00 5.21472E+00
   18 1.48240E+00  1.196E-03  1.308E+02  5.398E+00  0.543  3.594E+00 5.07662E+00
   19 1.29220E+00  1.160E-03  1.322E+02  5.343E+00  0.535  3.628E+00 4.91988E+00
   20 1.10620E+00  1.133E-03  1.332E+02  5.303E+00  0.529  3.653E+00 4.75884E+00
   21 9.23200E-01  1.116E-03  1.339E+02  5.276E+00  0.526  3.670E+00 4.59284E+00

                STEP METHOD COMPUTATIONS
     POTENTIAL CONTROL AT SECTION    1
        CONTROL TYPE =  NATURAL
```

```
   CONTROL DEPTH=    3.0648E+00 FT
   CONTROL ELEV.=    1.6188E+01 FT

POTENTIAL CONTROL AT SECTION    7
   CONTROL TYPE =  NATURAL
   CONTROL DEPTH=    2.4066E+00 FT
   CONTROL ELEV.=    1.2660E+01 FT

POTENTIAL CONTROL AT SECTION   21
   CONTROL TYPE =  NATURAL
   CONTROL DEPTH=    4.4291E+00 FT
   CONTROL ELEV.=    5.3523E+00 FT

NO CONVERGENCE AFTER 56 ITERATIONS AT STATION  12
   COMPUTED HEAD:  7.2569E+00
   GUESSED HEAD:   8.3848E+00
   HYDRAULIC JUMP HEAD LOSS:   0.0000E+00
   DIRECTION & FLOW TYPE UPSTREAM        S1
   MIN H ERROR=      0.527 AT WSEL=      7.007 KTMIN=   0
WSE BEFORE AND AFTER ADJUSTING  7.7667E+00  7.0068E+00      S1

CONTROL AT SECTION    1
   CONTROL TYPE =  NATURAL
   CONTROL DEPTH=    4.4291E+00 FT
   CONTROL ELEV.=    5.3523E+00 FT

CONTROL AT SECTION    7
   CONTROL TYPE =  NATURAL
   CONTROL DEPTH=    4.4291E+00 FT
   CONTROL ELEV.=    5.3523E+00 FT

CONTROL AT SECTION   21
   CONTROL TYPE =  NATURAL
   CONTROL DEPTH=    4.4291E+00 FT
   CONTROL ELEV.=    5.3523E+00 FT
```

CONVEYANCE TABLE FOR INDIVIDUAL STREAM TUBES

STA.	TUBE-1	TUBE-2	TUBE-3	TUBE-4	TUBE-5
1	1.5789E+04				
2	1.4857E+04				
3	1.3928E+04				
4	1.2949E+04				
5	1.2239E+04				
6	1.0998E+04				
7	1.0454E+04				
8	9.6714E+03				
9	8.7348E+03				
10	8.3061E+03				
11	7.9791E+03				
12	7.7875E+03				
13	1.5299E+04				
14	2.1693E+04				
15	2.3347E+04				
16	2.4374E+04				
17	2.5264E+04				
18	2.6134E+04				
19	2.7034E+04				
20	2.7980E+04				
21	2.8986E+04				

*** STREAM HYDRAULICS FOR TUBE NO. 1 ***

STA. #	AREA (ft^2)	WETTED PERIM (ft)	TOP WIDTH (ft)	DEPTH AT INTFACE (ft)	TUBE START (ft)	TUBE END (ft)
1	1.106E+02	4.152E+01	3.897E+01	0.000E+00	2.973E+01	6.870E+01
2	1.063E+02	4.121E+01	3.875E+01	0.000E+00	2.984E+01	6.859E+01
3	1.020E+02	4.089E+01	3.853E+01	0.000E+00	2.995E+01	6.848E+01
4	9.726E+01	4.055E+01	3.828E+01	0.000E+00	3.007E+01	6.835E+01
5	9.378E+01	4.029E+01	3.810E+01	0.000E+00	3.016E+01	6.826E+01
6	8.755E+01	3.983E+01	3.777E+01	0.000E+00	3.033E+01	6.810E+01
7	8.475E+01	3.962E+01	3.762E+01	0.000E+00	3.040E+01	6.802E+01
8	8.063E+01	3.930E+01	3.740E+01	0.000E+00	3.051E+01	6.791E+01
9	7.555E+01	3.892E+01	3.713E+01	0.000E+00	3.065E+01	6.778E+01
10	7.316E+01	3.874E+01	3.700E+01	0.000E+00	3.071E+01	6.771E+01
11	7.132E+01	3.860E+01	3.690E+01	0.000E+00	3.076E+01	6.766E+01
12	7.022E+01	3.851E+01	3.684E+01	0.000E+00	3.079E+01	6.763E+01
13	1.084E+02	4.136E+01	3.886E+01	0.000E+00	2.978E+01	6.864E+01
14	1.361E+02	4.335E+01	4.026E+01	0.000E+00	2.908E+01	6.934E+01
15	1.429E+02	4.382E+01	4.060E+01	0.000E+00	2.892E+01	6.951E+01
16	1.470E+02	4.411E+01	4.080E+01	0.000E+00	2.881E+01	6.961E+01
17	1.505E+02	4.435E+01	4.097E+01	0.000E+00	2.873E+01	6.970E+01
18	1.540E+02	4.459E+01	4.114E+01	0.000E+00	2.864E+01	6.978E+01
19	1.575E+02	4.483E+01	4.131E+01	0.000E+00	2.856E+01	6.987E+01
20	1.611E+02	4.508E+01	4.148E+01	0.000E+00	2.847E+01	6.995E+01
21	1.649E+02	4.534E+01	4.167E+01	0.000E+00	2.838E+01	7.005E+01

STA. #	HYDRAULIC RADIUS (ft)	VELOCITY (ft/s)	FRICTION SLOPE (-)	SHEAR VEL (ft/s)	SHEAR STRS (lb/ft^2)
1	2.663E+00	6.386E+00	2.001E-03	4.141E-01	3.327E-01
2	2.580E+00	6.644E+00	2.260E-03	4.331E-01	3.639E-01
3	2.493E+00	6.928E+00	2.572E-03	4.542E-01	4.002E-01
4	2.399E+00	7.262E+00	2.975E-03	4.792E-01	4.454E-01
5	2.328E+00	7.531E+00	3.330E-03	4.994E-01	4.839E-01
6	2.198E+00	8.067E+00	4.124E-03	5.401E-01	5.659E-01
7	2.139E+00	8.334E+00	4.564E-03	5.605E-01	6.095E-01
8	2.051E+00	8.760E+00	5.333E-03	5.933E-01	6.829E-01
9	1.941E+00	9.349E+00	6.538E-03	6.390E-01	7.922E-01
10	1.889E+00	9.654E+00	7.231E-03	6.629E-01	8.524E-01
11	1.848E+00	9.903E+00	7.835E-03	6.825E-01	9.037E-01
12	1.823E+00	1.006E+01	8.226E-03	6.947E-01	9.362E-01
13	2.620E+00	6.519E+00	2.131E-03	4.239E-01	3.485E-01
14	3.141E+00	5.188E+00	1.060E-03	3.273E-01	2.078E-01
15	3.261E+00	4.943E+00	9.152E-04	3.099E-01	1.863E-01
16	3.333E+00	4.804E+00	8.397E-04	3.001E-01	1.747E-01
17	3.394E+00	4.691E+00	7.815E-04	2.922E-01	1.656E-01
18	3.453E+00	4.587E+00	7.304E-04	2.849E-01	1.574E-01
19	3.513E+00	4.486E+00	6.826E-04	2.777E-01	1.497E-01
20	3.574E+00	4.384E+00	6.372E-04	2.707E-01	1.421E-01
21	3.638E+00	4.282E+00	5.937E-04	2.636E-01	1.348E-01

RUN ENDED: 13:37:26:79

The debug file contains mostly intermediate calculations, such as some of the normal depth flow properties, critical water depths, and stream tube hydraulics. These values do not constitute the primary GSTARS3 output. The principal need for the debug file stems from code development and debugging. As such, some of the messages that may appear there are geared towards code development and should not concern the user. One of such messages is, for example, the "NO CONVERGENCE AFTER 56 ITERATIONS AT STATION 12" that appears in the listing above. Those messages make sense only for those checking the inner workings of the GSTARS3 source code. (By the way, the above message does not signify that the GSTARS3 computations failed to converge and that the results produced by the model are, therefore, inaccurate!)

1.2.3 Water Surface Elevation File (.WPL)

Note that the water surface file (.WPL file) was designed to be easily imported into spreadsheet-type plotting programs. The data is organized in three columns of fixed width, thus allowing for easy import to any spreadsheet program, such as Microsoft's Excel. Output includes (column by column, from left to right) distance from outlet (location of the cross sections as defined in the input data file), bed elevation, and free surface elevation. One set of data is produced for each time step requested in record PW, starting at time step zero (i.e., before any computations take place). For each time step, a set of three numbers is printed, followed by the data in columnar format. The initial set of numbers contains an integer with the number of cross sections used in the study, the water discharge for that time step, and an integer with the time step number. For the first set printed, the value of the water discharge and time step appear with a zero (to indicate values preceding the simulation). The free surface of the first set of data also appears zeroed out, because the data is printed before the backwater computations are performed.

```
* Run on  7/ 1/2003 At 13:37:26:78
    Example problem for GSTARS3: mixed flow regime, hydraulics only.
        Set-up based on Test Problem 4 of MacDonald et al. (1997).
                   File set-up by F. Simoes, Dec. 2000.
        21           0           0
  3.28080E+03  1.31234E+01   0
  3.11680E+03  1.28252E+01   0
  2.95280E+03  1.24740E+01   0
  2.78870E+03  1.20578E+01   0
  2.62470E+03  1.15619E+01   0
  2.46060E+03  1.09680E+01   0
  2.29660E+03  1.02533E+01   0
  2.13250E+03  9.39070E+00   0
  1.96850E+03  8.36730E+00   0
  1.80450E+03  7.20160E+00   0
  1.64040E+03  5.93020E+00   0
  1.47640E+03  4.58920E+00   0
  1.31230E+03  3.20600E+00   0
  1.14830E+03  2.41690E+00   0
  9.84300E+02  2.11590E+00   0
  8.20200E+02  1.88590E+00   0
  6.56200E+02  1.67870E+00   0
  4.92100E+02  1.48240E+00   0
  3.28100E+02  1.29220E+00   0
  1.64000E+02  1.10620E+00   0
  0.00000E+00  9.23200E-01   0
        21   706.290000000000              1
```

```
3.28080E+03  1.31234E+01  1.62049E+01
3.11680E+03  1.28252E+01  1.57964E+01
2.95280E+03  1.24740E+01  1.53325E+01
2.78870E+03  1.20578E+01  1.47941E+01
2.62470E+03  1.15619E+01  1.42071E+01
2.46060E+03  1.09680E+01  1.34489E+01
2.29660E+03  1.02533E+01  1.26599E+01
2.13250E+03  9.39070E+00  1.16874E+01
1.96850E+03  8.36730E+00  1.05277E+01
1.80450E+03  7.20160E+00  9.29772E+00
1.64040E+03  5.93020E+00  7.97635E+00
1.47640E+03  4.58920E+00  6.60568E+00
1.31230E+03  3.20600E+00  6.22984E+00
1.14830E+03  2.41690E+00  6.14320E+00
9.84300E+02  2.11590E+00  6.00928E+00
8.20200E+02  1.88590E+00  5.88057E+00
6.56200E+02  1.67870E+00  5.75975E+00
4.92100E+02  1.48240E+00  5.64665E+00
3.28100E+02  1.29220E+00  5.54126E+00
1.64000E+02  1.10620E+00  5.44318E+00
0.00000E+00  9.23200E-01  5.35227E+00
```

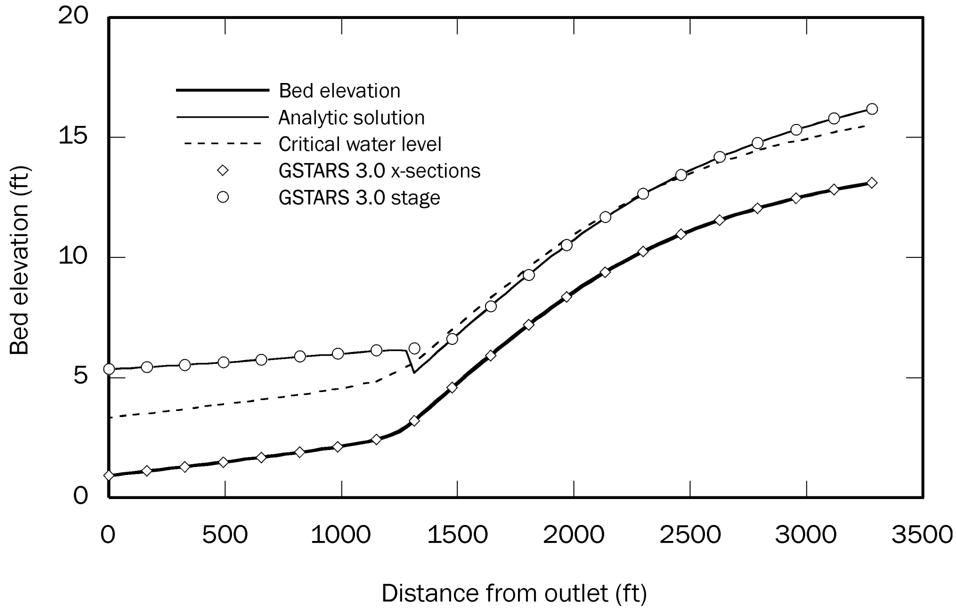
1.3 Results and Discussion

The results of the GSTARS3, shown in figure 1.1. Figure 1.1 was plotted using the data in the surface water elevation file (.WPL) and a typical commercial plotting package. The results present a very good agreement with the analytical solution. In particular, GSTARS3 was able to accurately compute the flow regime transitions. Note that the GSTARS3 cross sections used for this example run (i.e., their locations) are shown by the position of the diamond markers in figure 1.1. More accuracy in locating the hydraulic jump could be achieved by using more cross sections near the region of interest. For this run only 21 equally spaced cross sections are used, located 164 ft (50 m) apart.

1.4 References

MacDonald, I., Baines, M.J., Nichols, N.K., and Samuels, P.G. (1997). “Analytic benchmark solutions for open-channel flow,” *J. Hydr. Engng., ASCE*, **123**(11), 1041–1045.

Figure 1.1 Plot of test case #4 of MacDonald et al. (1997) showing channel geometry, analytical solution, and GSTARS3 computation.



EXAMPLE 2

MAIN CHANNEL WITH ONE TRIBUTARY INFLOW

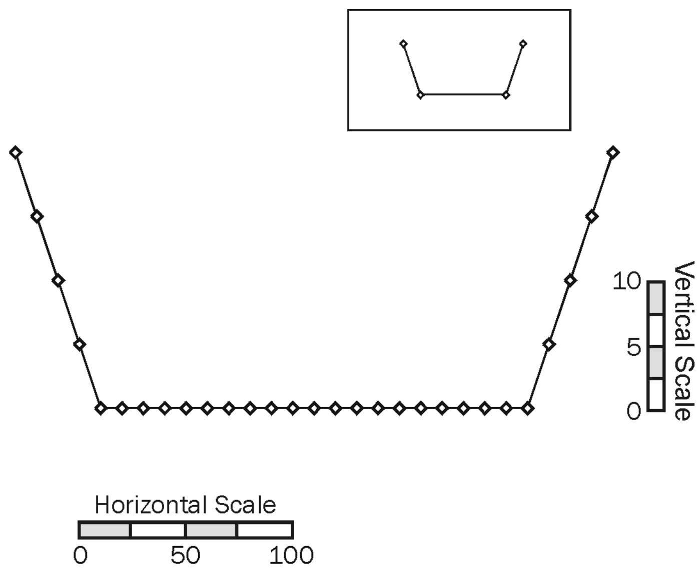
This example illustrates how to set-up sediment transport parameters and how to define tributary inflow data. A 5,000 ft long trapezoidal channel with bottom width of 200 ft and side slopes of 1V:2H is used. The channel slope is 0.0001, and it is set in medium sand with d_{50} = 0.447 mm. The main channel water discharge is 3,000 cfs and the downstream water surface elevation is set to normal depth (7.66 ft). The input sediment load is set to the equilibrium carrying capacity of the inlet cross section using one QR record. In this example only one size class is used in records SF/SG. The channel was discretized with 21 cross sections placed 250 ft apart.

Three stream tubes are used. To ensure that enough discretization points fall within each stream tube, each cross section uses 29 points, as shown in figure 2.1 (see the discussion on page 70 for further details). The cross section template is defined as a set of (y,x) points (record YX is used) and each elevation above datum is set using variable *BEC* in record ST.

Sediment transport is activated by the presence of record SE, which defines the transport equation used in the study. In example 2, the revised Ackers and White equation is used (*ISED* = 10 in record SE). Water temperature is necessary for sediment transport computations and is set at 50 degrees Fahrenheit in record TM. Since only one size fraction is used to define the bed composition, there is no need to specify the size distribution of the incoming sediment (it is assumed to be the same as the bed size distribution of the first cross section). Bed size distributions are set using SD records.

Tributary inflow data is defined at cross section #9, located 3,000 ft upstream from the downstream-most cross section. The incoming flow is laden with sediment such that it will exceed the channel's carrying capacity. Therefore, deposition is expected to occur at that cross section and, possibly, at nearby cross sections. Distribution across the stream tubes is uniform (see record MX in tributary datafile). Both the main input datafile and tributary datafile are presented in the next sections.

Figure 2.1 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 discretization points.



Finally, output control is set at level 3 (*IPRLVL* in record PR) for every 3,000 time steps. Since the run has 3,000 time steps overall, this means that output will take place only at the last time step. The same is defined for channel cross section plots (record PX). Water and bed profile plots (record PW) are printed at every 1,000 time steps, so that figure 2.2 can be plotted.

2.1 Input Data Files

The files shown in this and the next sections are part of the main GSTARS3 distribution package. They can be found under directory Example2.

2.1.1 Main Input Data File

```
TT GSTARS version 3.0  -  Example data file for Appendix B of user's manual.
TT Trapezoidal channel with sediment transport and tributary inflow.
TT Input sediment equals initial carrying capacity: no erosion or deposition.

*******************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
```

```
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  ------------------------------------------------------------------      ***
***  Problem Description: how to set up tributary inflows in GSTARS3.     ***
***  Data Filename: trapzoid.data                                            ***
***  Shape: trapezoidal channel, top width = 200 + 4y ft (61 + 4y m).        ***
***  Side Slopes: 1:2                                                        ***
***  Channel Length: 5000 ft (1524 m).                                       ***
***  Channel Slope (s): 0.0001                                               ***
***  Number of Stations: 21 equally spaced at 250 ft (76.2 m).               ***
***  ------------------------------------------------------------------      ***
********************************************************************************

***  Number of cross sections
NS    21

***  YX Record - Cross-Section Coordinate Order is Y-X
YX

ST  5000      29       0       0   0.500       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ===========================================================================
ST  4750      29       0       0   0.475       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ===========================================================================
ST  4500      29       0       0   0.450       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ===========================================================================
ST  4250      29       0       0   0.425       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ===========================================================================
ST  4000      29       0       0   0.400       1
```

```
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST  3750      29       0       0   0.375       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST  3500      29       0       0   0.350       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST  3250      29       0       0   0.325       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST  3000      29       0       0   0.300       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
LI tributary.data
***  ==========================================================================
ST  2750      29       0       0   0.275       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST  2500      29       0       0   0.250       1
```

```
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  2250     29       0      0   0.225      1
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  2000     29       0      0   0.200      1
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  1750     29       0      0   0.175      1
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  1500     29       0      0   0.150      1
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  1250     29       0      0   0.125      1
ND    1     280
XS  1020      0    1015     10    1010     20    1005     30    1000     40
XS  1000     50    1000     60    1000     70    1000     80    1000     90
XS  1000    100    1000    110    1000    120    1000    130    1000    140
XS  1000    150    1000    160    1000    170    1000    180    1000    190
XS  1000    200    1000    210    1000    220    1000    230    1000    240
XS  1005    250    1010    260    1015    270    1020    280
RH  0.03
***  ==========================================================================
ST  1000     29       0      0   0.100      1
ND    1     280
```

```
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST   750      29       0       0   0.075       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST   500      29       0       0   0.050       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST   250      29       0       0   0.025       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================
ST     0      29       1       1       0       1
ND     1     280
XS  1020       0    1015      10    1010      20    1005      30    1000      40
XS  1000      50    1000      60    1000      70    1000      80    1000      90
XS  1000     100    1000     110    1000     120    1000     130    1000     140
XS  1000     150    1000     160    1000     170    1000     180    1000     190
XS  1000     200    1000     210    1000     220    1000     230    1000     240
XS  1005     250    1010     260    1015     270    1020     280
RH  0.03
***  ==========================================================================

  RE Record (Using Mannings Equation)
RE      MANNING

***  NT Record - Number of Stream Tubes
NT     3

***  IT Record
IT  3000       1    30.0 MIN

***  QQ Record
QQ      TABLE OF DISCHARGES
***  SS Record
```

```
SS      STAGE DISCHARGE TABLE
***  TL Record
TL    21
***  SQ Record
SQ  3000 1007.66    3000

***  ------------------------------------------------------------------------------
***  Sediment Transport Records
***  ------------------------------------------------------------------------------

*** Sediment transport using the revised Ackers and White equation
SE    10
QR      EQUILIBRIUM

TM  3000    50.0

***  SF Record - medium sand (Dmean = 0.447 mm)
SF     1
SG  0.10     2.0

***  SD Records: size fractions falling within each size group. 1 record for
***  each Station. In this example: 1 group size => 1 value per SD record;
***  21 cross sections => 21 SD records; SD for cross section 1 defines size
***  distribution for sediment source.

SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0
SD   1.0

***  ------------------------------------------------------------------------------
***  Print-out Control
***  ------------------------------------------------------------------------------

PR     3    3000
PX  3000      CHANNEL CROSS SECTION PLOTS
PW  1000      WATER SURFACE PROFILE PLOTS

END
```

2.1.2 Input Data File with Tributary Data

```
********************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
```

```
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  -------------------------------------------------------------------     ***
***  Problem Description: how to set up tributary inflows in GSTARS3.     ***
***  Data Filename: trapzoid.data                                            ***
***  Shape: trapezoidal channel, top width = 200 + 4y ft (61 + 4y m).        ***
***  Side Slopes: 1:2                                                        ***
***  Channel Length: 5000 ft (1524 m).                                       ***
***  Channel Slope (s): 0.0001                                               ***
***  Number of Stations: 21 equally spaced at 250 ft (76.2 m).               ***
***  -------------------------------------------------------------------     ***
********************************************************************************
***               THIS FILE CONTAINS ALL THE TRIBUTARY DATA                  ***
********************************************************************************

DD  1000     0.0
DD  2000   200.0

MX 33.33   33.33   33.33

QS  1000     0.0
QS  2000   120.0

IQ     1   200.0
IS          1.00
```

2.2 Output Data Files

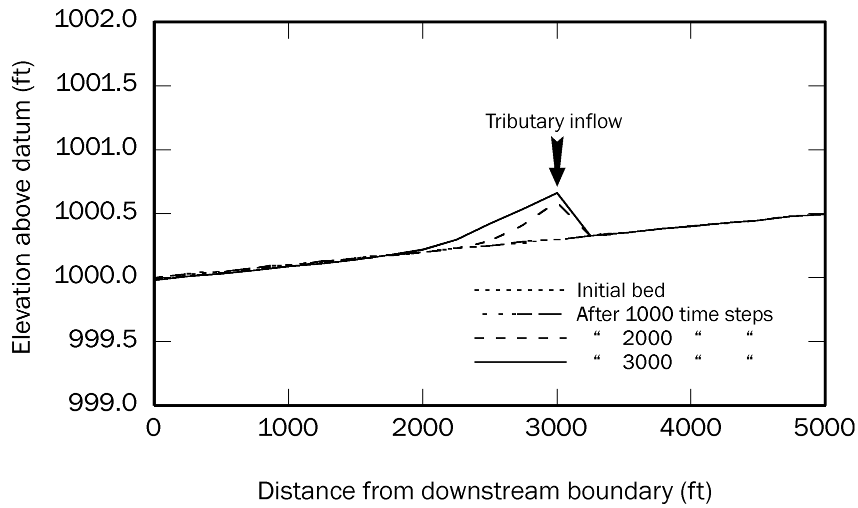
All of the output data files for this example can be found in electronic format in directory Example2 in the main GSTARS3 distribution package.

2.3 Results and Discussion

The run was set up such that the initial 1,000 time steps do not have tributary inflow. Under the conditions of equilibrium set for this problem, no bed changes are expected, and none are observed. For the remaining 2,000 time steps of the run, the tributary discharges 200 cfs of sediment laden water into the main channel. Tributary sediment inflow rate is 120 ton/day, far exceeding the sediment transport capacity of the channel. A depositional cusp is formed at the point of tributary inflow. The volume of deposited sediments grows with time, as shown in figure 2.2. Figure 2.2 was plotted using the bed elevation data from the GSTARS3 water surface elevation file (.WPL) and a traditional plotting program. All the GSTARS3 output files for this example are distributed in the standard GSTARS3 package under directory Example2.

The mass and volume of sediments in the tributary inflow, which is located at cross section 9, can also be observed in the main GSTARS3 output file (.OUT) in the table titled ACCUMULATED DEPOSITION FOR WHOLE STREAM. The displayed volume of sediments include the effect of the sediment's porosity. Only one grain size was used, therefore the bed sorting algorithm did not play a part in these computations.

Figure 2.2 Bed evolution profiles for example 2.

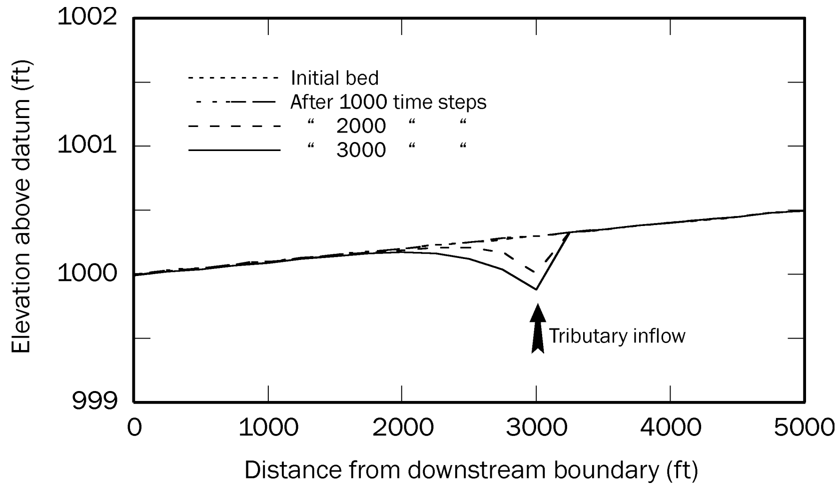


In this example, the distribution of tributary sediments across the stream tubes is uniform. As mentioned in section 6.6, this distribution is case-dependent. Unfortunately, there are no guiding criteria to help the users setting up such a distribution for each specific case. Careful calibration using engineering judgment supported by measured data should be used when dealing with this type of problems.

Finally, the case in which the tributary inflow is of clear water is considered. This case is similar to the previous one, except in which respects the tributary sediment load. Consequently, the carrying capacity of the channel increases with the increased discharge at the tributary input and downstream from it, resulting in bed erosion at that location. The resulting bed profiles plotted at 4 time intervals are presented in figure 2.3. As expected, a scour hole develops at the cross section with the tributary discharge (cross section 9) and progresses with time, increasing in depth and contributing to downstream scour.

The data files for this case are not included in this manual, but are included in the electronic distribution package of GSTARS3 under directory Example2.

Figure 2.3 Bed evolution for the same data configuration presented in example 2, except that the tributary discharges clear water into the main channel (Q_s = 0 in all records QS in the tributary input datafile).

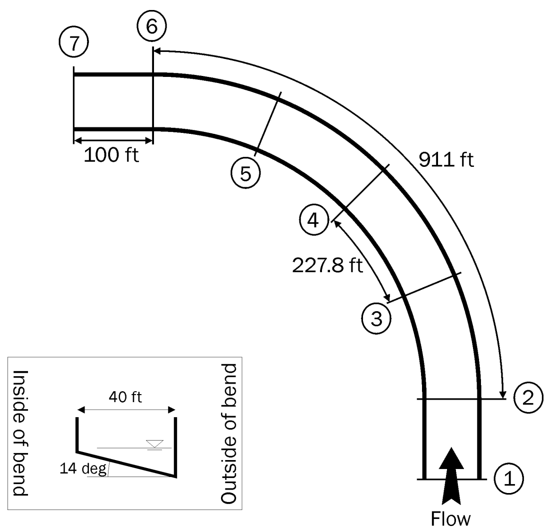


EXAMPLE 3

SEDIMENT TRANSPORT IN A CURVED CHANNEL

This example shows how to use the capabilities of GSTARS3 to compute the exchange of sediment across stream tube boundaries in the presence of transverse bed slope and channel curvature. For that purpose, an idealized channel is used, as sketched in figure 3.1. The channel has a trapezoidal cross section with vertical sides and a transverse bed slope of 14 degrees (see inset in figure 3.1). The longitudinal bed slope is S_0 = 0.0001 and the Manning's roughness is n = 0.020.

Figure 3.1 Plan view and cross-sectional geometry (inset) of the conceptual channel used in this example. The cross section numbering is shown by the circled numbers. The approximate water surface elevation for the runs presented here is also shown in the inset containing the cross section.



The channel has a constant water discharge of 350 cfs and sediment discharge of 20 ton/day. The channel bed is composed of three size classes ranging from 0.02 to 12.5 mm in particle size. The d_{50} of the incoming sediment is considerably finer than that of the bed, as is set using IQ/IS sets of records. Sediment transport is computed by the use of Yang's 1973 equation. Since the channel walls are vertical, the angle-of-repose computations were deactivated in record AR. A run of 3000 time steps was set up, with 20-minute time steps (record IT). Five stream tubes were used.

The radius of curvature of the channel is of 580 ft (positive, according to the convention defined in section 6.3.5). It is set in records CV at the bottom of the file. Cross sections 2 and 6 have a discontinuity in the radius of curvature, from 580 ft to infinity. For this run, the radius of curvature for those sections was arbitrarily set to 1000 ft to allow a smoother transition in the calculations from the curved part to the straight parts of the channel.

Output control is set at level 3, but output is requested only for the last time step.

3.1 Input Data File

The files shown in this and the next sections are part of the main GSTARS3 distribution package. They can be found under directory Example3.

```
TT  GSTARS version 3.0 - Example data file for Appendix B of user's manual.
TT  Test of the function that computes exchange of sediment across stream tube
TT  boundaries.  Data set by F. Simoes, 1-2-02

********************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  -------------------------------------------------------------------     ***
*** Curved channel, radius of curvatute = 580 ft                             ***
*** Rectangular cross section, width = 40 ft                                 ***
*** Transverse bed slope = 14 deg                                            ***
*** n = 0.020                                                                ***
*** S0 = 0.0001                                                              ***
*** Q = 100.0 cfs                                                            ***
*** Channel length = 1111.2 ft                                               ***
*** Sediment transport active with full curvature effects.                   ***
***  -------------------------------------------------------------------     ***
********************************************************************************


NS     7      15

ST1111.2      15               10.11112
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
```

```
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST1011.2      15               10.10112
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST 783.4      15               10.07834
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST 555.6      15               10.05556
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST 327.8      15               10.03278
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST 100.0      15                 10.010
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

ST   0.0      15       1       1    10.0
ND     1    80.0
XS -40.0   100.0   -40.     20.0     0.0    20.0     0.0    10.0     5.0    8.85
XS  10.0    7.50    15.0    6.25    20.0    5.00    25.0    3.75    30.0    2.50
XS  35.0    1.25    40.0     0.0    40.0    20.0    80.0    20.0    80.0   100.0
RH 0.020

*** Use average conveyance for M1 profile.
RE      3MANNING

NT      5

IT  3000       1      20 min
QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE

*** Discharge and stage section at cross section #7.
TL      7
SQ 350.0   20.50    3000

*** Sediment transport using Yang's equation (ISED = 6).
SE      6
```

```
QS  3000    20.0
TM  3000    65.0

SF     3
SG  0.02    0.50
SG  0.50    2.00
SG  2.00   12.50

SD  0.45    0.35    0.20
SD  0.45    0.35    0.20
SD  0.45    0.35    0.20
SD  0.45    0.35    0.20
SD  0.45    0.35    0.20
SD  0.45    0.35    0.20
SD  0.45    0.35    0.20

IQ     1   300.0
IS  fine   0.831
ISmedium   0.169
IScoarse     0.0

*** Effects of channel curvature.
CV   0.0
CV1000.0
CV 580.0
CV 580.0
CV 580.0
CV1000.0
CV   0.0

AR -90.0   -90.0

PR     3    3000
PX  3000  CROSS SECTION PLOTS
PW  3000  WATER SURFACE PROFILE PLOTS
END
```

3.2 Output Data Files

All of the output data files for this example can be found in electronic format in directory Example3 in the main GSTARS3 distribution package.

3.2.1 Main Output File (.OUT)

```
             GGGGG     SSSSS   TTTTTTTT     A     RRRRRR     SSSSS
            GGGGGGG   SSSSSSS  TTTTTTTT    AAA    RRRRRRR   SSSSSSS
           GG     GG SS     SS    TT      AA AA   RR    RR SS     SS
           GG        SS           TT     AA   AA  RR    RR SS
           GG  GGGGG  SSSSSSS     TT    AA     AA RRRRRRR   SSSSSSS
           GG  GGGGG   SSSSSSS    TT    AAAAAAAAA RRRRRR     SSSSSSS
           GG     GG        SS    TT    AAAAAAAAA RR RR           SS
           GG     GG SS     SS    TT    AA     AA RR  RR   SS     SS
            GGGGGGG   SSSSSSS     TT    AA     AA RR   RR   SSSSSSS
             GGGGG     SSSSS      TT    AA     AA RR    RR   SSSSS

GSTARS Version 3.0 - Dec 2002                          U.S. Bureau of Reclamation
```

```
INPUT FILE:  Ex3.dat                                   Technical Service Center
DATE OF RUN:  2 Jul 2003                               Denver, Colorado
TIME OF RUN: 13:15:28


*********************************************************************************
*   GSTARS version 3.0 - Example data file for Appendix B of user's manual.    *
*   Test of the function that computes exchange of sediment across stream tube *
*   boundaries.  Data set by F. Simoes, 1-2-02                                 *
*********************************************************************************


* * * * * * *   SUMMARY OF INPUT PARAMETERS   * * * * * * *

Number of cross sections:...........................     7
Number of stream tubes:.............................     5
Number of time steps:...............................  3000
Number of sediment time steps (NITRQS):.............     1
Duration of time step (days):.......................  1.3889E-02
Formula selected for conveyance calculations:........  MANNING
Formula selected for friction slope:.................  average conveyance
Formula for sediment transport: ..............  Yang (1973) with gravel (1984)
NALT for active layer thickness:....................    14
Transport parameter CFACTOR:........................  1.00
Printout control is  3; print interval:.............  3000
Number of time steps to generate x-sec plots:........  3000
Number of time steps for thalweg plots:.............  3000
No minimization requested.

Sect.  Location   ISWITCH  ITYP   Thalweg     Bed slope   Loss  NDIVI NPOINTS
   #     (ft)                      (ft)                   Coef.
-----------------------------------------------------------------------------
   1   1.1112E+03    0       0   1.0111E+01   1.0000E-04  0.00    1      15
   2   1.0112E+03    0       0   1.0101E+01   1.0000E-04  0.00    1      15
   3   7.8340E+02    0       0   1.0078E+01   1.0000E-04  0.00    1      15
   4   5.5560E+02    0       0   1.0056E+01   1.0000E-04  0.00    1      15
   5   3.2780E+02    0       0   1.0033E+01   1.0000E-04  0.00    1      15
   6   1.0000E+02    0       0   1.0010E+01   1.0000E-04  0.00    1      15
   7   0.0000E+00    1       1   1.0000E+01   1.0000E-04  0.00    1      15
-----------------------------------------------------------------------------

Coefficients used in Exner equation and in
computing hydraulic properties for sediment capacity
------------------------------------------------------------------------
      C1WP      C2WP      C3WP      C1WPD     C2WPD     C1WPU     C2WPU
     0.250     0.500     0.250     0.250     0.750     0.750     0.250
      C1Q       C2Q       C3Q        C1QD      C2QD      C1QU      C2QU
     0.000     1.000     0.000     0.000     1.000     1.000     0.000
------------------------------------------------------------------------

Number of particle size classes:  3
                                 Geometric  Dry specific
Class     DRL         DRU          mean        weight
  #       (mm)        (mm)         (mm)       (lb/ft^3)
--------------------------------------------------------
  1   2.0000E-02   5.0000E-01   1.0000E-01   9.9259E+01
  2   5.0000E-01   2.0000E+00   1.0000E+00   9.9259E+01
  3   2.0000E+00   1.2500E+01   5.0000E+00   9.9259E+01
--------------------------------------------------------
```

```
Percentage of bed material for each size fraction and for each cross section
Number of bed layers:  1
Section    Bed material size fraction for each group, layer #  1
   #     1      2      3
-----------------------------------------------------------------------------
   1    45.0   35.0   20.0
   2    45.0   35.0   20.0
   3    45.0   35.0   20.0
   4    45.0   35.0   20.0
   5    45.0   35.0   20.0
   6    45.0   35.0   20.0
   7    45.0   35.0   20.0
-----------------------------------------------------------------------------

                      Radius of curvature for each section
                                        Radius of
                        Station #      curvature (ft)
                      ------------------------------------
                             1            0.0000E+00
                             2            1.0000E+03
                             3            5.8000E+02
                             4            5.8000E+02
                             5            5.8000E+02
                             6            1.0000E+03
                             7            0.0000E+00
                      ------------------------------------


********************************************************************************
********************************************************************************
    TIME STEP NO.  3000 AFTER  4.1667E+01 DAYS; DISCHARGE IS  3.5000E+02 CFS
********************************************************************************
********************************************************************************


                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  3.5000E+02 C.F.S.      *
                 *********************************************

STA.  STATION   WATER SURFACE   FLOW AREA  FLOW VELCTY  ENERGY GRADE    FROUDE
  #     (ft)     ELEVATION(ft)    (ft^2)      (ft/s)     LINE ELEV(ft)   NUMBER
********************************************************************************
  1  1.1112E+03  2.05736E+01  1.94021E+02  1.80393E+00  2.06326E+01  1.55981E-01
  2  1.0112E+03  2.05668E+01  1.95978E+02  1.78591E+00  2.06223E+01  1.50584E-01
  3  7.8340E+02  2.05509E+01  2.06528E+02  1.69468E+00  2.06020E+01  1.40623E-01
  4  5.5560E+02  2.05360E+01  2.13701E+02  1.63780E+00  2.05843E+01  1.34455E-01
  5  3.2780E+02  2.05212E+01  2.17633E+02  1.60822E+00  2.05682E+01  1.31399E-01
  6  1.0000E+02  2.05063E+01  2.18576E+02  1.60128E+00  2.05528E+01  1.30515E-01
  7  0.0000E+00  2.05000E+01  2.18491E+02  1.60190E+00  2.05462E+01  1.00000E-03

          **************************************************************
          *       SEDIMENT ROUTING RESULTS FOR TIME STEP    3000       *
          **************************************************************

                --------------------------------------------------
                              INCOMING SEDIMENT PER SIZE FRACTION
                              SIZE FRACTION        QSED (TON/DAY)
                --------------------------------------------------
```

```
Stream tube #1      1                3.3240E+00
                    2                6.7600E-01
                    3                0.0000E+00
                  TOTAL              4.0000E+00
--------------------------------------------------
Stream tube #2      1                3.3240E+00
                    2                6.7600E-01
                    3                0.0000E+00
                  TOTAL              4.0000E+00
--------------------------------------------------
Stream tube #3      1                3.3240E+00
                    2                6.7600E-01
                    3                0.0000E+00
                  TOTAL              4.0000E+00
--------------------------------------------------
Stream tube #4      1                3.3240E+00
                    2                6.7600E-01
                    3                0.0000E+00
                  TOTAL              4.0000E+00
--------------------------------------------------
Stream tube #5      1                3.3240E+00
                    2                6.7600E-01
                    3                0.0000E+00
                  TOTAL              4.0000E+00
--------------------------------------------------

WARNING: stations    0 and    1 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    0 and    1 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    1 and    2 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    1 and    2 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    2 and    3 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    2 and    3 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    3 and    4 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    3 and    4 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    4 and    5 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.
```

```
WARNING: stations    4 and    5 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    4 and    5 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    5 and    6 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    5 and    6 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    5 and    6 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    6 and    7 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    6 and    7 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    6 and    7 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.


          ***************************************************************
          *                      STREAM TUBE NO.   1                     *
          ***************************************************************
           STA  DISTANCE           TOTAL LOAD          CHANGE   DIRECTION
                               (TONS)      (FT**3)      (FT)
          ***************************************************************
            1   1.1112E+03   4.6538E-03   5.6263E-02     0.000   VERTICAL
            2   1.0112E+03   6.6615E-03   8.0535E-02     0.000   VERTICAL
            3   7.8340E+02   5.5931E-03   6.7618E-02     0.000   VERTICAL
            4   5.5560E+02   4.3417E-03   5.2489E-02     0.000   VERTICAL
            5   3.2780E+02   3.7546E-03   4.5391E-02     0.000   VERTICAL
            6   1.0000E+02   3.1857E-03   3.8514E-02     0.000   VERTICAL
            7   0.0000E+00   1.0935E-03   1.3220E-02     0.000   VERTICAL


          ***************************************************************
          *                      STREAM TUBE NO.   2                     *
          ***************************************************************
           STA  DISTANCE           TOTAL LOAD          CHANGE   DIRECTION
                               (TONS)      (FT**3)      (FT)
          ***************************************************************
            1   1.1112E+03   5.3307E-02   6.4446E-01     0.000   VERTICAL
            2   1.0112E+03   3.2668E-02   3.9494E-01     0.000   VERTICAL
            3   7.8340E+02   1.8050E-02   2.1822E-01     0.000   VERTICAL
            4   5.5560E+02   1.2577E-02   1.5205E-01     0.000   VERTICAL
            5   3.2780E+02   1.0401E-02   1.2575E-01     0.000   VERTICAL
            6   1.0000E+02   9.5730E-03   1.1573E-01     0.000   VERTICAL
```

7	0.0000E+00	8.7156E-03	1.0537E-01	0.000	VERTICAL

****
*   STREAM TUBE NO.   3   *
****

STA	DISTANCE	TOTAL LOAD (TONS)	(FT**3)	CHANGE (FT)	DIRECTION
1	1.1112E+03	6.3429E-02	7.6683E-01	0.000	VERTICAL
2	1.0112E+03	7.0133E-02	8.4788E-01	0.002	VERTICAL
3	7.8340E+02	5.1651E-02	6.2444E-01	0.000	VERTICAL
4	5.5560E+02	1.7182E-02	2.0772E-01	0.000	VERTICAL
5	3.2780E+02	1.4717E-02	1.7792E-01	0.000	VERTICAL
6	1.0000E+02	1.3607E-02	1.6451E-01	0.000	VERTICAL
7	0.0000E+00	1.2718E-02	1.5376E-01	0.000	VERTICAL

****
*   STREAM TUBE NO.   4   *
****

STA	DISTANCE	TOTAL LOAD (TONS)	(FT**3)	CHANGE (FT)	DIRECTION
1	1.1112E+03	8.8933E-02	1.0752E+00	0.000	VERTICAL
2	1.0112E+03	7.7744E-02	9.3989E-01	-0.002	VERTICAL
3	7.8340E+02	6.2614E-02	7.5698E-01	0.000	VERTICAL
4	5.5560E+02	5.3994E-02	6.5276E-01	0.001	VERTICAL
5	3.2780E+02	4.5700E-02	5.5249E-01	0.000	VERTICAL
6	1.0000E+02	4.2490E-02	5.1369E-01	0.000	VERTICAL
7	0.0000E+00	4.4480E-02	5.3774E-01	0.000	VERTICAL

****
*   STREAM TUBE NO.   5   *
****

STA	DISTANCE	TOTAL LOAD (TONS)	(FT**3)	CHANGE (FT)	DIRECTION
1	1.1112E+03	6.6240E-02	8.0081E-01	0.000	VERTICAL
2	1.0112E+03	6.1737E-02	7.4638E-01	0.000	VERTICAL
3	7.8340E+02	5.0474E-02	6.1021E-01	0.000	VERTICAL
4	5.5560E+02	4.3230E-02	5.2263E-01	0.001	VERTICAL
5	3.2780E+02	4.0104E-02	4.8484E-01	0.000	VERTICAL
6	1.0000E+02	3.8964E-02	4.7106E-01	0.000	VERTICAL
7	0.0000E+00	3.7637E-02	4.5502E-01	0.000	VERTICAL

****
*** ACCUMMULATED DEPOSITION FOR WHOLE STREAM ***
****

STA NO.	ACCU.DEPS. (TONS)	ACCU DEPS. (FT^3)	ACCU. DEPS. FOR DIFFRNT SIZE GROUPS (FT^3) 1	2	3
1	6.3204E+01	1.2735E+03	6.3383E+02	6.3969E+02	0.0000E+00
2	2.0343E+02	4.0990E+03	3.3317E+03	7.6722E+02	0.0000E+00
3	1.5884E+02	3.2004E+03	2.8726E+03	3.2786E+02	0.0000E+00
4	7.3818E+01	1.4874E+03	1.4811E+03	6.2703E+00	0.0000E+00
5	2.8574E+01	5.7574E+02	6.2397E+02	-4.8234E+01	0.0000E+00

```
   6  1.6233E+01  3.2709E+02   3.6277E+02 -3.5680E+01  0.0000E+00
   7  6.2943E+00  1.2683E+02   1.1568E+02  1.1150E+01  0.0000E+00
 SUM  5.5039E+02  1.1090E+04   9.4217E+03  1.6683E+03  0.0000E+00

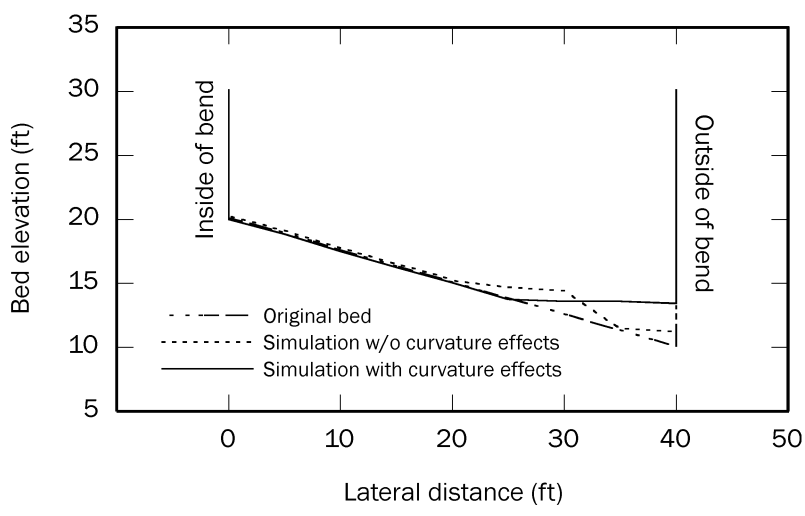
--------------------------------------------------------------------------------
         ACCUMULATED SEDIMENT DISTRIBUTION THAT EXITED THE REACH (TONS)
SIZE FR    TOTAL        TUBE #1     TUBE #2     TUBE #3     TUBE #4     TUBE #5
--------------------------------------------------------------------------------
   1    2.2491E+02    7.5855E+00  1.4643E+01  2.2167E+01  6.9885E+01  1.1063E+02
   2    5.8038E+01    0.0000E+00  1.4662E+01  2.2445E+01  2.0075E+01  8.5557E-01
   3    0.0000E+00    0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
 TOTAL  2.8295E+02    7.5855E+00  2.9305E+01  4.4612E+01  8.9961E+01  1.1148E+02
--------------------------------------------------------------------------------


* * * * * *  GSTARS run completed successfully  * * * * * *
```

3.3 Results and Discussion

It is easy to modify the input data file to observe the differences between the computations with and without exchange across the stream tubes due to the effects of bed slope and channel curvature: simply comment out, or delete, the CV records. A comparison of the two is presented in figure 3.2 for cross section 6, which is located at the end of the channel bend. The cross section plot of figure 3.2 was produced using data from the GSTARS3 cross section data output file (.XPL) and a typical plotting software package.

Figure 3.2 Cross-sectional profiles for cross section #6 for GSTARS3 runs with and without exchange of sediments across stream tube boundaries (designated by “curvature effects” in the legend).



The results match what is expected under the design conditions: the direction of the sediment transport has a significant transverse component, resulting in a movement of the particles from the inner to the outer side of the cross section. The depositional pattern corresponds to what is observed in similar experimental conditions. On the contrary, when the transverse component of the transport is ignored, the depositional pattern is significantly different and somewhat odd.

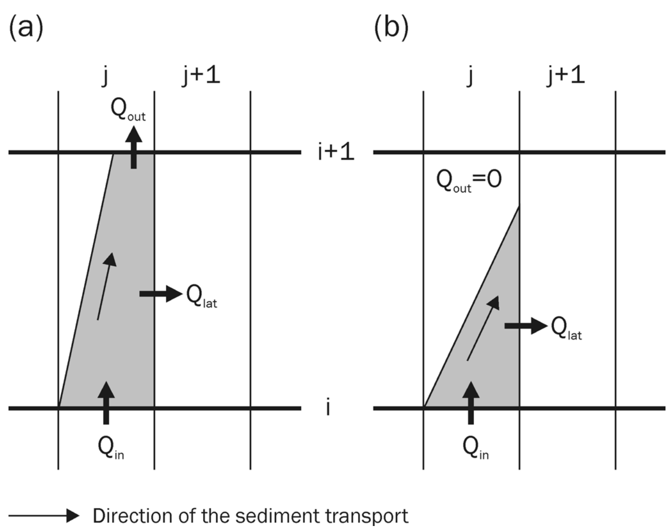
Finally, it is convenient to address the warning messages that appear in the main output file (see section 3.2.1). These have the form:

```
…
WARNING: stations    0 and    1 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.

WARNING: stations    1 and    2 are too far apart in sediment
transport computations. Reduce cross section spacing or deactivate
the computations of sediment exchange between stream tubes.
```

These messages indicate that the situation depicted in figure 3.3(b) has been encountered. This situation is undesirable because of how sediment transport capacities are calculated in relation to control volume boundaries. The simplest remedy is simply to use cross sections located closer to each other. By diminishing distance between cross sections, it becomes more likely that at least some sediment moves all the way to the downstream cross section that defines the lower boundary of the control volume. If the occurrence of these warning messages is infrequent, they can be safely ignored.

Figure 3.3 Representation of the sediment balance in a control volume between cross sections *i* and *i*+1, and two stream tubes, *j* and *j*+1. In (a), the direction of transport is such that $Q_{out} \neq 0$, while in (b) the balance between the transverse component and the distance between cross sections is such that $Q_{out} = 0$. In the latter case, all sediment exits the control volume through the stream tube boundary.



EXAMPLE 4

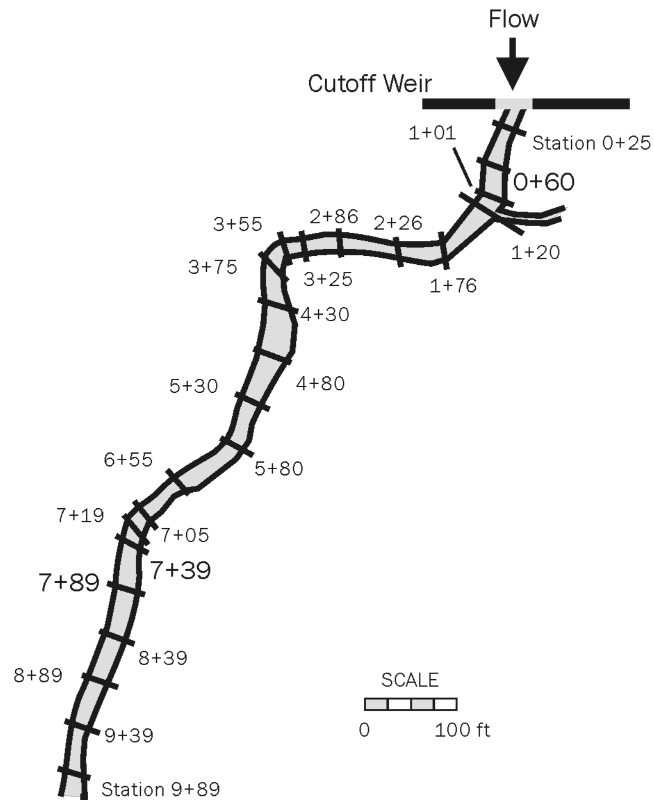
LAKE MESCALERO SPILLWAY CHANNEL

This example shows how to apply the concepts of bank stability and total stream power minimization implemented in GSTARS3. Together, these two concepts allow the computation of channel width variation and river meandering while maintaining the proper angle of repose of the river banks. To illustrate these features we use data from a study conducted on Lake Mescalero Dam and Dike. The study was performed by Song et al. (1995) using an earlier version of GSTARS. Their data was adopted, with modifications, for inclusion as an example in this manual.

The Lake Mescalero Dam and Dike were constructed in 1974 and are located at the confluence of Ciewegita and Carrige Creeks on the Mescalero Apache Indian Reservation about 2.5 miles southwest of Ruidoso, New Mexico. In this example we use data from the channel immediately downstream from the emergency spillway. The spillway is located in a bedrock cut in the sandstone and shale of the left abutment of the dam. The spillway consists of a 290-ft long approach channel, a 103.8-ft wide concrete weir, a 138-ft long concrete-lined discharge chute, a 15-ft long flip bucket, and a concrete erosion cutoff wall located about 250 ft downstream from the flip bucket. The spillway crest rises 5.0 ft above the spillway approach channel floor and the discharge chute floor, to a crest elevation of 6905.0 ft.

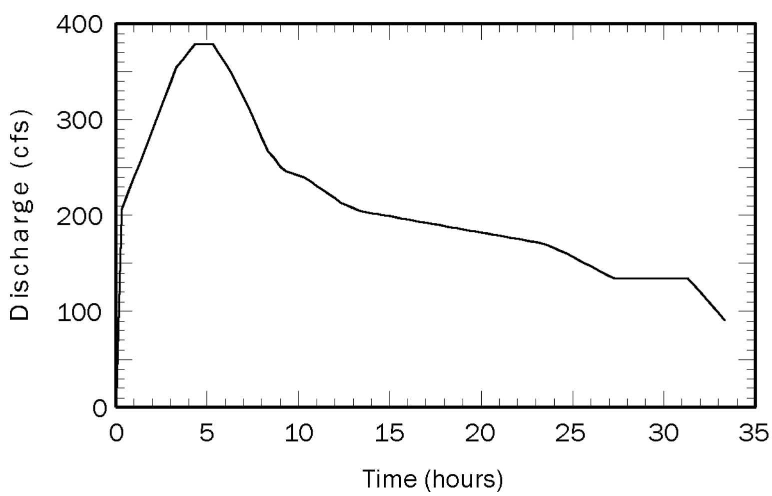
The data of the flood period of 20 December 1984 through 31 December 1984 is used in this example. The water surface elevation of the reservoir is available for that period. Cross-sectional data is taken from a detailed topographic survey of the study area carried out on 12 June 1979. Figure 4.1 shows the layout of the channel below the spillway at that time. Also, limited cross-sectional channel geometry is available after the 1984 flood. One of these sections is used later for comparison purposes.

Figure 4.1 Plan view of the channel below spillway used in this example datafile.



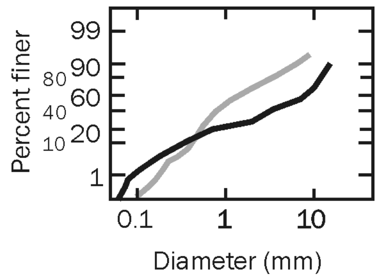
The water surface elevation of the reservoir is available for the period of the flood. The discharge hydrograph was generated using the water levels and a standard weir equation, $Q = CLH^{3/2}$ with $C = 3.65$. The flood hydrograph is shown in figure 4.2.

Figure 4.2 Spillway hydrograph for the December 1984 flood.



The sediment data used is based on bed samples collected from several sites along the channel. Two typical size distributions are plotted in figure 4.3. Based on the mean sediment size, a Manning's roughness coefficient of 0.06 is chosen for the stage-discharge computations.

Figure 4.3 Typical sediment particle size distributions collected in the spillway channel.



4.1 Input Data File

The files shown in this and the next sections are part of the main GSTARS3 distribution package. They can be found under directory Example4.

```
TT  GSTARS version 3.0  -  Example data file for Appendix B of user's manual
TT  Lake Mescalero Dam Spillway  -  St. Anthony Falls data file
TT  Stream power minimization calculations with bank stability routine

********************************************************************************
***                                                                          ***
***  NOTE: this is a simplified version of the datafile used to simulate     ***
***  the Lake Mescalero spillway.  It may not represent the actual flow and  ***
***  geological conditions at the site, and is used here only as an example  ***
***  of input data as it might be used in a GSTARS version 3.0 simulation.   ***
***  This file was constructed for didactic purposes only.                   ***
***                                                                          ***
********************************************************************************

NS    23
*** Cross Section Coordinate Order is X-Y
*** section 1
ST  989.      22     0.0     0.0     0.0     1.0     0.0
ND     1   227.0
XS 178.0   503.0   186.0   498.9   188.0   495.0   190.0   494.4   193.0   494.4
XS 195.0   494.3   196.5   494.3   198.0   494.3   199.0   494.3   200.0   494.2
XS 201.0   494.4   202.0   494.5   203.0   494.8   204.0   495.3   205.5   495.5
XS 208.0   496.5   210.0   497.7   215.0   497.9   220.0   498.1   223.0   498.3
XS 225.0   499.0   227.0   502.6
***
RH 0.060
*** ===========================================================================
***  section 2
ST 964.0      22     0.0     0.0     0.0     1.0     0.0
ND     1   214.0
```

```
***
XS 180.0   498.5   186.0   497.0   188.0   496.0   190.0   495.3   192.0   494.8
XS 194.0   493.8   195.5   493.4   197.0   493.0   198.5   492.8   200.0   492.7
XS 201.0   494.0   202.0   493.5   203.0   493.0   204.0   492.9   206.0   493.0
XS 207.0   494.0   208.0   493.1   210.0   495.5   212.0   497.0   214.0   498.7
XS 217.0   499.0   226.0   499.0
***
RH 0.060
*** ============================================================================
***   section 3
ST 929.0      20     0.0     0.0     0.0     1.0     0.0
ND     1   205.0

XS 172.0   498.5   178.0   494.1   180.0   491.5   183.0   491.0   185.0   490.5
XS 186.0   490.0   189.0   489.6   192.0   489.2   193.0   489.3   194.0   489.4
XS 195.0   489.5   196.0   489.6   197.0   489.7   198.4   489.8   199.0   490.1
XS 199.5   490.3   200.0   490.4   201.5   490.8   203.0   491.3   219.0   497.6
***
RH 0.060
*** ============================================================================
*** section 4
ST 888.0      22     0.0     0.0     0.0     1.0     0.0
ND     1   221.0

XS 177.0   495.0   179.0   492.9   181.0   487.5   181.7   486.5   182.5   486.4
XS 183.5   486.3   185.0   486.3   186.0   486.2   187.5   486.0   189.0   485.8
XS 190.0   485.6   192.0   485.3   193.0   487.0   194.0   488.0   195.0   491.0
XS 196.0   492.7   198.0   493.5   200.0   494.8   205.0   495.1   210.0   495.4
XS 215.0   495.8   221.0   496.1
***
RH 0.060
*** ============================================================================
*** section 5
ST 813.0      24     0.0     0.0     0.0     1.0     0.2
ND     1   182.0

XS 127.0   494.4   131.0   487.0   131.5   486.0   132.4   485.0   135.0   479.9
XS 136.0   480.3   137.0   480.6   138.0   480.8   139.0   481.0   140.0   481.5
XS 141.0   481.5   142.0   481.5   143.5   481.5   145.0   482.0   147.0   483.0
XS 150.0   484.0   157.0   486.0   161.0   487.7   165.0   489.0   170.0   490.0
XS 173.0   491.0   176.0   492.0   179.0   492.8   182.0   493.4
***
RH 0.060
*** ============================================================================
*** section 6
ST 763.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   185.0

XS 138.0   492.9   140.0   488.0   142.0   483.0   144.0   480.0   145.0   479.0
XS 148.0   479.0   150.0   478.6   151.0   478.6   153.0   478.7   155.0   478.7
XS 157.0   478.7   159.0   478.7   160.0   478.7   162.0   478.7   164.0   478.8
XS 165.0   478.8   167.0   478.9   168.5   478.9   170.0   478.9   172.0   479.2
XS 173.5   479.6   175.0   480.0   180.0   483.0   185.0   488.0
***
RH 0.060
*** ============================================================================
*** section 7
ST 703.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   198.5

XS 155.0   490.5   157.0   485.0   159.0   480.9   163.0   480.0   167.0   479.0
```

```
XS 168.5   478.0   170.0   478.0   171.0   477.8   172.0   477.8   173.0   477.0
XS 174.0   476.9   175.0   476.9   176.0   476.9   177.0   476.8   178.0   476.6
XS 179.0   476.6   180.0   476.3   181.5   478.0   183.0   480.0   186.0   484.5
XS 190.0   488.0   193.0   490.0   197.0   490.0   198.5   491.0
***
RH 0.060
*** ============================================================================
*** section 8
ST 664.0      21     0.0     0.0     0.0     1.0     0.0
ND     1   194.0

XS 158.0   488.3   160.0   483.0   162.0   480.0   165.0   478.0   166.0   477.0
XS 167.0   476.0   168.0   474.3   169.0   475.0   170.0   475.1   171.0   475.1
XS 172.0   475.2   174.0   475.2   176.0   475.3   178.0   475.4   179.0   475.4
XS 180.0   477.0   183.0   480.0   187.0   483.0   190.0   487.0   192.0   489.0
XS 194.0   489.5
***
RH 0.060
*** ============================================================================
***   section 9
ST 634.0      23     0.0     0.0     0.0     1.0     0.0
ND     1   194.0

XS 153.0   488.9   157.0   485.0   160.0   483.5   163.0   483.0   165.0   478.0
XS 166.0   476.0   167.0   475.0   168.0   474.0   169.0   474.0   170.0   474.1
XS 171.0   474.1   172.0   474.2   173.0   474.2   174.0   474.3   175.0   474.3
XS 176.0   474.4   177.0   475.4   178.0   476.0   180.0   477.0   183.0   480.0
XS 187.0   483.0   190.0   487.0   194.0   491.0
***
RH 0.060
*** ============================================================================
***   section 10
ST 614.0      22     0.0     0.0     0.0     1.0     0.2
ND     1   204.0

XS 148.0   489.3   150.0   482.0   152.0   477.7   155.0   477.0   157.0   476.0
XS 160.0   475.0   163.0   474.0   165.0   473.5   167.0   473.1   168.5   473.1
XS 170.0   473.1   173.0   473.0   176.0   473.0   179.0   473.1   182.0   477.1
XS 185.0   478.0   188.0   480.0   191.0   483.0   194.0   487.0   197.0   490.0
XS 200.0   492.3   204.0   492.3
***
RH 0.060
*** ============================================================================
***   section 11
ST 559.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   190.0

XS 135.0   488.0   138.0   480.0   139.0   475.0   141.5   472.5   143.0   472.6
XS 144.5   472.6   146.0   472.7   147.0   472.7   148.0   472.7   149.0   472.8
XS 150.0   472.8   153.0   472.9   155.0   473.0   157.0   473.0   158.0   473.0
XS 159.0   473.1   160.0   473.1   162.0   473.2   164.0   473.2   166.0   473.3
XS 170.0   473.4   175.0   477.0   185.0   479.5   190.0   491.0
***
RH 0.060
*** ============================================================================
***   section 12
ST 509.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   204.0

XS 130.0   485.1   131.5   480.0   133.0   475.6   137.0   474.0   140.0   473.0
XS 143.0   472.0   147.0   471.5   153.0   470.1   157.0   471.0   160.0   471.0
```

```
XS 164.0   471.0   167.0   473.0   170.0   475.0   173.0   478.0   177.0   481.0
XS 180.0   482.0   183.0   483.5   187.0   485.0   190.0   486.3   193.0   486.8
XS 197.0   487.0   200.0   487.3   202.0   487.5   204.0   487.6
***
RH 0.060
*** ============================================================================
***   section 13
ST 459.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   190.0

XS 123.0   483.9   130.0   480.0   135.0   478.0   140.0   476.0   143.0   474.0
XS 147.0   478.0   150.0   472.7   151.0   469.0   152.0   469.0   153.0   468.0
XS 155.0   467.0   157.0   467.0   159.0   466.7   161.0   466.5   163.0   466.2
XS 164.5   467.0   166.0   468.0   170.0   470.0   173.0   473.0   177.0   476.0
XS 180.0   479.0   182.0   483.2   186.0   484.0   190.0   485.5
***
RH 0.060
*** ============================================================================
***  section 14
ST 409.0      22     0.0     0.0     0.0     1.0     0.2
ND     1   205.0

XS 135.0   482.4   137.0   477.0   139.0   470.9   143.0   468.0   144.0   467.0
XS 146.0   466.0   148.0   465.0   150.0   464.0   151.0   463.6   153.0   463.2
XS 155.0   463.3   157.0   463.4   158.5   463.5   160.0   463.6   162.5   464.5
XS 165.0   466.0   170.0   469.0   175.0   472.0   180.0   474.0   185.0   476.0
XS 190.0   478.0   205.0   482.5
***
RH 0.060
*** ============================================================================
***   section 15
ST 334.0      23     0.0     0.0     0.0     1.0     0.0
ND     1   200.0

XS 144.0   479.7   147.0   478.0   150.0   475.0   153.0   473.0   157.0   471.0
XS 160.0   469.4   162.0   467.4   164.0   465.2   166.0   464.2   168.0   463.2
XS 169.5   462.3   171.0   461.5   172.0   461.3   173.0   461.1   174.0   460.7
XS 175.0   460.4   177.0   461.5   178.5   463.5   180.0   465.0   185.0   470.0
XS 190.0   475.0   195.0   478.0   200.0   480.5
***
RH 0.060
*** ============================================================================
***   section 16
ST 284.0      23     0.0     0.0     0.0     1.0     0.0
ND     1   197.0

XS 146.0   478.0   150.0   476.0   153.0   474.0   157.0   472.0   160.0   470.0
XS 164.0   468.5   167.0   465.5   168.5   464.5   170.0   463.5   172.0   461.5
XS 174.0   460.3   175.0   460.3   177.0   460.4   178.0   460.4   179.0   460.4
XS 180.0   460.5   182.0   460.6   184.0   465.0   187.0   470.0   189.0   475.2
XS 191.0   477.2   194.0   479.3   197.0   479.4
***
RH 0.060
*** ============================================================================
***   section 17
ST 270.0      24     0.0     0.0     0.0     1.0     0.2
ND     1   200.0

XS 145.0   477.7   148.0   475.7   150.0   473.7   153.0   472.2   157.0   469.0
XS 160.0   466.0   161.5   465.9   163.0   463.0   165.0   461.0   167.0   459.0
XS 168.5   458.9   170.0   458.6   172.5   458.5   175.0   459.0   177.5   459.3
```

```
XS 180.0   459.5   182.0   460.0   184.0   460.5   185.5   465.0   187.0   470.0
XS 190.0   478.1   193.0   478.3   197.0   478.6   200.0   478.8
***
RH 0.060
*** ============================================================================
***   section 18
ST 250.0      23     0.0     0.0     0.0     1.0     0.0
ND     1   211.0

XS 149.0   477.3   155.0   475.3   160.0   473.0   163.0   470.0   166.0   468.0
XS 167.0   462.0   169.0   460.0   171.0   458.0   172.5   458.0   174.0   458.1
XS 176.0   458.1   178.0   458.1   179.0   458.1   180.0   458.2   181.5   458.2
XS 183.0   458.2   185.5   460.0   187.0   462.0   190.0   466.0   197.0   472.0
XS 200.0   475.0   205.0   474.8   211.0   474.6
***
RH 0.060
*** ============================================================================
***   section 19
ST 200.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   188.0

XS 138.0   476.6   140.0   473.1   142.0   469.6   145.0   469.4   147.0   460.9
XS 149.0   457.4   151.0   457.2   153.0   457.0   155.0   456.8   157.0   456.6
XS 160.0   456.3   162.0   456.5   164.0   456.7   166.0   457.0   168.0   457.3
XS 170.0   457.6   172.0   457.8   174.0   458.0   176.0   458.2   178.0   460.7
XS 180.0   463.2   182.0   465.7   184.0   468.2   188.0   473.2
***
RH 0.060
*** ============================================================================
***   section 20
ST 150.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   190.0

XS 144.0   474.2   145.0   473.2   146.0   470.2   147.0   467.5   148.0   462.5
XS 150.0   461.3   152.0   460.1   154.0   459.0   156.0   457.8   158.0   456.5
XS 160.0   455.5   162.0   455.7   164.0   456.0   166.0   456.2   168.0   456.4
XS 170.0   456.6   172.0   456.7   174.0   456.6   176.0   456.9   178.0   457.0
XS 182.0   460.7   185.0   464.3   187.0   467.3   190.0   471.3
***
RH 0.060
*** ============================================================================
***   section 21
ST 100.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   190.0

XS 150.0   472.5   151.0   466.5   152.0   460.5   153.0   455.1   155.0   455.1
XS 157.0   455.1   159.0   455.0   161.0   455.0   163.0   455.0   165.0   454.9
XS 167.0   454.9   169.0   454.8   171.0   454.8   173.0   454.9   175.0   455.1
XS 177.0   455.2   179.0   455.4   181.0   455.5   183.0   455.6   186.0   455.7
XS 189.0   460.5   191.0   463.0   194.0   466.7   200.0   469.1
***
RH 0.060
*** ============================================================================
***   section 22
ST  50.0      24     0.0     0.0     0.0     1.0     0.0
ND     1   184.0

XS 144.0   470.2   147.0   469.0   150.0   467.5   154.0   466.3   155.0   464.0
XS 156.0   462.3   157.0   459.6   159.0   459.4   161.0   459.2   163.0   459.0
XS 165.0   458.9   168.0   458.7   170.0   458.0   172.0   457.3   174.0   456.6
XS 176.0   456.0   177.0   455.3   178.0   454.7   179.0   454.0   180.0   457.0
```

```
XS 181.0   460.0   182.0   463.0   183.0   466.0   184.0   468.7
***
RH 0.060
*** ==========================================================================
***   section 23
ST   0.0      24     1.0     1.0     0.0     1.0     0.0
ND     1   170.0

XS 129.0   463.8   133.0   463.0   136.0   462.1   139.0   461.2   141.0   460.0
XS 143.0   458.8   145.0   457.6   147.0   456.4   149.0   455.2   151.0   454.0
XS 152.0   452.6   153.0   452.5   154.0   452.4   155.0   452.4   156.0   452.3
XS 157.0   452.3   158.0   452.2   160.0   452.2   162.0   452.1   163.0   452.1
XS 165.0   455.6   167.0   459.0   169.0   462.5   170.0   466.2
***
RH 0.060
*** ==========================================================================
RE      MANNING
   number of stream tubes
NT     3
IT   100       1      20 min
QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE
TL    23

   stage discharge table for section cross section #23
SQ 206.4   454.0
SQ 222.8   454.0
SQ 239.3   454.0
SQ 255.7   454.0
SQ 272.1   454.0
SQ 288.6   454.0
SQ 305.0   454.0
SQ 321.4   454.0
SQ 337.8   454.0
SQ 354.2   454.0
SQ 362.4   454.0
SQ 370.7   454.0
SQ 378.9   454.0
SQ 378.9   454.0
SQ 378.9   454.0
SQ 378.9   454.0
SQ 368.7   454.0
SQ 358.6   454.0
SQ 348.2   454.0
SQ 335.6   454.0

SQ 323.0   454.0
SQ 310.4   454.0
SQ 295.9   454.0
SQ 281.4   454.0
SQ 267.0   454.0
SQ 260.0   454.0
SQ 251.0   454.0
SQ 246.1   454.0
SQ 243.9   454.0
SQ 241.7   454.0
SQ 239.6   454.0
SQ 235.3   454.0
SQ 231.0   454.0
SQ 226.6   454.0
SQ 222.3   454.0
```

```
SQ 218.3   454.0
SQ 213.6   454.0
SQ 210.6   454.0
SQ 207.6   454.0
SQ 204.7   454.0

SQ 203.6   454.0
SQ 202.5   454.0
SQ 201.4   454.0
SQ 200.3   454.0
SQ 199.2   454.0
SQ 198.0   454.0
SQ 196.9   454.0
SQ 195.8   454.0
SQ 194.6   454.0
SQ 193.5   454.0
SQ 192.4   454.0
SQ 191.3   454.0
SQ 190.2   454.0
SQ 189.1   454.0
SQ 187.9   454.0
SQ 186.9   454.0
SQ 185.7   454.0
SQ 184.5   454.0
SQ 183.4   454.0
SQ 182.3   454.0

SQ 181.2   454.0
SQ 180.1   454.0
SQ 179.0   454.0
SQ 177.8   454.0
SQ 176.7   454.0
SQ 175.6   454.0
SQ 174.4   454.0
SQ 173.3   454.0
SQ 172.2   454.0
SQ 171.1   454.0
SQ 168.6   454.0
SQ 166.2   454.0
SQ 163.7   454.0
SQ 160.4   454.0
SQ 157.1   454.0
SQ 153.8   454.0
SQ 150.5   454.0
SQ 147.2   454.0
SQ 143.9   454.0
SQ 140.6   454.0

SQ 137.3   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
SQ 134.0   454.0
```

```
SQ 134.0   454.0
SQ 127.0   454.0
SQ 120.0   454.0
SQ 112.7   454.0
SQ 105.6   454.0
SQ  98.5   454.0
SQ  91.4   454.0

    sediment
SE     6     100
QS   2.0     0.0
QS   2.0    11.0
QS   2.0    23.0
QS   2.0    17.0
QS   2.0    11.0
QS   2.0     6.0
QS  88.0     0.0

    water temperature
TM 100.0    70.0

    particle size classes
SF   5.0
SG   .06     .80
SG   .80    2.00
SG  2.00    5.00
SG  5.00   10.00
SG 10.00   20.00

    bed gradation
SD   .11     .17     .24     .41     .07
SD   .11     .17     .24     .41     .07
SD   .11     .17     .24     .41     .07
SD   .38     .30     .17     .10     .05
SD   .38     .30     .17     .10     .05
SD   .38     .30     .17     .10     .05
SD   .24     .26     .24     .09     .17
SD   .24     .26     .24     .09     .17
SD   .24     .26     .24     .09     .17
SD   .10     .23     .23     .19     .25
SD   .10     .23     .23     .19     .25
SD   .10     .23     .23     .19     .25
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15
SD   .06     .26     .30     .23     .15

AR    60      90

PR     2     100
PX   100  CROSS SECTION PLOTS
PW   100  WATER SURFACE PROFILE PLOTS

   minimization instructions
```

```
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   420.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0
MR   0.0   400.0   400.0   700.0

END
```

4.2 Output Data Files

All the output files for this example can be found in the standard GSTARS3 distribution package in electronic form, in directory Example4.

4.3 Results and DIscussion

In the GSTARS3 distribution are included both the input file of section 4.1 (file name mescal.dat under directory Example4) and a similar file for a run without using the stream power minimization routines (file name mescal_nm.dat under directory Example4). The files are identical with the exception of the stream power minimization records: the file mescal_nm.dat uses LM records to enforce the erosion limits and, of course, has no MR records. The results produced using both datafiles are shown in figure 4.4 for a cross section, and in figure 4.5 for the changes in the thalweg profile. The survey data is also plotted in those graphs.

The cross section data used to produce the plot in figure 4.4 was taken from the GSTARS3 cross section profile output file (file .XPL), and from the water surface profile output file (file .WPL) for figure 4.5. Section 0+60 is located 60 ft downstream from the spillway (section #3 in the GSTARS3 file, at 929 ft). In this cross section, significant differences are observed when stream power minimization calculations are activated. Both the shape of the cross section and its thalweg are more accurately predicted when the stream power minimization computations were activated by the use of the MR records.

Figure 4.4 Comparison of results produced by GSTARS3 and survey data, for runs with and without width changes due to stream power minimization. Section 0+60.

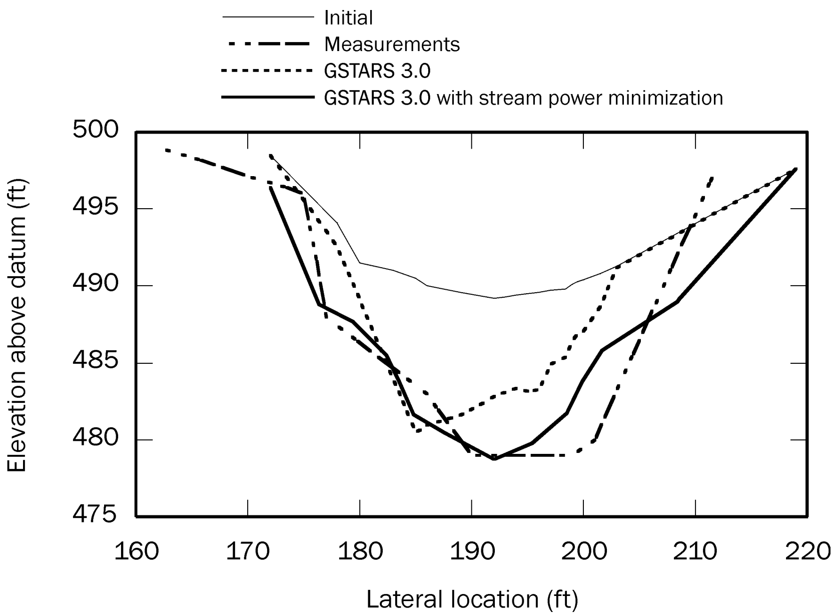
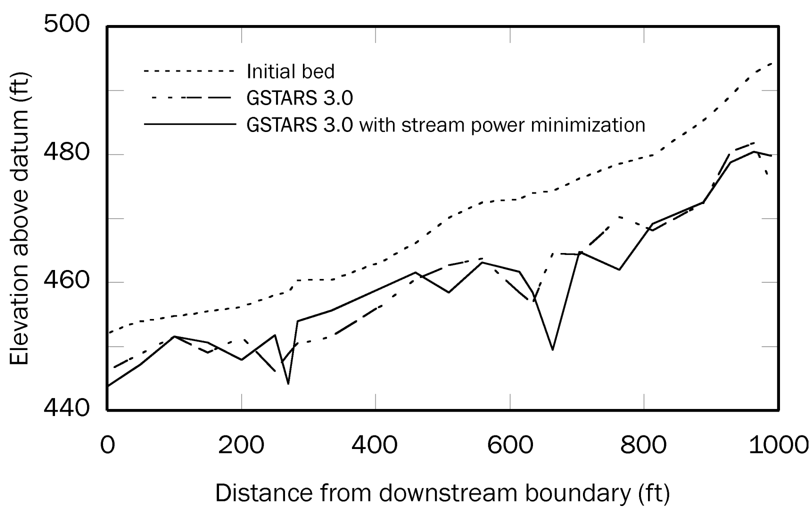


Figure 4.5 Plot of the thalweg for both GSTARS3 runs, i.e., for runs with and without stream power minimization computations.



Note that the results obtained with GSTARS3 and shown in this section differ from the results obtained earlier by Song et al. (1995). There are several reasons for these differences:

1 The version of GSTARS used by Song et al. (1995) was an early version, preceding even GSTARS 2.0, dated back to 1986. Their data file was adopted for the present example for didactic purposes only, therefore there was no attempt to recalibrate the data using GSTARS3.

2 Song et al. (1995) used an algorithm to compute exchange of sediment across stream tubes which is not activated in the present runs of GSTARS3.

3 Song et al. (1995) used a laboratory-derived method to compute the scour due to the water fall produced below the cut-off weir. That method uses an approach specifically developed to compute the scour by a free falling water jet. The free-falling jet occurs at the end of the spillway, which is formed by a concrete wall followed by an unpaved natural channel. As the unlined channel gets eroded, the difference in level between the lined (unerodible) spillway and the natural channel becomes too large and results in a free-falling jet. Such a method is not present in GSTARS3.

Furthermore, some differences between GSTARS3 output and its earlier versions, such as GSTARS 2.0 and 2.1, may be apparent. This is because some of the algorithms in GSTARS3 are different from earlier versions of the program, resulting in slightly different results, even if the same input data file is used. This means that **new calibration may be needed when using GSTARS3 on data files generated for older versions of the program**.

4.4 References

Song. C.C.S., Zheng, Y., and Yang, C.T. (1995). "Modeling of river morphologic changes," *Int. J. Sed. Res.* **10**(2), pp. 1–20.

EXAMPLE 5

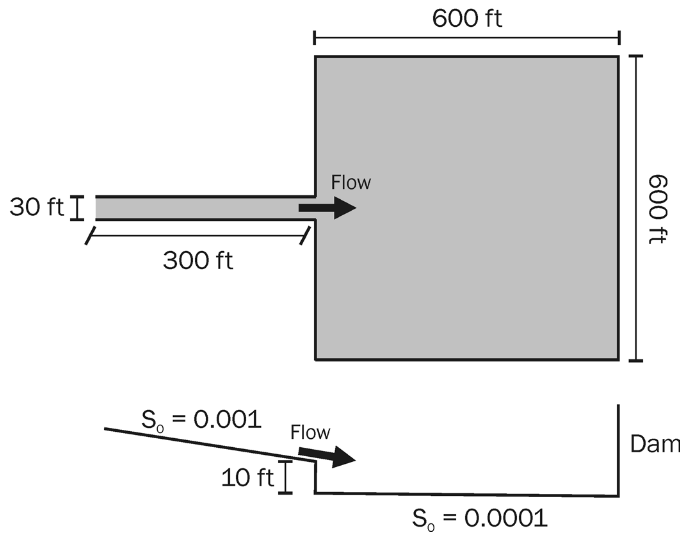
RESERVOIR ROUTING AND VOLUME COMPUTATIONS

GSTARS3 can calculate reservoir capacity tables and use them to determine reservoir volumes and corresponding water surface elevations at the dam. That is accomplished using mass conservation principles, as described in chapter 5. This example shows how to set-up a simple reservoir routing problem and how to interpret the results of the computations. For this purpose an idealized small reservoir is used, similar to what could be constructed to serve as a settling basin or pond, for example. The problem to be solved consists in computing the basin's volume and stage during a cycle in which the basin is emptied and refilled.

The basin is a 600-ft square placed at the downstream end of a 30-ft wide rectangular channel. The principal geometric characteristics of this configuration are sketched in figure 5.1. The study uses 14 cross sections, 7 in the pond and 7 in the approaching channel. The cross sections are placed 50 ft apart. However, the last cross section in the channel is placed only 10 ft from the first in the pond, which is done to ensure a certain level of accuracy in the reservoir volume computations.

The channel discharge is a constant 100 cfs. In this example, the pond is emptied at a rate of 120 cfs. When the low water mark is reached, at 2 ft of elevation at the dam, the outlet discharge is reduced to 90 cfs to allow for a slower refilling of the pond. To simplify the problem, no sediment transport is involved. This allows for the pond's capacity table to be calculated only once, at the beginning of the computations: because the pond's geometry does not change, there is no need to recompute that table. Using daily time steps and the hydrology described above, only ten daily time steps are needed to complete the cycle.

Figure 5.1 Plan view (top) and side view (bottom) of the idealized pond and approach channel used in example 5.



The hydrology is specified using DISCHARGE AT DAM in record SS, with DISCRETIZED DISCHARGES in record QQ. This configuration requires DD records for the inflow discharges, and RQ records for the pond outflow discharges. Record HR is used to define the major reservoir parameters.

Finally, due to the simplicity of this problem, minimal output is requested: *IPRLVL* set to 0 in record PR, with output requested every second time step. No cross-sectional or water profile plotting is requested in records PX and PW.

5.1 Input Data File

The files shown in this and the next section are part of the main GSTARS3 distribution package. They can be found under directory Example5.

```
TT   GSTARS version 3.0  -  Example data file for Appendix B of user's manual
TT  Simulation of emptying and refilling of a retention pond to illustrate the
TT    reservoir routing capabilities of GSTARS3    ---HYDRAULICS ONLY---

********************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It represents a      ***
***  ficticious case and it sould be viewed as such.  It should not be used  ***
***  for any other purpose without appropriate verification and validation.  ***
***                                                                          ***
***  -------------------------------------------------------------           ***
***  Problem Description: draw-down and refilling of impoundment             ***
***  Data Filename: Pond.dat                                                 ***
***  Shape: square pond, 600 x 600 ft, rectangular cross sections            ***
***  Channel Length: 300 ft                                                  ***
***  Bed slope: 0.001 (channel) and 0.0001 (impoundment)                     ***
```

```
***  Number of Stations: 14 (7 on channel, 7 in impoundment)                ***
***  Testing: reservoir routing and volume routines of GSTARS3            ***
***  ------------------------------------------------------------           ***
****************************************************************************

NS    14      10

***  Approach channel (S0 = 0.001).
ST   900       4                  10.30
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   850       4                  10.25
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   800       4                  10.20
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   750       4                  10.15
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   700       4                  10.10
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   650       4                  10.05
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030

ST   610       4                  10.01
ND     1     600
XS     0      30       0       0      30       0      30      30
RH 0.030


***  Pond starts here.
ST   600       4                   0.06
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST   500       4                   0.05
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST   400       4                   0.04
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST   300       4                   0.03
```

```
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST   200       4                    0.02
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST   100       4                    0.01
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

ST     0       4       1       1
ND     1     600
XS     0      30       0       0     600       0     600      30
RH 0.030

NT     1

IT    10       1       1     DAY

QQ      DISCRETIZED DISCHARGES
SS      DISCHARGE AT DAM

HR            15       2      25
DD    10     100
RQ     1     100
RQ     2     120
RQ     1     115
RQ     6      90


   Print control
PR             2
PX
PW

END
```

5.2 Output Data File

5.2.1 Main Output File (.OUT)

```
             GGGGG     SSSSS   TTTTTTTT     A     RRRRRR     SSSSS
            GGGGGGG   SSSSSSS  TTTTTTTT    AAA    RRRRRRR   SSSSSSS
           GG     GG SS     SS    TT      AA AA   RR     RR SS     SS
           GG         SS          TT     AA   AA  RR     RR SS
           GG  GGGGG  SSSSSSS     TT    AA     AA RRRRRRR   SSSSSSS
           GG  GGGGG   SSSSSSS    TT    AAAAAAAAA RRRRRR     SSSSSSS
           GG     GG        SS    TT    AAAAAAAAA RR RR           SS
           GG     GG SS     SS    TT    AA     AA RR  RR   SS     SS
            GGGGGGG   SSSSSSS     TT    AA     AA RR   RR   SSSSSSS
             GGGGG     SSSSS      TT    AA     AA RR    RR   SSSSS

GSTARS Version 3.0 - Dec 2002                         U.S. Bureau of Reclamation
```

```
INPUT FILE:  Pond.dat                                    Technical Service Center
DATE OF RUN:  7 Jul 2003                                 Denver, Colorado
TIME OF RUN: 21:42:30


********************************************************************************
*    GSTARS version 3.0  -  Example data file for Appendix B of user's manual  *
*   Simulation of emptying and refilling of a retention pond to illustrate the *
*     reservoir routing capabilities of GSTARS3    ---HYDRAULICS ONLY---    *
********************************************************************************


* * * * * * *   SUMMARY OF INPUT PARAMETERS   * * * * * * *

Number of cross sections:..........................    14
Number of stream tubes:............................     1
Number of time steps:..............................    10
Duration of time step (days):......................  1.0000E+00
Formula selected for conveyance calculations:........  MANNING
Formula selected for friction slope:.................  average
Computation of reservoir capacity table (time steps):    12
Printout control is  0; print interval:.............     2
Do not generate x-sec plots.
Do not generate thalweg plots.
No minimization requested.

Sect.  Location   ISWITCH  ITYP   Thalweg     Bed slope   Loss  NDIVI NPOINTS
   #     (ft)                       (ft)                  Coef.
------------------------------------------------------------------------------
   1   9.0000E+02    0       0   1.0300E+01   1.0000E-03  0.00    1       4
   2   8.5000E+02    0       0   1.0250E+01   1.0000E-03  0.00    1       4
   3   8.0000E+02    0       0   1.0200E+01   1.0000E-03  0.00    1       4
   4   7.5000E+02    0       0   1.0150E+01   1.0000E-03  0.00    1       4
   5   7.0000E+02    0       0   1.0100E+01   1.0000E-03  0.00    1       4
   6   6.5000E+02    0       0   1.0050E+01   1.0000E-03  0.00    1       4
   7   6.1000E+02    0       0   1.0010E+01   1.0000E-03  0.00    1       4
   8   6.0000E+02    0       0   6.0000E-02   9.9500E-01  0.00    1       4
   9   5.0000E+02    0       0   5.0000E-02   1.0000E-04  0.00    1       4
  10   4.0000E+02    0       0   4.0000E-02   1.0000E-04  0.00    1       4
  11   3.0000E+02    0       0   3.0000E-02   1.0000E-04  0.00    1       4
  12   2.0000E+02    0       0   2.0000E-02   1.0000E-04  0.00    1       4
  13   1.0000E+02    0       0   1.0000E-02   1.0000E-04  0.00    1       4
  14   0.0000E+00    1       1   0.0000E+00   1.0000E-04  0.00    1       4
------------------------------------------------------------------------------


********************************************************************************
********************************************************************************
    TIME STEP NO.     2 AFTER  2.0000E+00 DAYS; DISCHARGE IS  1.0000E+02 CFS
********************************************************************************
********************************************************************************


                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  1.0004E+02 C.F.S.      *
                 *********************************************

STA.  STATION   WATER SURFACE   FLOW AREA  FLOW VELCTY  ENERGY GRADE    FROUDE
```

```
 #    (ft)     ELEVATION(ft)    (ft^2)      (ft/s)     LINE ELEV(ft)   NUMBER
*******************************************************************************
 1  9.0000E+02  1.50644E+01  1.42933E+02  6.99911E-01  1.50720E+01  5.65082E-02
 2  8.5000E+02  1.50628E+01  1.44383E+02  6.93440E-01  1.50702E+01  5.57040E-02
 3  8.0000E+02  1.50611E+01  1.45834E+02  6.87093E-01  1.50685E+01  5.49187E-02
 4  7.5000E+02  1.50595E+01  1.47287E+02  6.80864E-01  1.50667E+01  5.41518E-02
 5  7.0000E+02  1.50580E+01  1.48741E+02  6.74751E-01  1.50651E+01  5.34027E-02
 6  6.5000E+02  1.50565E+01  1.50196E+02  6.68697E-01  1.50635E+01  5.26666E-02
 7  6.1000E+02  1.50554E+01  1.51361E+02  6.63815E-01  1.50622E+01  5.20804E-02
 8  6.0000E+02  1.50600E+01  9.00000E+03  1.13612E-02  1.50600E+01  5.16953E-04
 9  5.0000E+02  1.50500E+01  9.00000E+03  1.17198E-02  1.50500E+01  5.33268E-04
10  4.0000E+02  1.50400E+01  9.00000E+03  1.20783E-02  1.50400E+01  5.49584E-04
11  3.0000E+02  1.50300E+01  9.00000E+03  1.24369E-02  1.50300E+01  5.65899E-04
12  2.0000E+02  1.50200E+01  9.00000E+03  1.27955E-02  1.50200E+01  5.82215E-04
13  1.0000E+02  1.50100E+01  9.00000E+03  1.31540E-02  1.50100E+01  5.98530E-04
14  0.0000E+00  1.50000E+01  9.00000E+03  1.33333E-02  1.50000E+01  8.01459E-02


     ********************************************************************
                          RESERVOIR ROUTING TABLES
      STA.  LOCATION     DISCHARGE    A-COEFFS.      STAGE       VOLUME
        #     (ft)       (ft^3/s)       (-)          (ft)         (ft^3)
     ********************************************************************
        1  9.00000E+02  1.00040E+02  2.01695E-03  1.03000E+01  3.71972E+06
        2  8.50000E+02  1.00121E+02  4.03390E-03  1.02500E+01  3.70115E+06
        3  8.00000E+02  1.00202E+02  4.03390E-03  1.02000E+01  3.68265E+06
        4  7.50000E+02  1.00282E+02  4.03390E-03  1.01500E+01  3.66420E+06
        5  7.00000E+02  1.00363E+02  4.03390E-03  1.01000E+01  3.64582E+06
        6  6.50000E+02  1.00436E+02  3.63051E-03  1.00500E+01  3.62748E+06
        7  6.10000E+02  1.00476E+02  2.01695E-03  1.00100E+01  3.61270E+06
        8  6.00000E+02  1.02251E+02  8.87455E-02  6.00000E-02  1.06554E+04
        9  5.00000E+02  1.05478E+02  1.61355E-01  5.00000E-02  7.35999E+03
       10  4.00000E+02  1.08705E+02  1.61355E-01  4.00000E-02  4.66556E+03
       11  3.00000E+02  1.11932E+02  1.61355E-01  3.00000E-02  2.57274E+03
       12  2.00000E+02  1.15159E+02  1.61355E-01  2.00000E-02  1.08284E+03
       13  1.00000E+02  1.18386E+02  1.61355E-01  1.00000E-02  2.00000E+02
       14  0.00000E+00  1.20000E+02  8.06777E-02  0.00000E+00  0.00000E+00
     STAGE AT DAM:                                1.03481E+01
     MINIMUM STAGE AT DAM:                        2.00000E+00
     MAXIMUM STAGE AT DAM:                        2.50000E+01
     DISCHARGE AT DAM:  1.20000E+02
     VOLUME OF RESERVOIR:                                      3.73759E+06
     ********************************************************************

*******************************************************************************
*******************************************************************************
    TIME STEP NO.     4 AFTER  4.0000E+00 DAYS; DISCHARGE IS  1.0000E+02 CFS
*******************************************************************************
*******************************************************************************


                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  1.0000E+02 C.F.S.      *
                 *********************************************

STA.  STATION   WATER SURFACE   FLOW AREA  FLOW VELCTY  ENERGY GRADE    FROUDE
 #    (ft)     ELEVATION(ft)    (ft^2)      (ft/s)     LINE ELEV(ft)   NUMBER
*******************************************************************************
 1  9.0000E+02  1.17797E+01  4.43911E+01  2.25270E+00  1.18585E+01  3.26355E-01
 2  8.5000E+02  1.17053E+01  4.36603E+01  2.29041E+00  1.17868E+01  3.34584E-01
```

3	8.0000E+02	1.16257E+01	4.27719E+01	2.33798E+00	1.17106E+01	3.45062E-01
4	7.5000E+02	1.15389E+01	4.16676E+01	2.39994E+00	1.16284E+01	3.58870E-01
5	7.0000E+02	1.14416E+01	4.02473E+01	2.48464E+00	1.15374E+01	3.78033E-01
6	6.5000E+02	1.13272E+01	3.83147E+01	2.60997E+00	1.14329E+01	4.06993E-01
7	6.1000E+02	1.07196E+01	2.12870E+01	4.69769E+00	1.10622E+01	9.82792E-01
8	6.0000E+02	5.64170E+00	3.34902E+03	3.02666E-02	5.64172E+00	2.25763E-03
9	5.0000E+02	5.63170E+00	3.34902E+03	3.10069E-02	5.63172E+00	2.31285E-03
10	4.0000E+02	5.62170E+00	3.34902E+03	3.17473E-02	5.62172E+00	2.36807E-03
11	3.0000E+02	5.61170E+00	3.34902E+03	3.24876E-02	5.61172E+00	2.42329E-03
12	2.0000E+02	5.60170E+00	3.34902E+03	3.32279E-02	5.60172E+00	2.47852E-03
13	1.0000E+02	5.59170E+00	3.34902E+03	3.39682E-02	5.59172E+00	2.53374E-03
14	0.0000E+00	5.58170E+00	3.34902E+03	3.43384E-02	5.58172E+00	7.96938E-02

```
*********************************************************************
                      RESERVOIR ROUTING TABLES
 STA.  LOCATION     DISCHARGE    A-COEFFS.      STAGE       VOLUME
   #     (ft)       (ft^3/s)        (-)          (ft)        (ft^3)
*********************************************************************
    1  9.00000E+02  1.00000E+02
    2  8.50000E+02  1.00000E+02
    3  8.00000E+02  1.00000E+02
    4  7.50000E+02  1.00000E+02
    5  7.00000E+02  1.00000E+02
    6  6.50000E+02  1.00000E+02
    7  6.10000E+02  1.00000E+02
    8  6.00000E+02  1.01364E+02  9.09091E-02  6.00000E-02  1.06554E+04
    9  5.00000E+02  1.03843E+02  1.65289E-01  5.00000E-02  7.35999E+03
   10  4.00000E+02  1.06322E+02  1.65289E-01  4.00000E-02  4.66556E+03
   11  3.00000E+02  1.08802E+02  1.65289E-01  3.00000E-02  2.57274E+03
   12  2.00000E+02  1.11281E+02  1.65289E-01  2.00000E-02  1.08284E+03
   13  1.00000E+02  1.13760E+02  1.65289E-01  1.00000E-02  2.00000E+02
   14  0.00000E+00  1.15000E+02  8.26446E-02  0.00000E+00  0.00000E+00
STAGE AT DAM:                                2.00174E+00
MINIMUM STAGE AT DAM:                        2.00000E+00
MAXIMUM STAGE AT DAM:                        2.50000E+01
DISCHARGE AT DAM:  1.15000E+02
VOLUME OF RESERVOIR:                                      7.13593E+05
*********************************************************************

********************************************************************************
********************************************************************************
 TIME STEP NO.     6 AFTER  6.0000E+00 DAYS; DISCHARGE IS  1.0000E+02 CFS
********************************************************************************
********************************************************************************

                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  1.0000E+02 C.F.S.      *
                 *********************************************
```

STA. #	STATION (ft)	WATER SURFACE ELEVATION(ft)	FLOW AREA (ft^2)	FLOW VELCTY (ft/s)	ENERGY GRADE LINE ELEV(ft)	FROUDE NUMBER
1	9.0000E+02	1.17923E+01	4.47683E+01	2.23372E+00	1.18697E+01	3.22240E-01
2	8.5000E+02	1.17204E+01	4.41124E+01	2.26693E+00	1.18002E+01	3.29453E-01
3	8.0000E+02	1.16441E+01	4.33235E+01	2.30822E+00	1.17268E+01	3.38493E-01
4	7.5000E+02	1.15619E+01	4.23568E+01	2.36089E+00	1.16484E+01	3.50146E-01
5	7.0000E+02	1.14713E+01	4.11406E+01	2.43069E+00	1.15631E+01	3.65787E-01
6	6.5000E+02	1.07523E+01	2.10699E+01	4.74612E+00	1.11021E+01	9.98028E-01

```
  7  6.1000E+02  4.45202E+00  1.50001E+01  6.66664E+00  5.14215E+00  1.66148E+00
  8  6.0000E+02  4.44838E+00  2.63303E+03  3.76338E-02  4.44840E+00  3.16591E-03
  9  5.0000E+02  4.43838E+00  2.63303E+03  3.70061E-02  4.43840E+00  3.11310E-03
 10  4.0000E+02  4.42838E+00  2.63303E+03  3.63783E-02  4.42840E+00  3.06029E-03
 11  3.0000E+02  4.41838E+00  2.63303E+03  3.57505E-02  4.41840E+00  3.00748E-03
 12  2.0000E+02  4.40838E+00  2.63303E+03  3.51228E-02  4.40840E+00  2.95467E-03
 13  1.0000E+02  4.39838E+00  2.63303E+03  3.44950E-02  4.39840E+00  2.90186E-03
 14  0.0000E+00  4.38838E+00  2.63303E+03  3.41812E-02  4.38840E+00  7.70706E-02


     **********************************************************************
                          RESERVOIR ROUTING TABLES
      STA.  LOCATION     DISCHARGE    A-COEFFS.      STAGE       VOLUME
        #     (ft)       (ft^3/s)        (-)         (ft)        (ft^3)
     **********************************************************************
        1  9.00000E+02  1.00000E+02
        2  8.50000E+02  1.00000E+02
        3  8.00000E+02  1.00000E+02
        4  7.50000E+02  1.00000E+02
        5  7.00000E+02  1.00000E+02
        6  6.50000E+02  1.00000E+02
        7  6.10000E+02  1.00000E+02
        8  6.00000E+02  9.90909E+01  9.09091E-02  6.00000E-02  1.06554E+04
        9  5.00000E+02  9.74380E+01  1.65289E-01  5.00000E-02  7.35999E+03
       10  4.00000E+02  9.57851E+01  1.65289E-01  4.00000E-02  4.66556E+03
       11  3.00000E+02  9.41322E+01  1.65289E-01  3.00000E-02  2.57274E+03
       12  2.00000E+02  9.24793E+01  1.65289E-01  2.00000E-02  1.08284E+03
       13  1.00000E+02  9.08264E+01  1.65289E-01  1.00000E-02  2.00000E+02
       14  0.00000E+00  9.00000E+01  8.26446E-02  0.00000E+00  0.00000E+00
     STAGE AT DAM:                                6.77503E+00
     MINIMUM STAGE AT DAM:                        2.00000E+00
     MAXIMUM STAGE AT DAM:                        2.50000E+01
     DISCHARGE AT DAM:  9.00000E+01
     VOLUME OF RESERVOIR:                                      2.44159E+06
     **********************************************************************

********************************************************************************
********************************************************************************
    TIME STEP NO.     8 AFTER  8.0000E+00 DAYS; DISCHARGE IS  1.0000E+02 CFS
********************************************************************************
********************************************************************************


                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  1.0000E+02 C.F.S.      *
                 *********************************************

STA.  STATION   WATER SURFACE   FLOW AREA  FLOW VELCTY  ENERGY GRADE    FROUDE
  #     (ft)     ELEVATION(ft)    (ft^2)      (ft/s)     LINE ELEV(ft)   NUMBER
********************************************************************************
  1  9.0000E+02  1.17813E+01  4.44390E+01  2.25028E+00  1.18599E+01  3.25828E-01
  2  8.5000E+02  1.17073E+01  4.37178E+01  2.28740E+00  1.17885E+01  3.33924E-01
  3  8.0000E+02  1.16281E+01  4.28425E+01  2.33413E+00  1.17127E+01  3.44209E-01
  4  7.5000E+02  1.15419E+01  4.17565E+01  2.39484E+00  1.16309E+01  3.57725E-01
  5  7.0000E+02  1.14455E+01  4.03639E+01  2.47746E+00  1.15408E+01  3.76396E-01
  6  6.5000E+02  1.13326E+01  3.84790E+01  2.59882E+00  1.14375E+01  4.04388E-01
  7  6.1000E+02  1.07161E+01  2.11836E+01  4.72064E+00  1.10622E+01  9.90002E-01
  8  6.0000E+02  9.22167E+00  5.49700E+03  1.80264E-02  9.22168E+00  1.04952E-03
  9  5.0000E+02  9.21167E+00  5.49700E+03  1.77257E-02  9.21167E+00  1.03202E-03
 10  4.0000E+02  9.20167E+00  5.49700E+03  1.74250E-02  9.20167E+00  1.01451E-03
```

11	3.0000E+02	9.19167E+00	5.49700E+03	1.71243E-02	9.19167E+00	9.97005E-04
12	2.0000E+02	9.18167E+00	5.49700E+03	1.68236E-02	9.18167E+00	9.79498E-04
13	1.0000E+02	9.17167E+00	5.49700E+03	1.65229E-02	9.17167E+00	9.61991E-04
14	0.0000E+00	9.16167E+00	5.49700E+03	1.63726E-02	9.16167E+00	7.70706E-02

```
*********************************************************************
                      RESERVOIR ROUTING TABLES
 STA.  LOCATION     DISCHARGE    A-COEFFS.      STAGE       VOLUME
   #     (ft)        (ft^3/s)       (-)          (ft)        (ft^3)
*********************************************************************
    1  9.00000E+02  1.00000E+02
    2  8.50000E+02  1.00000E+02
    3  8.00000E+02  1.00000E+02
    4  7.50000E+02  1.00000E+02
    5  7.00000E+02  1.00000E+02
    6  6.50000E+02  1.00000E+02
    7  6.10000E+02  1.00000E+02
    8  6.00000E+02  9.90909E+01  9.09091E-02  6.00000E-02  1.06554E+04
    9  5.00000E+02  9.74380E+01  1.65289E-01  5.00000E-02  7.35999E+03
   10  4.00000E+02  9.57851E+01  1.65289E-01  4.00000E-02  4.66556E+03
   11  3.00000E+02  9.41322E+01  1.65289E-01  3.00000E-02  2.57274E+03
   12  2.00000E+02  9.24793E+01  1.65289E-01  2.00000E-02  1.08284E+03
   13  1.00000E+02  9.08264E+01  1.65289E-01  1.00000E-02  2.00000E+02
   14  0.00000E+00  9.00000E+01  8.26446E-02  0.00000E+00  0.00000E+00
STAGE AT DAM:                                 1.15111E+01
MINIMUM STAGE AT DAM:                         2.00000E+00
MAXIMUM STAGE AT DAM:                         2.50000E+01
DISCHARGE AT DAM:  9.00000E+01
VOLUME OF RESERVOIR:                                       4.16959E+06
*********************************************************************

*******************************************************************************
*******************************************************************************
    TIME STEP NO.    10 AFTER  1.0000E+01 DAYS; DISCHARGE IS  1.0000E+02 CFS
*******************************************************************************
*******************************************************************************

                 *********************************************
                 *     RESULTS OF BACKWATER COMPUTATIONS     *
                 *       DISCHARGE =  9.9980E+01 C.F.S.      *
                 *********************************************
```

STA. #	STATION (ft)	WATER SURFACE ELEVATION(ft)	FLOW AREA (ft^2)	FLOW VELCTY (ft/s)	ENERGY GRADE LINE ELEV(ft)	FROUDE NUMBER
1	9.0000E+02	1.39098E+01	1.08294E+02	9.23225E-01	1.39230E+01	8.56329E-02
2	8.5000E+02	1.39059E+01	1.09678E+02	9.11206E-01	1.39188E+01	8.39830E-02
3	8.0000E+02	1.39022E+01	1.11067E+02	8.99450E-01	1.39148E+01	8.23795E-02
4	7.5000E+02	1.38987E+01	1.12460E+02	8.87950E-01	1.39109E+01	8.08210E-02
5	7.0000E+02	1.38952E+01	1.13857E+02	8.76699E-01	1.39072E+01	7.93059E-02
6	6.5000E+02	1.38919E+01	1.15258E+02	8.65728E-01	1.39036E+01	7.78360E-02
7	6.1000E+02	1.38894E+01	1.16382E+02	8.57197E-01	1.39008E+01	7.66961E-02
8	6.0000E+02	1.38970E+01	8.30222E+03	1.19094E-02	1.38970E+01	5.64211E-04
9	5.0000E+02	1.38870E+01	8.30222E+03	1.17151E-02	1.38870E+01	5.55003E-04
10	4.0000E+02	1.38770E+01	8.30222E+03	1.15207E-02	1.38770E+01	5.45796E-04
11	3.0000E+02	1.38670E+01	8.30222E+03	1.13264E-02	1.38670E+01	5.36588E-04
12	2.0000E+02	1.38570E+01	8.30222E+03	1.11320E-02	1.38570E+01	5.27381E-04
13	1.0000E+02	1.38470E+01	8.30222E+03	1.09377E-02	1.38470E+01	5.18173E-04
14	0.0000E+00	1.38370E+01	8.30222E+03	1.08405E-02	1.38370E+01	7.70706E-02

```
*******************************************************************
                    RESERVOIR ROUTING TABLES
 STA.  LOCATION     DISCHARGE    A-COEFFS.     STAGE       VOLUME
   #     (ft)       (ft^3/s)       (-)         (ft)        (ft^3)
*******************************************************************
    1  9.00000E+02  9.99798E+01  2.01695E-03  1.03000E+01  3.71972E+06
    2  8.50000E+02  9.99395E+01  4.03390E-03  1.02500E+01  3.70115E+06
    3  8.00000E+02  9.98992E+01  4.03390E-03  1.02000E+01  3.68265E+06
    4  7.50000E+02  9.98588E+01  4.03390E-03  1.01500E+01  3.66420E+06
    5  7.00000E+02  9.98185E+01  4.03390E-03  1.01000E+01  3.64582E+06
    6  6.50000E+02  9.97822E+01  3.63051E-03  1.00500E+01  3.62748E+06
    7  6.10000E+02  9.97620E+01  2.01695E-03  1.00100E+01  3.61270E+06
    8  6.00000E+02  9.88745E+01  8.87455E-02  6.00000E-02  1.06554E+04
    9  5.00000E+02  9.72610E+01  1.61355E-01  5.00000E-02  7.35999E+03
   10  4.00000E+02  9.56474E+01  1.61355E-01  4.00000E-02  4.66556E+03
   11  3.00000E+02  9.40339E+01  1.61355E-01  3.00000E-02  2.57274E+03
   12  2.00000E+02  9.24203E+01  1.61355E-01  2.00000E-02  1.08284E+03
   13  1.00000E+02  9.08068E+01  1.61355E-01  1.00000E-02  2.00000E+02
   14  0.00000E+00  9.00000E+01  8.06777E-02  0.00000E+00  0.00000E+00
STAGE AT DAM:                                 1.61630E+01
MINIMUM STAGE AT DAM:                         2.00000E+00
MAXIMUM STAGE AT DAM:                         2.50000E+01
DISCHARGE AT DAM:  9.00000E+01
VOLUME OF RESERVOIR:                                       5.89759E+06
*******************************************************************


* * * * * *  GSTARS run completed successfully  * * * * * *
```

5.3 Results and Discussion

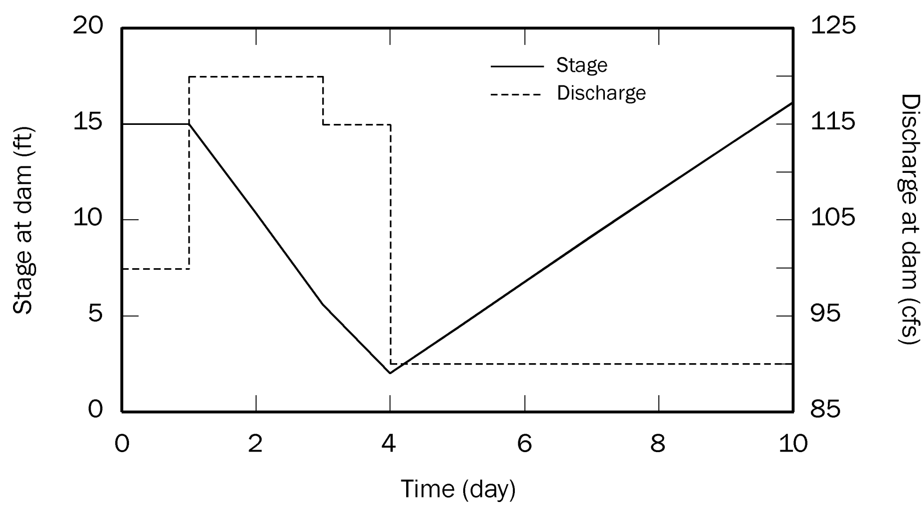
The reservoir routing tables are generated at the end of each time step (see the GSTARS3 main output file, .OUT, in section 5.2.1). They show the state of the reservoir at the end of the time step. These quantities will only be used in the next time step, as starting conditions. Of interest are the computed discharges for each cross section and the coefficients that are used in eq. (120). The volume of reservoir is the result of the mass balance for the time step in question, computed at the end of the time step, and it is the initial condition for the following time step. The same can be said about the stage at the dam.

Note that in some cases the discharge at the first cross section is not the same as the inflow discharge. That happens when the stage at the reservoir is higher than the thalweg of the first cross section. GSTARS3 assumes that all cross sections with thalweg lower than the stage at the dam belong to the reservoir, therefore their corresponding discharges are computed using the technique described in chapter 5. That means that those cross sections effectively contribute to reservoir storage, therefore their discharge will be higher than the inflow discharge in the case of reservoir draw-down, and will be lower in the case of reservoir fill-up. That can be observed in time steps 10 and 4, respectively.

Note that time step 4 has an outlet discharge of only 115 cfs, versus 120 cfs for the previous time steps. This is done so that the reservoir level never drops below 2 ft, which is the minimum reservoir depth allowed (see variable *RSTGMIN* in record HR). This example was set in this manner to emphasize the nature of the GSTARS3 computations in this case. Although the computations would proceed in the usual manner, if the stage at the dam falls below *RSTGMIN*, GSTARS3 simply resets the stage back up to *RSTGMIN* for the next time step. However, this results in conservation of reservoir volume being violated, because volume is artificially introduced in the reservoir as a result of that water level increase. During the computations the user should verify that this condition never happens. *RSTGMIN* should be viewed as a "safety net" for the backwater computations. Similarly, the stage at the dam should never allowed to become higher that *RSTGMAX* (also in record HR), as the resetting of the stage in this instance would result in the loss of reservoir volume. In this example, this problem could also be avoided by using 11 quarter-day time steps with an outflow discharge of 105 cfs—instead of 2 one-day time steps with 120 cfs followed by one with 115 cfs. The computations would be longer (more time steps to compute), but the results would be more accurate. This also illustrates the importance of choosing the right time step for the job at hand.

Finally, for illustration purposes, the data in the main output data file in section 5.2.1 was used to show the entire cycle simulated in this example (see figure 5.2). Note that the lowest stage at the dam reaches a value of 2.0017 ft, which is just above the minimum allowed in record HR. Note also that there is a change of slope in the draw-down rate of the reservoir at time step 3, which results from lowering the outlet discharge from 120 to 115 cfs. This change would not exist if the quarter-day time steps suggested in the previous paragraph were employed.

Figure 5.2 Outlet discharge and water surface elevation at the dam.

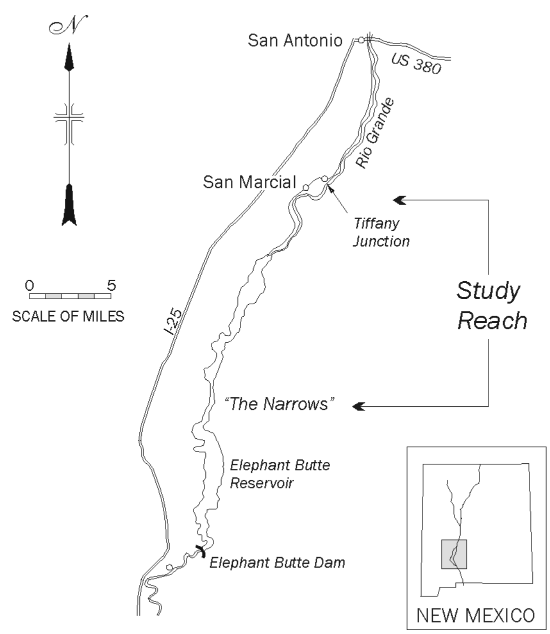


EXAMPLE 6

RIO GRANDE FLOODWAY

Example 6 is included here to illustrate the use of the cohesive sediment transport features of GSTARS3, as well as the use of non-equilibrium sediment transport. For this purpose some actual survey data collected in the Rio Grande floodway are used. The data corresponds to a stretch of the Rio Grande between San Marcial, New Mexico, and the upper end of Elephant Butte Reservoir, as shown in figure 6.1. This example consists of a reservoir sedimentation problem, with very fine sediments entering a reservoir and depositing in the upper reach of the modeled region (delta formation).

Figure 6.1 Location of the reach modeled in this example problem.



For this example, a total of 33 cross sections are used to represent a reach approximately 28 miles in length. The values of the Manning's roughness coefficients used are 0.024 for the main channel and 0.080 for the flood plains (RH records; see the input data file given in the next section). The hydrology data consist of daily flows and monthly water temperatures at the upstream end of the reach, and of daily reservoir elevations at the downstream end (figures 6.2 and 6.3). The input of these data is made by the use of the STAGE DISCHARGE TABLE (records QQ and SS) using SQ and TM records. The simulation is carried out for an 8-year period with time steps of 1 day for the hydraulics, with 5 sediment time steps per day (see record IT).

Figure 6.2 Hydrologic data for the Rio Grande example problem.

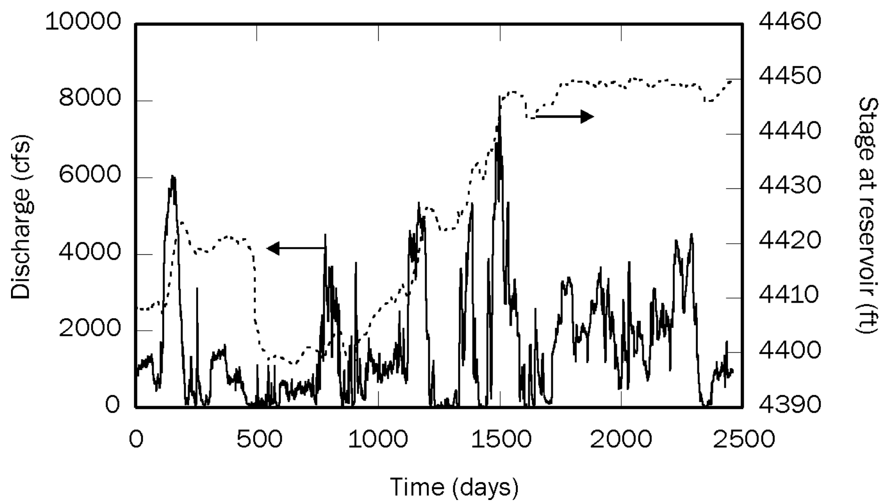
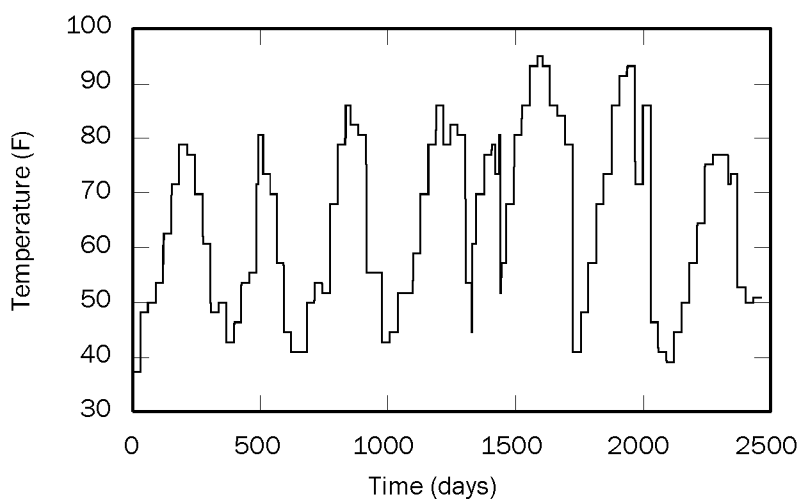


Figure 6.3 Monthly water temperatures used in the present example problem.

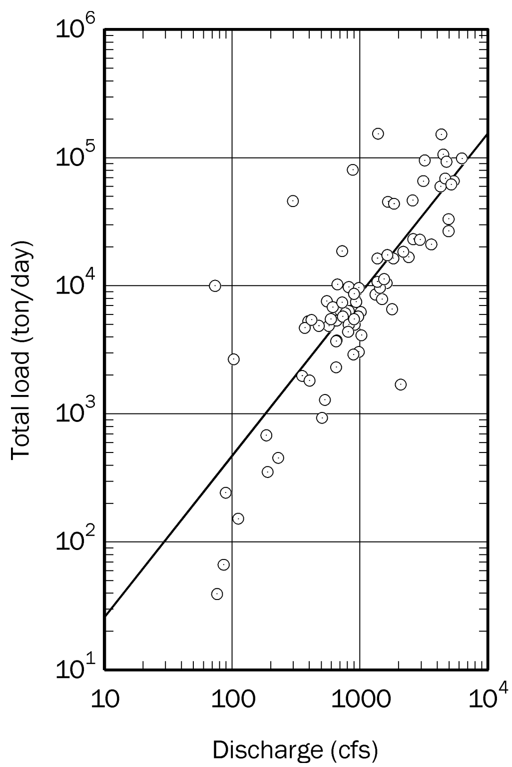


The incoming sediment discharge is specified as a function of the water discharge, and is given by the relation

$$Q_s = 1.415Q^{1.261}$$

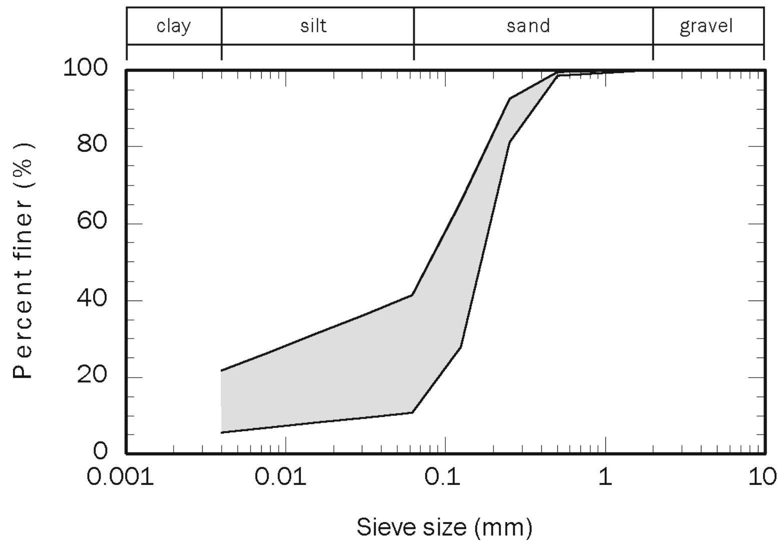
where Q_s = sediment discharge (ton/day) and Q = water discharge (ft^3/s). This rating curve was determined from least squares fitting to the data collected at the San Marcial gaging station (see figure 6.4) and is given in record QR. The bed material has a relatively high percentage of very fine particles, in the silt and clay range. The incoming sediment distribution is given as a function of the water discharge and specified by the use of IQ and IS records. The bed material distribution over the simulated reach is known at specific locations (rangelines) and interpolated between those locations. This is accomplished by the use of NB/BG records. Note that if NB/BG records are used, the locations where the bed distribution is specified do not need to coincide with the cross sections specified by ST/ND/XS/RH sets of records. In this example there are 33 cross sections, but only 8 sets of NB/BG records. The range of bed material size distributions is shown in figure 6.5.

Figure 6.4 Rating curve used in the study. The data used (circles) were measured at the San Marcial gaging station during the 1980-1988 period.



The non-equilibrium parameters are specified using N0 records. Since we are modeling a reach with mixed characteristics (river-like upstream and reservoir-like downstream), different values for the recovery factors were defined. The reach is in depositional mode, therefore only the recovery factor for deposition is important In this case. The values were determined by numerical calibration, and vary between 0.5 and 0.0001.

Figure 6.5 Range of bed material size distributions used in this study.



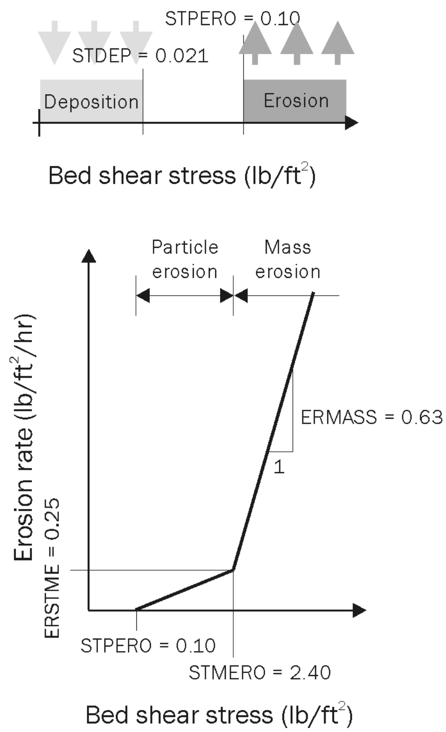
The cohesive sediment transport parameters are specified in record CS. These parameters, which characterize the particles with a diameter smaller than 62 μm, should be determined in situ or by laboratory tests. They are highly dependent on the local conditions and may vary widely from case to case, always requiring field verification. In the present example, the characteristics of the cohesive sediments are the following: the threshold value for the shear stress above which there is no deposition of silts or clays is 0.021 lb/ft^2; the threshold value for the shear stress above which there is particle erosion of cohesive sediments is 0.10 lb/ft^2; the threshold value for the shear stress above which there is mass erosion is 2.40 lb/ft^2 ; the slope of the mass erosion rate line is 0.63, in units of hour^{-1}; the erosion rate of cohesive sediment when the bed shear stress equals 2.40 lb/ft^2 is 0.250 lb/ft^2/hr ; finally, the last entry indicates the threshold for the percentage of clay, in the bed, above which the erosion rates of the other particle sizes become limited to the erosion rate of clay. All these values are schematically represented in figure 6.6.

Unfortunately, there is no information about the flocculation or hindered settling limits, or their corresponding fall velocities. For that reason, only particulate fall velocities are used in the simulation runs. That is done by setting high values for the parameters *CS1* and *CS2* in record CH.

6.1 Input Data File

Due to the length of this data file, the full extent of records SQ and TM is not included. The complete data file is bundled in the GSTARS3 distribution files in directory Example6. All the files shown in this and the next sections are included in the main GSTARS3 distribution package.

Figure 6.6 Schematic representation of the parameters used to model the transport of cohesive sediments in record CS of example 6.




```
TT GSTARS version 3.0  -  Example data file for Appendix B of user's manual
TT Middle Rio Grande, 1980 survey data, rangelines 9 to 59
TT Simulation of nonequilibrium and cohesive sediment transport

*********************************************************************************
***                                                                           ***
***  NOTE: this is a simplified version of the datafile used to simulate     ***
***  the Rio Grande floodway between San Marcial and the upper reach of the  ***
***  Elephant Butte Reservoir (to The Narrows).  It may not contain an       ***
***  accurate representation of the actual flow and geological conditions    ***
***  at the site.  This data file should be viewed only as an example of     ***
***  input data as it might be used in a GSTARS version 3.0 simulation.      ***
***  This file was constructed for didactic purposes only.                   ***
***                                                                           ***
*********************************************************************************

***
NS    33     200
YX
*** Station #2
ST148011      50       0       0       0       0     0.0
ND     3   124.0   494.0  1882.0
XS4486.4       0  4479.3      21  4474.3      37  4472.6      68  4473.5      83
XS4479.7      95  4482.5     102  4484.2     106  4484.2     124  4482.6     129
XS4472.5     147    4471     178  4468.7     179  4464.3     182    4464     217
XS4464.1     237  4463.5     249  4464.5     264  4464.8     273  4464.5     288
XS4462.1     303  4462.8     321  4467.3     346  4469.8     355    4471     367
XS4471.3     470    4472     494    4471     526  4471.1     572  4471.4     696
XS4471.1     785  4473.2     804  4470.1     834  4471.1     861  4470.5     944
```

```
XS4470.4    1042  4469.4    1142  4468.9    1225  4470.4    1254  4469.9    1301
XS4469.8    1411  4470.1    1509  4469.2    1589  4466.9    1608  4470.1    1640
XS4469.4    1704  4469.6    1797  4473.6    1839  4478.9    1859  4479.1    1882
RH 0.080   0.024   0.080
*** Station #3
ST145471      35       0       0       0       0     0.0
ND     2  1012.0  2050.0
XS4478.5   298.0  4473.5   326.0  4472.7   333.0  4470.6   340.0  4463.8   346.0
XS4463.9   377.0  4469.3   391.0  4469.2   452.0  4468.6   551.0  4467.1   626.0
XS4464.5   635.0  4463.9   780.0  4464.5   810.0  4464.1   825.0  4463.2   830.0
XS4462.5   870.0  4462.6   890.0  4462.7   948.0  4462.3   972.0  4469.5   978.0
XS4469.7   981.0  4471.3  1012.0  4469.6  1043.0  4469.5  1121.0  4468.3  1196.0
XS4468.7  1290.0  4467.5  1390.0  4468.5  1494.0  4468.3  1587.0  4468.3  1693.0
XS4468.0  1794.0  4467.6  1904.0  4467.1  2010.0  4471.9  2041.0  4476.0  2050.0
RH 0.024   0.080
***
ST134151      47       0       0       0       0     0.0
ND     3  2021.0  2150.0  3119.0
XS4471.4  1521.0  4469.0  1561.0  4468.2  1610.0  4466.9  1654.0  4466.4  1690.0
XS4465.2  1734.0  4464.2  1762.0  4463.5  1809.0  4462.8  1836.0  4464.3  1873.0
XS4464.6  1910.0  4464.7  1943.0  4464.5  1968.0  4465.0  1991.0  4464.1  2003.0
XS4464.8  2021.0  4464.3  2028.0  4457.3  2037.0  4455.1  2057.0  4453.1  2074.0
XS4451.0  2089.0  4451.3  2107.0  4452.5  2119.0  4463.1  2140.0  4464.1  2144.0
XS4464.9  2150.0  4464.4  2219.0  4464.4  2286.0  4464.7  2355.0  4464.2  2427.0
XS4464.2  2502.0  4464.3  2573.0  4464.1  2642.0  4463.7  2706.0  4463.2  2786.0
XS4462.5  2847.0  4461.5  2867.0  4466.4  2898.0  4464.4  2914.0  4462.8  2981.0
XS4461.1  3013.0  4460.4  3056.0  4460.0  3072.0  4462.7  3087.0  4464.1  3097.0
XS4469.4  3112.0  4469.7  3119.0
RH 0.080   0.024   0.080
*** Station #5
ST133100      39       0       0       0       0     0.0
ND     3   199.0   319.0  1209.0
XS4468.0   111.0  4465.5   128.0  4463.7   164.0  4462.8   183.0  4464.1   199.0
XS4464.0   205.0  4454.8   220.0  4452.1   227.0  4450.4   240.0  4451.0   260.0
XS4450.8   276.0  4450.2   285.0  4461.8   302.0  4463.0   310.0  4463.5   319.0
XS4463.7   374.0  4463.5   451.0  4463.4   516.0  4463.4   587.0  4463.4   654.0
XS4463.2   710.0  4461.9   752.0  4461.6   808.0  4461.7   860.0  4461.7   901.0
XS4460.5   929.0  4462.2   970.0  4463.0  1013.0  4461.5  1031.0  4461.2  1072.0
XS4460.0  1116.0  4462.1  1138.0  4461.5  1147.0  4458.7  1170.0  4462.0  1184.0
XS4461.5  1189.0  4463.9  1197.0  4467.8  1206.0  4467.9  1209.0
RH 0.080   0.024   0.080
***
ST126460      44       0       0       0       0     0.0
ND     3   150.0   284.0  1226.0
XS4470.6    49.0  4463.6    61.0  4461.8    78.0  4458.9    90.0  4459.6    97.0
XS4459.3   117.0  4460.0   131.0  4459.9   150.0  4459.4   157.0  4459.4   161.0
XS4455.6   168.0  4451.6   171.0  4449.6   175.0  4454.2   203.0  4448.9   217.0
XS4448.2   238.0  4446.4   261.0  4454.2   268.0  4459.0   274.0  4460.1   284.0
XS4460.0   321.0  4459.9   355.0  4457.2   392.0  4458.1   419.0  4464.3   449.0
XS4459.9   499.0  4460.0   545.0  4457.7   568.0  4459.6   614.0  4460.4   664.0
XS4460.3   711.0  4460.2   766.0  4462.8   816.0  4460.5   868.0  4458.6   915.0
XS4461.2   975.0  4461.4  1027.0  4461.2  1073.0  4461.6  1119.0  4460.8  1163.0
XS4462.7  1195.0  4466.1  1202.0  4468.5  1213.0  4468.7  1226.0
RH 0.080   0.024   0.080
*** Station #7
ST124560      40       0       0       0       0     0.0
ND     2   181.0  1095.0
XS4468.0    55.0  4462.2    64.0  4461.5    72.0  4460.6    77.0  4457.3    81.0
XS4444.3    95.0  4444.9   106.0  4446.9   118.0  4447.6   135.0  4447.8   148.0
XS4449.4   151.0  4450.8   154.0  4458.5   181.0  4457.6   209.0  4461.5   231.0
XS4457.4   266.0  4456.0   281.0  4457.2   300.0  4460.4   337.0  4460.0   379.0
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XS4457.2   411.0  4458.8   464.0  4459.0   521.0  4455.6   572.0  4457.6   606.0
XS4458.6   644.0  4458.1   697.0  4457.8   756.0  4458.1   805.0  4457.6   848.0
XS4456.2   872.0  4458.7   898.0  4458.5   910.0  4460.1   921.0  4458.6   937.0
XS4457.6   972.0  4459.6   994.0  4460.7  1048.0  4466.5  1088.0  4467.5  1095.0
RH 0.024   0.080
***
ST118694      29       0       0       0       0     0.0
ND     3    89.0   194.0  1147.0
XS4464.0    56.0  4457.4    67.0  4453.8    85.0  4454.2    89.0  4444.4   105.0
XS4444.1   121.0  4444.3   137.0  4444.2   155.0  4444.4   171.0  4444.5   176.0
XS4451.4   187.0  4451.6   194.0  4450.7   230.0  4452.3   262.0  4453.5   314.0
XS4454.1   386.0  4454.7   456.0  4454.6   530.0  4454.9   602.0  4456.1   669.0
XS4455.4   728.0  4455.8   776.0  4455.6   828.0  4454.8   897.0  4456.4   949.0
XS4456.8   997.0  4459.0  1068.0  4462.1  1123.0  4464.8  1147.0
RH 0.080   0.024   0.080
*** Station #9
ST111414      48       0       0       0       0     0.0
ND     3   222.0   371.0  1178.0
XS4462.5   163.0  4455.7   178.0  4451.5   185.0  4451.9   222.0  4451.8   227.0
XS4447.3   237.0  4444.4   247.0  4441.4   251.0  4441.9   272.0  4442.3   294.0
XS4440.7   321.0  4440.1   341.0  4441.5   344.0  4444.5   350.0  4446.8   355.0
XS4448.3   363.0  4451.5   368.0  4451.9   371.0  4451.7   375.0  4450.7   389.0
XS4452.0   401.0  4451.5   404.0  4451.8   409.0  4455.0   417.0  4455.4   423.0
XS4451.8   438.0  4451.2   478.0  4452.5   515.0  4450.7   565.0  4450.2   615.0
XS4451.2   654.0  4450.5   697.0  4451.0   745.0  4450.9   792.0  4450.7   837.0
XS4450.6   886.0  4451.0   921.0  4450.9   946.0  4450.5   994.0  4450.2  1029.0
XS4448.8  1064.0  4448.9  1090.0  4450.8  1101.0  4452.3  1129.0  4454.2  1141.0
XS4460.9  1152.0  4461.1  1155.0  4461.0  1178.0
RH 0.080   0.024   0.080
***
ST100814      89       0       0       0       0     0.0
ND     2  6218.0  9249.0
XS4463.5  4922.0  4460.8  4934.0  4460.9  4945.0  4456.0  4954.0  4451.2  4970.0
XS4445.5  4978.0  4443.5  4996.0  4443.9  5004.0  4446.1  5021.0  4447.2  5040.0
XS4446.9  5065.0  4442.8  5087.0  4441.9  5108.0  4441.4  5122.0  4441.5  5127.0
XS4433.9  5140.0  4430.7  5158.0  4430.5  5178.0  4430.0  5197.0  4429.5  5215.0
XS4434.4  5220.0  4440.0  5232.0  4440.2  5237.0  4439.0  5287.0  4442.0  5316.0
XS4446.0  5331.0  4447.0  5376.0  4446.9  5426.0  4446.5  5481.0  4445.9  5558.0
XS4445.2  5634.0  4444.2  5701.0  4443.5  5783.0  4443.0  5859.0  4442.6  5936.0
XS4442.2  5981.0  4443.0  6019.0  4442.0  6079.0  4441.5  6139.0  4442.6  6169.0
XS4445.9  6192.0  4451.8  6208.0  4456.4  6218.0  4456.2  6245.0  4442.8  6284.0
XS4440.9  6299.0  4441.7  6336.0  4429.9  6359.0  4429.0  6373.0  4430.5  6392.0
XS4440.4  6413.0  4440.5  6416.0  4440.3  6455.0  4439.2  6458.0  4439.8  6463.0
XS4439.3  6512.0  4440.0  6528.0  4439.4  6615.0  4438.8  6704.0  4439.5  6795.0
XS4438.8  6884.0  4438.8  6977.0  4438.8  7061.0  4439.0  7151.0  4438.7  7250.0
XS4439.8  7350.0  4439.7  7446.0  4438.7  7548.0  4438.9  7648.0  4438.7  7746.0
XS4438.9  7845.0  4439.7  7944.0  4440.3  8039.0  4442.2  8077.0  4441.7  8184.0
XS4443.0  8279.0  4441.2  8334.0  4441.6  8380.0  4439.8  8435.0  4440.0  8515.0
XS4442.7  8615.0  4446.9  8669.0  4448.7  8717.0  4451.0  8820.0  4453.8  8917.0
XS4454.9  9011.0  4451.7  9179.0  4455.0  9194.0  4459.4  9249.0
RH 0.024   0.080
*** Station #11
ST96977.     102       0       0       0       0     0.0
ND     3  3673.0  4785.0  9392.0
XS4450.3  3434.0  4447.3  3439.0  4443.9  3448.0  4442.2  3462.0  4442.3  3502.0
XS4443.8  3542.0  4444.2  3580.0  4445.8  3617.0  4448.2  3653.0  4449.0  3673.0
XS4448.0  3680.0  4443.7  3688.0  4441.7  3696.0  4439.5  3703.0  4431.2  3706.0
XS4431.3  3725.0  4431.2  3745.0  4431.5  3762.0  4431.5  3773.0  4432.2  3778.0
XS4435.2  3780.0  4440.2  3790.0  4441.0  3802.0  4440.8  3834.0  4445.4  3849.0
XS4449.0  3867.0  4447.8  3885.0  4447.2  3943.0  4446.7  4000.0  4446.5  4064.0
XS4445.4  4116.0  4446.2  4160.0  4445.1  4224.0  4444.2  4299.0  4444.2  4373.0
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XS4444.0  4450.0  4444.2  4520.0  4443.6  4570.0  4441.5  4600.0  4443.8  4622.0
XS4442.5  4639.0  4442.6  4699.0  4443.6  4749.0  4446.6  4769.0  4456.0  4785.0
XS4455.1  4815.0  4443.8  4836.0  4442.7  4880.0  4431.5  4900.0  4431.7  4935.0
XS4441.0  4951.0  4440.1  5062.0  4440.6  5154.0  4440.7  5247.0  4441.0  5338.0
XS4439.9  5436.0  4440.5  5531.0  4440.3  5629.0  4439.8  5728.0  4439.6  5823.0
XS4439.6  5914.0  4440.5  6002.0  4439.9  6112.0  4439.4  6202.0  4438.9  6297.0
XS4439.4  6391.0  4440.0  6491.0  4439.3  6582.0  4439.7  6677.0  4439.2  6795.0
XS4439.1  6882.0  4439.0  6965.0  4437.6  7052.0  4438.4  7157.0  4438.1  7252.0
XS4438.6  7345.0  4438.3  7442.0  4437.9  7534.0  4437.7  7630.0  4437.5  7724.0
XS4437.4  7814.0  4437.7  7906.0  4437.6  7930.0  4437.6  8023.0  4438.2  8119.0
XS4437.9  8206.0  4435.7  8242.0  4435.3  8337.0  4435.8  8431.0  4436.2  8527.0
XS4435.5  8550.0  4436.3  8573.0  4436.5  8669.0  4435.4  8763.0  4435.3  8858.0
XS4435.3  8955.0  4435.7  9051.0  4435.7  9146.0  4435.6  9240.0  4435.5  9329.0
XS4444.6  9382.0  4450.3  9392.0
RH 0.080   0.024   0.080
***
ST88577.     170       0       0       0       0     0.0
ND     3  1181.0  8926.0  9726.0
XS4450.3   168.0  4449.9   174.0  4447.3   210.0  4444.5   225.0  4444.4   233.0
XS4446.5   246.0  4448.1   266.0  4447.3   290.0  4446.4   314.0  4445.6   321.0
XS4441.8   331.0  4437.1   346.0  4436.1   398.0  4436.8   447.0  4437.0   510.0
XS4436.8   551.0  4436.8   591.0  4436.4   612.0  4436.9   638.0  4436.7   680.0
XS4436.5   721.0  4436.2   754.0  4435.9   804.0  4436.2   843.0  4436.4   887.0
XS4436.6   922.0  4437.3   954.0  4437.3   985.0  4435.8   990.0  4436.2  1008.0
XS4435.7  1042.0  4436.4  1090.0  4436.5  1094.0  4430.5  1098.0  4438.9  1101.0
XS4439.3  1146.0  4432.8  1170.0  4439.7  1181.0  4428.6  1214.0  4428.1  1269.0
XS4429.3  1277.0  4430.5  1282.0  4436.0  1319.0  4436.6  1329.0  4436.0  1336.0
XS4437.4  1342.0  4437.5  1347.0  4436.8  1378.0  4438.1  1401.0  4442.1  1423.0
XS4442.6  1431.0  4439.7  1444.0  4437.2  1466.0  4436.7  1502.0  4436.8  1569.0
XS4437.1  1637.0  4437.3  1703.0  4437.5  1770.0  4437.8  1847.0  4437.5  1917.0
XS4437.5  1987.0  4437.8  2056.0  4438.4  2122.0  4436.9  2157.0  4438.0  2187.0
XS4437.3  2213.0  4439.0  2240.0  4438.3  2301.0  4441.2  2325.0  4438.5  2341.0
XS4438.0  2368.0  4439.0  2398.0  4445.8  2428.0  4449.9  2480.0  4441.1  2499.0
XS4439.4  2536.0  4440.6  2575.0  4427.9  2600.0  4426.6  2651.0  4438.8  2681.0
XS4439.1  2759.0  4439.4  2763.0  4438.4  2776.0  4438.5  2900.0  4438.2  3001.0
XS4438.0  3108.0  4438.0  3235.0  4438.1  3336.0  4438.2  3437.0  4438.4  3541.0
XS4438.5  3642.0  4439.2  3743.0  4439.4  3902.0  4439.5  4013.0  4439.4  4100.0
XS4439.9  4205.0  4439.6  4309.0  4439.4  4391.0  4439.6  4490.0  4439.7  4597.0
XS4439.8  4681.0  4439.5  4701.0  4440.1  4811.0  4440.4  4904.0  4440.3  4995.0
XS4440.9  5098.0  4440.4  5199.0  4441.3  5313.0  4441.1  5407.0  4441.0  5515.0
XS4440.6  5607.0  4441.8  5709.0  4442.3  5800.0  4441.3  5828.0  4441.2  5914.0
XS4440.6  5971.0  4439.9  6072.0  4440.5  6165.0  4440.1  6193.0  4439.6  6290.0
XS4439.3  6384.0  4438.5  6465.0  4438.1  6568.0  4438.2  6662.0  4437.2  6782.0
XS4438.2  6826.0  4437.6  6876.0  4437.2  6973.0  4436.3  7006.0  4437.5  7040.0
XS4434.6  7152.0  4433.2  7251.0  4433.7  7316.0  4433.1  7383.0  4435.4  7418.0
XS4435.7  7447.0  4436.3  7542.0  4435.8  7638.0  4435.5  7735.0  4435.1  7804.0
XS4435.9  7857.0  4435.7  7892.0  4435.7  7990.0  4435.2  8085.0  4434.2  8185.0
XS4433.9  8284.0  4434.2  8394.0  4435.8  8503.0  4437.5  8605.0  4438.9  8705.0
XS4438.2  8748.0  4439.2  8780.0  4439.3  8831.0  4441.4  8926.0  4436.6  9016.0
XS4435.6  9074.0  4434.0  9095.0  4433.9  9146.0  4435.3  9239.0  4438.5  9289.0
XS4438.1  9358.0  4439.3  9391.0  4438.7  9414.0  4439.3  9434.0  4438.1  9468.0
XS4440.3  9563.0  4445.0  9617.0  4446.8  9669.0  4448.9  9699.0  4450.3  9726.0
RH 0.080   0.024   0.080
*** Station #13
ST83227.     196       0       0       0       0     0.0
ND     2  9908.0 12710.0
XS4447.4  1423.0  4448.2  1434.0  4446.5  1452.0
XS4444.5  1483.0  4444.0  1527.0  4443.7  1667.0  4444.4  1720.0  4442.2  1764.0
XS4441.8  1778.0  4443.5  1789.0  4441.8  1805.0  4444.4  1825.0  4442.0  1849.0
XS4440.6  1885.0  4440.1  1919.0  4439.3  1975.0  4440.3  1997.0  4438.9  2022.0
XS4441.5  2055.0  4438.7  2125.0  4439.2  2147.0  4437.3  2180.0  4437.6  2212.0
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XS4439.5  2284.0  4440.2  2305.0  4439.6  2325.0  4437.5  2406.0  4435.5  2435.0
XS4433.7  2464.0  4433.1  2498.0  4433.5  2507.0  4433.9  2630.0  4432.4  2725.0
XS4430.6  2730.0  4427.1  2738.0  4424.3  2749.0  4420.3  2766.0  4420.9  2779.0
XS4422.9  2797.0  4423.8  2805.0  4426.8  2811.0  4427.1  2815.0  4430.1  2818.0
XS4433.0  2827.0  4433.4  2857.0  4432.5  2875.0  4433.9  2925.0  4433.2  3010.0
XS4434.7  3029.0  4432.8  3055.0  4433.4  3194.0  4433.0  3330.0  4433.0  3433.0
XS4432.3  3500.0  4431.2  3559.0  4432.0  3605.0  4436.9  3680.0  4439.1  3697.0
XS4430.5  3753.0  4430.1  3763.0  4429.4  3765.0  4430.4  3773.0  4430.7  3796.0
XS4419.6  3815.0  4419.2  3829.0  4430.2  3869.0  4429.4  3911.0  4429.8  3913.0
XS4430.2  3922.0  4429.5  3941.0  4429.1  4021.0  4430.6  4039.0  4430.8  4145.0
XS4429.7  4173.0  4430.4  4185.0  4430.9  4267.0  4430.6  4382.0  4429.8  4502.0
XS4431.2  4524.0  4430.7  4532.0  4430.3  4632.0  4430.8  4661.0  4429.9  4729.0
XS4430.9  4759.0  4430.5  4816.0  4430.9  4861.0  4431.2  4912.0  4429.8  4958.0
XS4430.7  4980.0  4431.3  5028.0  4430.6  5042.0  4431.2  5091.0  4431.7  5166.0
XS4430.8  5186.0  4431.1  5314.0  4430.4  5331.0  4431.1  5355.0  4431.3  5495.0
XS4431.2  5678.0  4430.7  5791.0  4428.2  5835.0  4429.6  5862.0  4430.0  5893.0
XS4431.0  5904.0  4431.5  5917.0  4430.7  5938.0  4431.8  5964.0  4431.3  5968.0
XS4431.9  5985.0  4431.3  6035.0  4431.7  6053.0  4430.1  6140.0  4430.7  6155.0
XS4430.2  6166.0  4431.0  6184.0  4431.4  6227.0  4429.6  6314.0  4431.1  6330.0
XS4432.0  6506.0  4431.7  6607.0  4431.2  6705.0  4431.2  6815.0  4430.8  6864.0
XS4431.3  6897.0  4430.7  6923.0  4431.4  6962.0  4431.9  6980.0  4431.5  7069.0
XS4430.5  7079.0  4431.7  7089.0  4430.7  7158.0  4431.7  7162.0  4432.1  7290.0
XS4431.6  7397.0  4432.2  7467.0  4431.9  7555.0  4432.5  7575.0  4431.8  7666.0
XS4432.8  7762.0  4431.7  7780.0  4432.6  7792.0  4433.1  7925.0  4432.6  8014.0
XS4432.1  8114.0  4432.0  8308.0  4432.4  8606.0  4433.3  8707.0  4433.6  8802.0
XS4434.8  8920.0  4435.1  8986.0  4434.6  9081.0  4437.0  9126.0  4432.2  9168.0
XS4435.7  9216.0  4436.5  9319.0  4436.9  9421.0  4437.3  9522.0  4438.0  9620.0
XS4438.4  9718.0  4438.9  9814.0  4439.9  9908.0  4438.2  9959.0  4438.7 10017.0
XS4433.1 10057.0  4437.6 10099.0  4439.6 10118.0  4439.1 10170.0  4438.8 10210.0
XS4437.8 10394.0  4437.3 10484.0  4436.2 10530.0  4437.4 10558.0  4437.1 10671.0
XS4437.6 10860.0  4437.3 10955.0  4436.7 11141.0  4436.5 11337.0  4436.3 11437.0
XS4435.2 11535.0  4434.4 11544.0  4436.3 11600.0  4434.0 11695.0  4433.5 11712.0
XS4435.1 11734.0  4435.2 11884.0  4435.8 11913.0  4436.7 12003.0  4436.4 12106.0
XS4437.6 12206.0  4438.9 12305.0  4440.1 12400.0  4442.2 12500.0  4444.2 12568.0
XS4443.8 12578.0  4446.0 12616.0  4450.1 12710.0
RH 0.024   0.080
***
ST73142.     131       0       0       0       0     0.0
ND     1  7930.0
XS4450.3  2829.0  4442.3  2838.0  4429.0  2872.0  4426.9  2886.0  4425.9  2925.0
XS4426.1  2964.0  4427.0  2980.0  4427.0  2980.0  4426.3  2986.0  4425.9  2989.0
XS4424.0  2997.0  4421.3  2998.0  4421.0  3005.0  4417.6  3009.0  4417.4  3046.0
XS4419.0  3076.0  4419.6  3102.0  4416.9  3122.0  4416.6  3139.0  4421.0  3144.0
XS4425.2  3152.0  4425.4  3154.0  4426.4  3174.0  4425.0  3210.0  4426.1  3247.0
XS4430.2  3275.0  4426.7  3302.0  4426.9  3398.0  4427.4  3497.0  4426.5  3575.0
XS4425.2  3613.0  4426.5  3667.0  4426.8  3760.0  4426.2  3835.0  4425.9  3916.0
XS4424.8  3974.0  4426.3  3991.0  4425.1  4067.0  4424.2  4132.0  4431.6  4175.0
XS4434.0  4193.0  4432.5  4244.0  4423.0  4270.0  4423.2  4301.0  4415.4  4315.0
XS4414.0  4347.0  4425.1  4370.0  4424.6  4402.0  4422.4  4423.0  4423.2  4471.0
XS4428.1  4481.0  4428.2  4488.0  4428.3  4497.0  4422.3  4511.0  4420.1  4561.0
XS4420.6  4576.0  4420.6  4649.0  4421.5  4741.0  4422.2  4757.0  4420.9  4772.0
XS4421.0  4864.0  4420.4  4929.0  4420.9  4949.0  4420.3  4970.0  4420.8  5007.0
XS4420.4  5095.0  4420.5  5143.0  4419.8  5165.0  4419.7  5207.0  4420.3  5223.0
XS4420.3  5314.0  4419.4  5342.0  4420.3  5375.0  4420.6  5448.0  4420.4  5544.0
XS4420.6  5635.0  4420.3  5659.0  4419.7  5720.0  4420.6  5773.0  4419.9  5843.0
XS4419.1  5863.0  4417.2  5896.0  4418.9  5921.0  4419.4  6018.0  4419.6  6110.0
XS4419.9  6203.0  4419.4  6295.0  4419.8  6335.0  4419.2  6378.0  4419.0  6402.0
XS4418.4  6413.0  4418.4  6471.0  4418.6  6513.0  4418.3  6542.0  4418.8  6628.0
XS4418.3  6642.0  4419.1  6664.0  4417.7  6685.0  4418.6  6702.0  4418.7  6743.0
XS4418.6  6828.0  4418.6  6882.0  4417.7  6903.0  4419.7  6921.0  4418.3  6953.0
XS4413.9  6978.0  4414.3  6999.0  4417.1  7034.0  4418.1  7052.0  4418.1  7116.0
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XS4418.7  7143.0  4418.5  7230.0  4417.6  7267.0  4419.0  7287.0  4418.7  7335.0
XS4417.2  7369.0  4417.9  7395.0  4417.0  7432.0  4417.7  7471.0  4417.0  7513.0
XS4418.7  7571.0  4418.3  7664.0  4418.8  7737.0  4421.5  7777.0  4424.4  7839.0
XS4428.6  7861.0  4436.6  7887.0  4436.1  7900.0  4443.5  7910.0  4445.2  7916.0
XS4450.3  7930.0
RH 0.024
*** Station #15
ST69002.     110       0       0       0       0     0.0
ND     1  6187.0
XS4450.3  2062.0  4448.6  2062.0  4440.3  2077.0  4433.9  2089.0  4431.9  2096.0
XS4425.5  2113.0  4422.9  2138.0  4422.5  2173.0  4421.9  2193.0  4421.1  2217.0
XS4421.4  2250.0  4422.9  2266.0  4422.8  2291.0  4423.9  2316.0  4425.3  2341.0
XS4423.5  2351.0  4423.6  2378.0  4423.9  2408.0  4424.3  2428.0  4423.9  2441.0
XS4421.7  2444.0  4420.4  2448.0  4419.3  2450.0  4415.8  2454.0  4408.0  2484.0
XS4406.3  2499.0  4415.1  2520.0  4419.3  2526.0  4419.3  2546.0  4418.8  2574.0
XS4419.8  2576.0  4422.1  2581.0  4423.3  2586.0  4423.7  2614.0  4423.8  2645.0
XS4422.8  2671.0  4423.7  2691.0  4424.6  2712.0  4424.2  2748.0  4424.2  2784.0
XS4424.4  2819.0  4423.9  2861.0  4424.3  2901.0  4424.4  2948.0  4423.4  2981.0
XS4423.4  3024.0  4423.2  3066.0  4423.6  3109.0  4422.5  3144.0  4423.6  3177.0
XS4424.0  3211.0  4422.6  3242.0  4427.2  3271.0  4431.0  3293.0  4431.0  3332.0
XS4421.2  3351.0  4421.1  3377.0  4411.6  3391.0  4411.6  3422.0  4423.1  3442.0
XS4422.6  3474.0  4421.3  3494.0  4421.8  3516.0  4425.9  3546.0  4426.0  3557.0
XS4423.6  3567.0  4421.4  3651.0  4419.9  3694.0  4420.0  3752.0  4420.5  3863.0
XS4419.6  3972.0  4419.5  4069.0  4420.0  4166.0  4420.1  4266.0  4419.8  4364.0
XS4419.4  4434.0  4421.2  4474.0  4421.1  4517.0  4420.7  4618.0  4419.7  4717.0
XS4419.2  4814.0  4420.2  4855.0  4418.8  4900.0  4419.2  4962.0  4419.3  5056.0
XS4419.2  5081.0  4419.7  5147.0  4419.4  5247.0  4419.7  5346.0  4422.1  5431.0
XS4422.1  5495.0  4421.1  5531.0  4418.7  5622.0  4417.9  5719.0  4416.1  5779.0
XS4412.9  5801.0  4412.3  5821.0  4414.2  5865.0  4414.3  5902.0  4413.8  5917.0
XS4416.0  6002.0  4415.8  6042.0  4419.2  6080.0  4423.4  6098.0  4424.0  6115.0
XS4429.7  6126.0  4433.1  6138.0  4439.0  6161.0  4444.9  6173.0  4450.3  6187.0
RH 0.024
***
ST63722.     130       0       0       0       0     0.0
ND     1  4484.0
XS4450.3    75.0  4441.3    94.0  4427.4   120.0  4420.8   145.0  4420.3   171.0
XS4418.7   178.0  4418.5   187.0  4418.8   191.0  4417.9   197.0  4417.5   213.0
XS4418.2   231.0  4419.2   237.0  4419.5   269.0  4420.6   305.0  4420.8   324.0
XS4420.0   344.0  4418.9   350.0  4419.6   354.0  4418.7   367.0  4418.9   392.0
XS4418.4   429.0  4418.7   469.0  4418.5   501.0  4419.6   527.0  4418.7   530.0
XS4419.4   533.0  4419.2   571.0  4420.1   607.0  4420.1   642.0  4421.1   674.0
XS4421.5   706.0  4421.6   737.0  4421.7   756.0  4421.6   779.0  4421.5   782.0
XS4420.6   783.0  4420.6   790.0  4418.6   793.0  4417.2   797.0  4415.7   801.0
XS4415.1   822.0  4414.1   844.0  4411.4   878.0  4417.2   885.0  4420.9   888.0
XS4421.2   924.0  4421.9   929.0  4421.5  1029.0  4421.1  1059.0  4421.4  1067.0
XS4420.9  1085.0  4419.3  1096.0  4418.2  1115.0  4416.8  1127.0  4417.4  1159.0
XS4419.8  1164.0  4418.5  1174.0  4416.0  1180.0  4416.5  1228.0  4420.3  1269.0
XS4427.0  1298.0  4426.2  1344.0  4417.1  1362.0  4417.4  1388.0  4408.9  1403.0
XS4408.4  1412.0  4407.6  1420.0  4409.0  1432.0  4420.6  1453.0  4419.8  1475.0
XS4416.9  1498.0  4417.9  1526.0  4423.5  1537.0  4422.9  1541.0  4415.3  1577.0
XS4413.9  1638.0  4412.0  1657.0  4414.6  1690.0  4415.5  1726.0  4414.2  1761.0
XS4415.2  1793.0  4414.4  1894.0  4413.5  1912.0  4414.5  1932.0  4414.0  2023.0
XS4414.0  2108.0  4413.7  2209.0  4414.2  2245.0  4413.2  2285.0  4413.8  2300.0
XS4413.9  2354.0  4413.3  2376.0  4414.1  2404.0  4413.9  2507.0  4413.4  2528.0
XS4414.5  2558.0  4415.1  2628.0  4414.6  2663.0  4415.0  2753.0  4413.8  2810.0
XS4414.0  2831.0  4414.0  2872.0  4413.1  2882.0  4414.0  2890.0  4414.4  2983.0
XS4414.1  3075.0  4415.0  3119.0  4414.1  3155.0  4415.3  3218.0  4414.3  3264.0
XS4415.0  3281.0  4414.7  3376.0  4415.5  3472.0  4415.7  3565.0  4416.8  3650.0
XS4416.9  3695.0  4415.5  3723.0  4414.6  3778.0  4413.7  3803.0  4411.6  3820.0
XS4419.6  4027.0  4419.8  4121.0  4419.9  4127.0  4421.3  4218.0  4423.5  4310.0
XS4425.2  4325.0  4427.9  4374.0  4446.0  4456.0  4450.1  4483.0  4450.3  4484.0
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RH 0.024
*** Station #17
ST59883.     101       0       0       0       0     0.0
ND     1  5842.0
XS4450.3   157.0  4418.3   258.0  4413.7   359.0  4414.6   663.0  4415.2   865.0
XS4416.0  1068.0  4415.3  1119.0  4417.3  1341.0  4408.9  1372.0  4419.0  1380.0
XS4417.7  1393.0  4417.6  1403.0  4419.1  1419.0  4419.3  1508.0  4418.4  1541.0
XS4419.4  1547.0  4419.2  1573.0  4418.5  1578.0  4419.3  1589.0  4419.4  1627.0
XS4417.9  1635.0  4418.3  1666.0  4418.4  1763.0  4417.4  1769.0  4417.2  1794.0
XS4417.9  1805.0  4418.1  1846.0  4417.7  1886.0  4415.5  1917.0  4415.9  1972.0
XS4423.3  2001.0  4423.9  2025.0  4421.9  2033.0  4422.1  2054.0  4414.7  2072.0
XS4415.0  2095.0  4410.6  2100.0  4410.6  2146.0  4418.5  2158.0  4418.0  2190.0
XS4414.3  2224.0  4415.1  2260.0  4419.7  2272.0  4419.5  2281.0  4416.2  2287.0
XS4414.7  2295.0  4413.3  2309.0  4410.2  2343.0  4410.6  2396.0  4410.2  2434.0
XS4411.3  2514.0  4410.8  2589.0  4410.3  2708.0  4409.2  2741.0  4410.5  2765.0
XS4411.5  2861.0  4412.0  2956.0  4411.3  3003.0  4413.3  3084.0  4413.1  3141.0
XS4412.1  3221.0  4413.1  3274.0  4413.7  3389.0  4414.6  3514.0  4415.0  3633.0
XS4413.8  3723.0  4412.8  3839.0  4412.3  3872.0  4413.4  3924.0  4412.7  4029.0
XS4413.1  4135.0  4412.6  4256.0  4412.0  4369.0  4412.2  4485.0  4411.5  4596.0
XS4411.4  4700.0  4410.1  4773.0  4411.1  4815.0  4411.3  4892.0  4412.0  4938.0
XS4410.8  4968.0  4411.9  5010.0  4411.8  5035.0  4407.0  5116.0  4413.7  5184.0
XS4413.7  5240.0  4410.4  5312.0  4412.5  5343.0  4413.1  5366.0  4412.5  5405.0
XS4414.1  5485.0  4413.4  5559.0  4409.2  5605.0  4405.3  5657.0  4411.3  5719.0
XS4425.3  5767.0  4425.2  5774.0  4425.6  5779.0  4427.7  5783.0  4430.1  5794.0
XS4450.3  5842.0
RH 0.024
***
ST57665.      95       0       0       0       0     0.0
ND     1  3773.0
XS4450.3   210.0  4446.6   227.0  4438.3   250.0  4429.6   287.0  4421.4   344.0
XS4415.5   386.0  4414.1   479.0  4414.5   549.0  4417.1   636.0  4418.7   738.0
XS4417.5   793.0  4418.8   849.0  4419.1   901.0  4414.2   907.0  4407.9   912.0
XS4407.0   947.0  4412.2   983.0  4414.2   988.0  4418.9   999.0  4418.5  1071.0
XS4416.4  1088.0  4417.2  1102.0  4417.6  1115.0  4418.2  1124.0  4418.2  1167.0
XS4418.8  1173.0  4418.8  1228.0  4417.9  1235.0  4418.8  1241.0  4418.8  1315.0
XS4416.3  1361.0  4417.7  1431.0  4418.4  1451.0  4414.9  1483.0  4413.9  1519.0
XS4415.0  1529.0  4414.8  1587.0  4414.3  1595.0  4423.1  1631.0  4423.1  1649.0
XS4423.1  1681.0  4415.4  1697.0  4415.3  1749.0  4418.6  1753.0  4415.2  1758.0
XS4410.3  1777.0  4410.2  1785.0  4411.6  1800.0  4418.6  1811.0  4418.5  1824.0
XS4418.1  1838.0  4417.7  1856.0  4414.2  1901.0  4414.1  1928.0  4419.5  1952.0
XS4419.7  1966.0  4414.1  1985.0  4414.3  2006.0  4412.9  2033.0  4413.3  2050.0
XS4411.9  2071.0  4413.3  2094.0  4413.9  2122.0  4412.9  2173.0  4414.4  2207.0
XS4414.7  2250.0  4414.4  2308.0  4414.7  2381.0  4416.2  2490.0  4414.2  2610.0
XS4412.7  2707.0  4412.0  2803.0  4410.8  2817.0  4411.1  2864.0  4411.2  2900.0
XS4409.3  2954.0  4410.0  2982.0  4410.2  3002.0  4409.4  3030.0  4411.1  3071.0
XS4410.4  3126.0  4410.9  3206.0  4411.4  3222.0  4412.0  3310.0  4410.1  3334.0
XS4410.9  3350.0  4410.5  3363.0  4410.5  3391.0  4411.8  3407.0  4410.4  3416.0
XS4424.4  3660.0  4424.8  3678.0  4436.1  3721.0  4448.0  3765.0  4450.3  3773.0
RH 0.024
*** Station #19
ST54321.     108       0       0       0       0     0.0
ND     1  5521.0
XS4450.3   180.0  4445.1   198.0  4443.8   198.0  4436.8   212.0  4429.7   243.0
XS4424.5   314.0  4417.4   410.0  4415.6   492.0  4414.0   543.0  4413.3   587.0
XS4413.1   659.0  4412.3   751.0  4412.3   823.0  4411.8   892.0  4411.7   993.0
XS4412.5  1059.0  4412.4  1090.0  4414.2  1121.0  4413.3  1182.0  4412.4  1192.0
XS4414.3  1209.0  4414.3  1271.0  4415.0  1327.0  4416.5  1402.0  4416.7  1494.0
XS4405.6  1505.0  4405.4  1523.0  4407.6  1555.0  4414.5  1568.0  4415.7  1576.0
XS4416.1  1634.0  4414.6  1648.0  4414.2  1664.0  4415.0  1677.0  4415.1  1699.0
XS4414.3  1776.0  4414.4  1830.0  4415.6  1859.0  4415.6  1958.0  4416.3  2045.0
XS4414.2  2082.0  4413.3  2176.0  4415.0  2200.0  4414.1  2249.0  4420.9  2280.0
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XS4421.2  2300.0  4421.3  2317.0  4413.6  2349.0  4413.2  2385.0  4404.8  2395.0
XS4405.1  2425.0  4417.5  2447.0  4417.6  2449.0  4417.7  2458.0  4417.3  2469.0
XS4413.3  2508.0  4413.0  2545.0  4417.8  2559.0  4417.5  2586.0  4413.1  2605.0
XS4412.2  2618.0  4407.9  2644.0  4413.3  2672.0  4416.1  2727.0  4416.4  2759.0
XS4415.1  2774.0  4417.5  2789.0  4416.7  2860.0  4416.4  2886.0  4416.9  2903.0
XS4416.6  2993.0  4416.0  3036.0  4416.9  3086.0  4417.3  3198.0  4418.2  3288.0
XS4419.1  3376.0  4420.4  3478.0  4421.7  3578.0  4423.3  3657.0  4423.3  3743.0
XS4425.7  3878.0  4427.0  3992.0  4428.7  4085.0  4431.3  4209.0  4431.4  4293.0
XS4432.5  4388.0  4433.7  4476.0  4435.8  4594.0  4438.1  4700.0  4440.5  4731.0
XS4440.2  4756.0  4441.7  4784.0  4442.6  4832.0  4444.3  4866.0  4442.6  4917.0
XS4441.8  4975.0  4441.7  5000.0  4441.5  5021.0  4443.7  5145.0  4445.5  5243.0
XS4446.6  5303.0  4446.5  5349.0  4450.5  5418.0  4452.8  5469.0  4449.8  5498.0
XS4449.2  5511.0  4447.7  5516.0  4450.3  5521.0
RH 0.024
***
ST50167.     127       0       0       0       0     0.0
ND     1  8110.0
XS4450.3   210.0  4428.6   253.0  4417.6   311.0  4412.5   359.0  4411.6   451.0
XS4414.0   530.0  4413.7   534.0  4411.5   536.0  4410.3   558.0  4409.4   588.0
XS4408.4   616.0  4410.6   626.0  4412.7   629.0  4414.1   701.0  4412.6   761.0
XS4412.9   864.0  4412.8   964.0  4416.0  1054.0  4413.3  1080.0  4413.2  1188.0
XS4411.8  1247.0  4411.1  1299.0  4412.3  1329.0  4412.9  1434.0  4411.0  1481.0
XS4410.7  1536.0  4405.7  1572.0  4407.5  1596.0  4411.2  1634.0  4410.9  1686.0
XS4411.1  1715.0  4418.9  1747.0  4419.3  1765.0  4419.3  1781.0  4421.3  1810.0
XS4414.6  1823.0  4418.5  1840.0  4404.8  1854.0  4400.8  2038.0  4400.6  2050.0
XS4400.8  2068.0  4405.0  2076.0  4408.0  2091.0  4413.6  2107.0  4412.7  2131.0
XS4416.0  2154.0  4415.9  2207.0  4411.3  2240.0  4406.2  2267.0  4405.6  2303.0
XS4409.0  2327.0  4409.4  2372.0  4408.3  2433.0  4405.9  2468.0  4403.8  2505.0
XS4403.4  2555.0  4404.5  2636.0  4407.3  2697.0  4408.0  2763.0  4407.7  2817.0
XS4407.1  2889.0  4406.1  2984.0  4406.8  3058.0  4406.6  3138.0  4406.8  3211.0
XS4406.8  3215.0  4406.1  3289.0  4406.4  3370.0  4407.0  3453.0  4406.2  3471.0
XS4407.2  3496.0  4407.4  3559.0  4406.1  3602.0  4406.4  3634.0  4407.0  3729.0
XS4406.2  3848.0  4407.1  3929.0  4406.2  3962.0  4407.1  3979.0  4407.1  4053.0
XS4408.1  4114.0  4405.2  4170.0  4404.3  4260.0  4403.1  4293.0  4404.1  4317.0
XS4403.5  4333.0  4404.3  4356.0  4403.9  4432.0  4403.2  4484.0  4404.5  4508.0
XS4405.4  4559.0  4406.8  4609.0  4407.2  4630.0  4408.3  4657.0  4409.5  4716.0
XS4411.9  4791.0  4411.1  4933.0  4411.6  4998.0  4412.6  5072.0  4412.8  5171.0
XS4412.9  5255.0  4412.9  5385.0  4413.0  5470.0  4413.1  5599.0  4413.3  5712.0
XS4414.1  5818.0  4414.8  5913.0  4415.2  6026.0  4415.7  6129.0  4417.8  6235.0
XS4418.9  6353.0  4420.3  6466.0  4421.8  6590.0  4423.2  6696.0  4425.0  6804.0
XS4426.2  6889.0  4426.0  6913.0  4426.8  6940.0  4429.1  7048.0  4430.7  7171.0
XS4433.1  7305.0  4435.3  7414.0  4438.7  7567.0  4441.4  7696.0  4445.3  7865.0
XS4448.3  8026.0  4450.3  8110.0
RH 0.024
*** Station #21
ST47263.      93       0       0       0       0     0.0
ND     1  6911.0
XS4450.3    62.0  4443.2    73.0  4412.8   134.0  4411.1   252.0  4412.5   336.0
XS4409.9   365.0  4409.7   389.0  4409.4   481.0  4408.8   579.0  4407.5   669.0
XS4407.1   713.0  4406.1   816.0  4406.3   902.0  4406.3   993.0  4405.8  1089.0
XS4406.2  1184.0  4404.7  1242.0  4405.8  1263.0  4405.3  1342.0  4413.1  1390.0
XS4413.1  1398.0  4410.1  1487.0  4407.9  1490.0  4403.0  1496.0  4399.8  1503.0
XS4399.7  1521.0  4399.3  1534.0  4399.4  1546.0  4407.9  1553.0  4410.6  1557.0
XS4411.2  1568.0  4410.9  1579.0  4408.8  1601.0  4411.0  1615.0  4410.6  1667.0
XS4401.7  1723.0  4400.9  1736.0  4402.0  1746.0  4403.9  1760.0  4404.7  1797.0
XS4407.2  1809.0  4405.1  1893.0  4404.6  1999.0  4402.5  2077.0  4402.7  2134.0
XS4404.2  2175.0  4403.4  2227.0  4402.1  2281.0  4404.1  2328.0  4404.5  2433.0
XS4403.3  2538.0  4403.5  2631.0  4403.5  2749.0  4405.1  3797.0  4399.5  3977.0
XS4402.0  4023.0  4404.8  4160.0  4403.5  4280.0  4403.7  4355.0  4403.1  4416.0
XS4403.0  4462.0  4402.7  4539.0  4402.8  4611.0  4402.4  4654.0  4408.2  4752.0
XS4409.0  4841.0  4410.8  4923.0  4412.5  5019.0  4413.5  5121.0  4413.5  5226.0
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XS4414.1  5328.0  4415.4  5349.0  4415.8  5425.0  4415.5  5443.0  4417.6  5478.0
XS4418.1  5517.0  4420.4  5613.0  4420.8  5657.0  4421.9  5681.0  4423.5  5770.0
XS4424.7  5868.0  4427.3  5958.0  4427.8  6004.0  4430.5  6104.0  4430.7  6139.0
XS4433.0  6177.0  4434.7  6232.0  4435.3  6316.0  4437.1  6365.0  4440.3  6493.0
XS4442.2  6622.0  4446.4  6828.0  4450.3  6911.0
RH 0.024
***
ST32521.      89       0       0       0       0     0.0
ND     1  7370.0
XS4450.3  1362.0  4449.9  1370.0  4448.0  1401.0  4445.7  1430.0  4442.8  1457.0
XS4441.4  1480.0  4439.7  1493.0  4435.7  1514.0  4432.8  1523.0  4432.1  1532.0
XS4425.7  1549.0  4426.5  1553.0  4423.6  1562.0  4423.1  1571.0  4419.9  1583.0
XS4416.8  1586.0  4412.0  1603.0  4410.0  1612.0  4410.5  1612.0  4404.6  1876.0
XS4403.0  1941.0  4402.2  2024.0  4404.1  2057.0  4411.8  2257.0  4411.8  2268.0
XS4411.7  2280.0  4410.5  2281.0  4407.9  2291.0  4404.9  2296.0  4395.9  2328.0
XS4394.9  2424.0  4395.2  2432.0  4403.9  2480.0  4392.2  2529.0  4391.9  2551.0
XS4390.9  2664.0  4390.3  2720.0  4390.9  2777.0  4392.9  2834.0  4392.9  2891.0
XS4392.6  3006.0  4392.2  3122.0  4392.5  3239.0  4393.7  3357.0  4392.4  3477.0
XS4392.9  3597.0  4393.9  3699.0  4393.9  3802.0  4393.0  3843.0  4392.9  3968.0
XS4392.4  4095.0  4391.9  4224.0  4391.6  4355.0  4392.7  4487.0  4392.1  4622.0
XS4392.3  4760.0  4391.9  4900.0  4391.9  5042.0  4392.7  5188.0  4392.5  5336.0
XS4393.9  5488.0  4392.5  5643.0  4390.9  5801.0  4391.1  5964.0  4390.7  6130.0
XS4390.9  6238.0  4394.6  6524.0  4398.2  6596.0  4407.9  6737.0  4409.3  6746.0
XS4415.7  6802.0  4421.9  6845.0  4429.3  6891.0  4437.2  6910.0  4441.4  6925.0
XS4443.3  6934.0  4444.7  6960.0  4443.9  6982.0  4436.5  7021.0  4430.4  7056.0
XS4429.0  7076.0  4426.6  7118.0  4427.3  7161.0  4429.2  7239.0  4437.3  7295.0
XS4446.2  7344.0  4444.9  7347.0  4447.3  7351.0  4450.3  7370.0
RH 0.024
*** Station #23
ST30480.     111       0       0       0       0     0.0
ND     1  7975.0
XS4450.3   977.0  4446.8  1000.0  4444.9  1017.0  4441.1  1052.0  4439.1  1097.0
XS4436.8  1120.0  4433.9  1128.0  4436.7  1134.0  4439.1  1145.0  4442.0  1168.0
XS4442.5  1211.0  4443.4  1244.0  4442.5  1271.0  4440.7  1288.0  4440.0  1296.0
XS4439.1  1304.0  4435.9  1312.0  4433.2  1322.0  4428.4  1332.0  4424.5  1349.0
XS4423.0  1356.0  4419.0  1367.0  4416.8  1375.0  4415.5  1385.0  4411.0  1397.0
XS4409.6  1404.0  4403.9  1636.0  4398.4  1650.0  4397.6  1774.0  4397.4  1875.0
XS4398.1  1976.0  4407.9  2013.0  4405.9  2020.0  4392.9  2085.0  4392.6  2091.0
XS4392.7  2130.0  4403.7  2191.0  4405.4  2240.0  4392.7  2290.0  4394.4  2344.0
XS4392.7  2388.0  4394.4  2428.0  4392.9  2485.0  4393.9  2581.0  4392.4  2677.0
XS4391.6  2772.0  4391.0  2866.0  4390.9  2959.0  4390.8  3052.0  4390.7  3145.0
XS4390.4  3237.0  4390.4  3329.0  4390.9  3421.0  4390.4  3513.0  4391.1  3604.0
XS4391.2  3695.0  4391.1  3786.0  4391.2  3878.0  4391.9  3969.0  4391.3  4060.0
XS4390.7  4152.0  4391.7  4244.0  4391.9  4336.0  4391.9  4428.0  4391.5  4513.0
XS4389.9  4521.0  4390.1  4614.0  4390.9  4708.0  4391.0  4803.0  4391.4  4874.0
XS4390.6  4898.0  4390.0  4993.0  4389.7  5025.0  4390.6  5090.0  4390.8  5187.0
XS4390.2  5286.0  4388.9  5385.0  4388.6  5427.0  4389.9  5486.0  4389.8  5587.0
XS4389.8  5690.0  4389.8  5794.0  4389.6  5900.0  4389.7  6007.0  4389.4  6116.0
XS4389.1  6226.0  4389.4  6339.0  4389.4  6453.0  4394.4  6505.0  4388.4  6569.0
XS4388.9  6688.0  4389.1  6808.0  4390.1  6932.0  4391.8  6992.0  4389.7  7058.0
XS4389.3  7186.0  4388.8  7318.0  4389.0  7453.0  4389.7  7511.0  4397.4  7591.0
XS4407.9  7697.0  4413.1  7721.0  4416.4  7754.0  4419.9  7776.0  4425.8  7804.0
XS4430.0  7833.0  4435.5  7849.0  4439.7  7877.0  4441.4  7899.0  4445.3  7923.0
XS4450.3  7975.0
RH 0.024
***
ST27647.     101       0       0       0       0     0.0
ND     1  8963.0
XS4450.3  2377.0  4449.2  2412.0  4447.8  2465.0  4445.4  2513.0  4444.5  2535.0
XS4443.6  2591.0  4441.7  2649.0  4439.9  2663.0  4439.4  2675.0  4439.5  2735.0
XS4438.3  2778.0  4436.7  2832.0  4434.4  2886.0  4433.2  2900.0  4433.6  2916.0
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XS4433.1  2955.0  4431.6  3008.0  4429.7  3062.0  4428.3  3114.0  4425.9  3167.0
XS4424.1  3221.0  4421.8  3269.0  4420.2  3319.0  4417.3  3374.0  4415.8  3425.0
XS4414.3  3482.0  4412.8  3541.0  4411.3  3593.0  4407.9  3624.0  4409.6  3640.0
XS4404.4  3649.0  4409.6  3717.0  4402.6  3734.0  4403.8  3769.0  4403.1  3772.0
XS4395.9  3810.0  4404.9  3848.0  4403.9  3894.0  4403.1  3904.0  4403.3  3992.0
XS4405.4  4020.0  4407.9  4061.0  4407.1  4068.0  4411.0  4076.0  4410.6  4084.0
XS4407.9  4088.0  4399.6  4146.0  4394.6  4162.0  4395.1  4235.0  4401.9  4284.0
XS4401.4  4319.0  4394.9  4329.0  4391.4  4360.0  4392.9  4428.0  4392.7  4533.0
XS4390.9  4645.0  4390.7  4764.0  4390.4  4891.0  4389.9  5027.0  4389.4  5173.0
XS4389.2  5413.0  4389.4  5500.0  4389.4  5590.0  4389.4  5684.0  4389.1  5816.0
XS4389.1  5885.0  4388.9  5956.0  4388.4  6105.0  4388.4  6183.0  4388.4  6263.0
XS4388.1  6346.0  4388.1  6432.0  4388.1  6521.0  4388.1  6614.0  4388.1  6709.0
XS4388.1  6808.0  4388.3  6911.0  4388.3  7017.0  4388.1  7131.0  4387.9  7243.0
XS4388.1  7363.0  4387.9  7489.0  4387.7  7619.0  4387.9  7755.0  4388.4  7897.0
XS4388.9  8046.0  4389.9  8141.0  4393.3  8201.0  4407.9  8365.0  4409.7  8408.0
XS4415.1  8469.0  4416.5  8515.0  4419.1  8585.0  4422.2  8646.0  4425.3  8688.0
XS4431.3  8737.0  4436.9  8829.0  4436.0  8859.0  4437.5  8897.0  4443.2  8937.0
XS4450.3  8963.0
RH 0.024
*** Station #25
ST25059.      77       0       0       0       0     0.0
ND     1  5350.0
XS4450.3   836.0  4448.4   854.0  4449.0   879.0  4449.2   912.0  4448.4   959.0
XS4446.2  1015.0  4442.5  1052.0  4442.0  1090.0  4442.5  1111.0  4441.0  1150.0
XS4439.4  1182.0  4439.0  1185.0  4434.3  1207.0  4428.6  1229.0  4426.0  1246.0
XS4423.1  1262.0  4421.2  1276.0  4419.0  1306.0  4413.0  1355.0  4411.6  1379.0
XS4410.8  1393.0  4410.9  1419.0  4408.7  1454.0  4407.1  1481.0  4405.5  1550.0
XS4407.2  1577.0  4414.9  1607.0  4415.1  1636.0  4412.5  1665.0  4408.7  1700.0
XS4408.9  1707.0  4410.1  1708.0  4407.9  1731.0  4402.9  1751.0  4400.4  1807.0
XS4400.4  1889.0  4400.1  1972.0  4400.4  2055.0  4400.1  2139.0  4400.4  2225.0
XS4400.6  2311.0  4400.9  2366.0  4405.9  2764.0  4402.2  2832.0  4401.9  2855.0
XS4402.2  2871.0  4404.9  2950.0  4402.1  3048.0  4401.8  3147.0  4401.4  3234.0
XS4400.9  3248.0  4400.2  3267.0  4400.2  3306.0  4405.3  3339.0  4403.9  3352.0
XS4398.6  3371.0  4398.1  3457.0  4397.3  3565.0  4397.0  3675.0  4395.6  3788.0
XS4394.9  3904.0  4394.6  4023.0  4391.9  4145.0  4391.3  4270.0  4390.9  4399.0
XS4390.9  4531.0  4390.8  4668.0  4390.0  4809.0  4389.9  4955.0  4405.4  5063.0
XS4408.3  5107.0  4410.3  5122.0  4412.4  5156.0  4416.5  5184.0  4420.5  5249.0
XS4443.1  5319.0  4450.3  5350.0
RH 0.024
***
ST23335.      44       0       0       0       0     0.0
ND     1  1707.0
XS4450.3   132.0  4447.3   138.0  4446.3   142.0  4443.3   142.0  4434.6   154.0
XS4418.6   156.0  4414.1   168.0  4413.2   175.0  4414.1   178.0  4411.4   182.0
XS4408.4   190.0  4402.2   281.0  4398.2   329.0  4402.8   395.0  4400.2   471.0
XS4403.4   547.0  4403.7   595.0  4402.2   663.0  4402.5   702.0  4399.4   779.0
XS4397.7   780.0  4397.8   826.0  4403.8   836.0  4403.8  1423.0  4408.8  1431.0
XS4419.3  1449.0  4422.7  1451.0  4423.2  1453.0  4426.2  1453.0  4426.7  1456.0
XS4432.0  1467.0  4435.9  1469.0  4437.9  1474.0  4439.7  1475.0  4441.4  1481.0
XS4443.8  1508.0  4445.6  1524.0  4446.5  1574.0  4445.1  1602.0  4445.6  1612.0
XS4445.5  1625.0  4445.2  1655.0  4447.1  1682.0  4449.9  1707.0
RH 0.024
*** Station #27
ST20325.      89       0       0       0       0     0.0
ND     1  4129.0
XS4450.3   651.0  4450.0   652.0  4447.4   687.0  4447.6   710.0  4447.8   736.0
XS4444.7   762.0  4439.1   781.0  4439.2   803.0  4443.5   831.0  4442.4   866.0
XS4439.0   902.0  4435.9   929.0  4436.1   947.0  4432.2   985.0  4430.1  1011.0
XS4426.8  1038.0  4427.2  1070.0  4427.6  1086.0  4424.0  1096.0  4421.2  1111.0
XS4420.7  1120.0  4417.8  1130.0  4411.6  1135.0  4410.7  1149.0  4410.0  1159.0
XS4410.0  1160.0  4408.4  1164.0  4403.1  1205.0  4401.3  1252.0  4400.8  1294.0
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XS4399.6  1390.0  4400.0  1626.0  4399.9  1688.0  4399.7  1738.0  4399.3  1993.0
XS4400.3  2004.0  4396.9  2021.0  4396.1  2065.0  4398.9  2102.0  4402.4  2181.0
XS4399.4  2443.0  4399.5  2466.0  4397.3  2475.0  4397.9  2480.0  4398.2  2508.0
XS4398.7  2540.0  4398.7  2946.0  4398.4  2983.0  4398.4  3040.0  4398.3  3097.0
XS4397.9  3153.0  4397.8  3208.0  4397.8  3261.0  4398.1  3314.0  4397.6  3366.0
XS4397.5  3418.0  4397.3  3469.0  4397.4  3493.0  4398.9  3519.0  4402.9  3568.0
XS4407.9  3598.0  4411.9  3609.0  4412.6  3622.0  4409.1  3651.0  4409.7  3663.0
XS4408.3  3676.0  4407.9  3685.0  4405.9  3692.0  4403.8  3714.0  4399.3  3762.0
XS4398.9  3809.0  4399.1  3823.0  4404.3  3856.0  4408.5  3887.0  4411.5  3912.0
XS4411.9  3931.0  4412.4  3943.0  4412.1  3958.0  4410.5  3968.0  4410.6  3982.0
XS4411.9  4001.0  4409.2  4012.0  4411.2  4022.0  4414.4  4033.0  4412.7  4040.0
XS4420.8  4052.0  4426.7  4067.0  4427.4  4126.0  4450.3  4129.0
RH 0.024
***
ST17611.      36       0       0       0       0     0.0
ND     1  1536.0
XS4450.3   241.0  4447.0   266.0  4445.2   297.0  4440.3   332.0  4436.9   352.0
XS4433.4   381.0  4429.4   409.0  4426.3   441.0  4423.2   469.0  4420.6   489.0
XS4420.5   502.0  4418.4   512.0  4413.8   520.0  4407.9   526.0  4399.9   544.0
XS4399.0   586.0  4399.5   623.0  4401.7   713.0  4396.3   755.0  4393.9   788.0
XS4394.4   797.0  4397.9   801.0  4396.6   810.0  4398.1  1061.0  4395.7  1316.0
XS4394.9  1340.0  4393.0  1359.0  4396.0  1383.0  4395.6  1426.0  4395.9  1459.0
XS4407.9  1504.0  4408.4  1506.0  4411.4  1512.0  4420.6  1523.0  4427.5  1534.0
XS4450.3  1536.0
RH 0.024
*** Station #29
ST15288.      49       0       0       0       0     0.0
ND     1  1577.0
XS4450.3   199.0  4445.9   211.0  4439.1   229.0  4430.1   261.0  4425.9   273.0
XS4423.8   278.0  4426.2   287.0  4425.9   310.0  4422.5   346.0  4419.3   369.0
XS4416.0   389.0  4413.1   408.0  4410.1   424.0  4407.9   433.0  4399.9   468.0
XS4391.6   527.0  4391.2   533.0  4390.9   567.0  4393.2   617.0  4400.4   660.0
XS4400.2   668.0  4397.1   697.0  4396.1   806.0  4395.2   845.0  4395.8   896.0
XS4395.5   955.0  4395.3  1008.0  4395.7  1029.0  4395.9  1056.0  4395.9  1075.0
XS4396.7  1093.0  4404.9  1100.0  4409.9  1144.0  4413.1  1194.0  4415.3  1239.0
XS4418.3  1280.0  4418.9  1313.0  4418.3  1328.0  4420.5  1340.0  4424.0  1375.0
XS4425.3  1402.0  4425.5  1408.0  4429.9  1440.0  4434.6  1460.0  4438.8  1496.0
XS4438.6  1502.0  4440.7  1513.0  4446.7  1556.0  4450.3  1577.0
RH 0.024
***
ST13070.      62       0       0       0       0     0.0
ND     2   605.0  1588.0
XS4440.0     0.0  4442.1     6.0  4440.0    19.0  4437.4    34.0  4436.4    43.0
XS4433.3    48.0  4431.6    75.0  4425.8   106.0  4425.2   136.0  4423.5   168.0
XS4422.7   198.0  4422.8   226.0  4422.5   257.0  4422.1   275.0  4423.4   322.0
XS4424.9   361.0  4426.7   394.0  4427.8   426.0  4425.1   460.0  4422.8   492.0
XS4422.7   518.0  4425.7   546.0  4436.8   578.0  4443.2   605.0  4442.4   617.0
XS4440.8   618.0  4437.2   630.0  4432.1   630.0  4428.5   653.0  4420.9   669.0
XS4416.9   685.0  4413.8   707.0  4412.7   712.0  4409.3   724.0  4408.0   725.0
XS4395.6   743.0  4394.8   791.0  4394.9   840.0  4395.3   890.0  4396.0   911.0
XS4395.9   946.0  4398.9  1017.0  4393.9  1046.0  4391.9  1072.0  4392.0  1099.0
XS4394.1  1154.0  4399.2  1181.0  4400.2  1210.0  4398.7  1236.0  4398.2  1264.0
XS4395.9  1277.0  4403.9  1322.0  4407.9  1325.0  4416.6  1347.0  4418.1  1365.0
XS4419.0  1385.0  4426.7  1433.0  4427.6  1468.0  4429.4  1501.0  4432.5  1542.0
XS4436.4  1571.0  4438.5  1588.0
RH 0.080   0.024
*** Station #31
ST10470.      22       0       0       0       0     0.0
ND     1  1536.0
XS4450.3   766.0  4449.1   768.0  4446.4   773.0  4442.4   776.0  4433.2   790.0
XS4428.7   796.0  4424.5   811.0  4419.3   813.0  4417.1   819.0  4411.4   826.0
```

```
XS4393.3   895.0  4394.4   944.0  4390.4   998.0  4391.1  1046.0  4392.7  1094.0
XS4394.6  1203.0  4393.4  1250.0  4393.9  1334.0  4393.9  1353.0  4393.1  1414.0
XS4431.1  1498.0  4450.3  1536.0
RH 0.024
***
ST 5630.      41       0       0       0       0     0.0
ND     1  1508.0
XS4450.3   288.0  4446.5   294.0  4438.9   311.0  4430.2   335.0  4421.0   367.0
XS4412.7   395.0  4408.7   413.0  4407.9   414.0  4405.9   418.0  4397.1   458.0
XS4390.9   493.0  4390.2   518.0  4389.7   576.0  4389.7   634.0  4389.9   690.0
XS4390.0   746.0  4390.5   801.0  4390.8   855.0  4391.1   908.0  4391.1   934.0
XS4391.1   956.0  4394.1   961.0  4395.3  1003.0  4397.1  1011.0  4393.9  1013.0
XS4393.4  1065.0  4391.5  1116.0  4391.5  1138.0  4396.9  1148.0  4396.1  1167.0
XS4391.6  1217.0  4390.6  1267.0  4390.2  1316.0  4390.9  1354.0  4394.3  1365.0
XS4408.1  1438.0  4417.2  1453.0  4425.2  1453.0  4439.3  1485.0  4444.9  1504.0
XS4450.3  1508.0
RH 0.024
*** Station #33
ST 2709.      48       0       0       0       0     0.0
ND     1  2345.0
XS4450.3   853.0  4449.1   854.0  4442.4   861.0  4437.7   864.0  4434.2   871.0
XS4423.7   873.0  4417.0   880.0  4409.8   890.0  4408.0   893.0  4404.5   900.0
XS4389.3   915.0  4389.2   934.0  4389.5  1010.0  4391.8  1041.0  4393.5  1094.0
XS4387.4  1120.0  4386.6  1181.0  4386.8  1202.0  4391.5  1237.0  4391.7  1293.0
XS4390.4  1404.0  4389.0  1424.0  4389.2  1502.0  4390.8  1516.0  4398.0  1628.0
XS4403.6  1741.0  4405.0  1752.0  4405.2  1782.0  4400.5  1804.0  4401.0  1815.0
XS4408.5  1829.0  4409.5  1837.0  4410.1  1863.0  4407.5  1901.0  4409.8  1938.0
XS4408.4  1957.0  4409.3  2110.0  4411.9  2145.0  4417.1  2177.0  4422.4  2211.0
XS4428.3  2239.0  4434.5  2267.0  4438.3  2294.0  4440.6  2309.0  4440.9  2315.0
XS4441.3  2327.0  4449.3  2344.0  4450.3  2345.0
RH 0.024
***  Outlet
ST   0.0      46       1       1       0       0     0.0
ND     1  3289.0
XS4453.3  1890.0  4450.3  1920.0  4450.3  1920.0  4447.5  1925.0  4436.5  1932.0
XS4427.9  1951.0  4421.6  1969.0  4414.0  1986.0  4410.8  1992.0  4390.2  2084.0
XS4390.1  2110.0  4389.7  2157.0  4393.4  2347.0  4388.0  2373.0  4387.0  2396.0
XS4385.8  2446.0  4385.8  2472.0  4389.5  2494.0  4392.0  2496.0  4393.1  2504.0
XS4391.5  2547.0  4390.2  2599.0  4389.8  2622.0  4389.3  2651.0  4389.2  2705.0
XS4389.3  2759.0  4389.3  2814.0  4389.8  2871.0  4388.0  2877.0  4388.6  2928.0
XS4389.4  2973.0  4388.7  2987.0  4388.7  3000.0  4386.9  3010.0  4386.9  3027.0
XS4389.1  3037.0  4389.1  3047.0  4388.0  3108.0  4387.4  3166.0  4403.3  3211.0
XS4408.0  3228.0  4409.0  3230.0  4431.3  3266.0  4441.5  3287.0  4449.9  3288.0
XS4450.3  3289.0
RH 0.024
***  Number of stream tubes
NT     3
***
IT  2460       5     1.0     DAY
***
***  Boundary conditions: table with stage and discharge
***
QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE
TL    33
SQ 1190.  4408.2       1
SQ 1010.  4408.2       1
...
...
SQ  965.  4449.9       1
SQ  965.  4449.9       1
```

```
***
***  Sediment transport data ***************************************************
***
SE     6
***
***  Non-equilibrium transport parameters
***
N0 79500    0.01     1.0
N0 80000   0.001     1.0
N0124500  0.0003     1.0
N0148000  0.0001     1.0
***
***  Sediment rating curve
***
QR 1.415   1.261
***
***  Temperature records
***
TM    31    37.4   F
TM    29    48.2   F
...
...
TM    31    50.0   F
TM    29    50.9   F
***
***  Bed sorting information
***
SF     9    99.3
SG.00025    .004    41.0
SG  .004    .008    50.0
SG  .008    .016    50.0
SG  .016    .031    50.0
SG  .031    .062    50.0
SG  .062    .125    74.0
SG  .125    .250    74.0
SG  .250    .50     74.0
SG  .50    2.0      74.0
***
***  Bed gradation using interpolated values from known stations.
***
***  Rangelines 59 and 24 have the same bed gradations
NB100814
BG.16800  .03635  .03635  .03468  .03635  .26545  .33341  .08469  .00472
***  Rangeline 20
NB111414
BG.21700  .04965  .04965  .04738  .04965  .24563  .26711  .06977  .00417
***  Rangeline 18
NB118694
BG.16300  .01734  .01734  .01655  .01734  .16472  .44834  .14730  .00806
***  Rangeline 17
NB124560
BG.05600  .01307  .01307  .01247  .01307  .17262  .53313  .17377  .01282
***  Rangeline 16
NB126460
BG.11700  .02756  .02756  .02629  .02756  .15085  .46832  .14821  .00665
***  Rangeline 14
NB133100
BG.15600  .03706  .03706  .03536  .03706  .21470  .36961  .10850  .00465
***  Rangeline 13
NB134151
BG.15100  .03587  .03587  .03423  .03587  .15747  .40906  .13405  .00658
```

```
***  Rangeline 10
NB145471
BG.12700  .02257  .02257  .02153  .02257  .25894  .39618  .12186  .00679
***
***  Cohesive sediment data
***
CS 0.021    0.10    2.40    0.63   0.250    0.05
CH 1.0e9   5.0e9              -1      -1      -1
***
***  Distribution of incoming sediment
***
IQ     1     20.     20.    225.    425.    700.   1175.   2000.   3250.   4750.
8000.
IS  clay    .020    .398    .176    .228    .149    .202    .209    .113    .213
.172
IS vfslt    .020    .051    .093    .062    .041    .045    .049    .023    .038
.027
IS  fslt    .020    .052    .093    .062    .042    .046    .050    .022    .040
.028
IS  mslt    .030    .032     .08     .10    .089    .091    .140    .158    .134
.100
IS  cslt    .100    .036     .08    .101    .094    .098    .142    .157    .137
.100
IS vfsnd    .400    .136    .087    .179    .236    .206    .201    .306    .249
.334
IS  fsnd    .350    .252    .344    .215    .291    .270    .191    .202    .174
.218
IS  msnd    .059    .042    .043    .051    .057    .041    .018    .019    .015
.021
IS other    .001    .001    .004    .002    .001    .001    .000    .000    .000
.000
***
***  Angle of repose
***
AR   -90     -90
***
***  Output options
***
PR     2    2460
PX  2460
PW  2460
END
```

6.2 Output Data Files

All the output files for this example are included, in electronic format, in the GSTARS3 distribution in directory Example6.

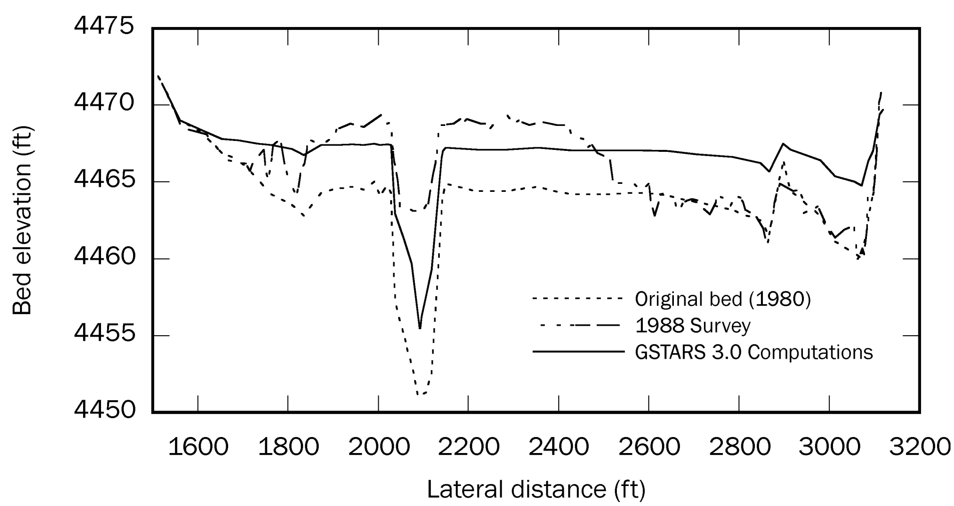
6.3 Results and Discussion

In this section we present a brief discussion of the simulation results. The data used to set-up the input datafiles was based on a survey of 1980. Since we also have access to survey data of 1988, corresponding to the end of the time span of the

GSTARS3 simulation in this example, that data is used for comparison purposes. Note that this example does not constitute a detailed sedimentation study of the region. It is included here for didactic purposes only. A more detailed and accurate analysis was presented in Yang et al. (1998). In this study there are several quantities that differ from the original Yang et al. (1998) study, as well as from Example 4 in the GSTARS 2.1 manual (Yang and Simões, 2000). For example, a different rating curve was used. The rating curve used in this study is based directly on measured data, but it underlines the need for further model calibration, making it of pedagogic interest. Therefore, the results presented in this section are not directly comparable to those presented in Yang et al. (1998) and in Yang and Simões (2000).

The results of the simulation are shown in figures 6.7 through 6.10 for four cross sections representative of the upper reach of the study. The results of the GSTARS3 generally match the 1988 measurements in this region of the modeled reach. The GSTARS3 calibration runs for this example were done by matching deposition volumes rather than thalwegs. As a result, the computed thalwegs are underpredicted in almost the entire reach of the study, as shown in figure 6.11. This choice of calibration is used here not only to present an example of reservoir sedimentation modeling, but also because in reservoir sedimentation it is often more important to predict deposition volumes accurately than the corresponding thalwegs.

Figure 6.7 Computed and measured cross sections at rangeline 57, which is located at a distance of approximately 134,151 ft from the downstream boundary.



In this study, it is observed that there are no bed changes in the lower one third of the reach, therefore the computed deposition volumes there are nearly zero. Measurements indicate that they are small, but not negligible. The differences between measured and computed quantities in that region are attributed to a poor sediment inflow rating curve. As can be seen in figure 6.4, the scatter of the data is high. With the rating curve derived using this data, the inflow volume of sediment into the reservoir is severely underpredicted. This underlines one more of the limitations and caveats of using sediment inflow rating curves that are a power function of the water discharge. Although this type of relationships is useful in many branches of hydrology, it is inadequate and sometimes even dangerous when used in complex sediment transport models, such as GSTARS3. A more appropriate procedure might be to try to match the rating curve not only to the data of figure 6.4, but also to the measured deposition volumes in the reservoir. That was accomplished in the study by Yang et al. (1998), resulting in a much accurate modeling of the reservoir deposits and thalwegs.

Figure 6.8 Computed and measured cross sections at rangeline 50, which is located at a distance of approximately 100,814 ft from the downstream boundary.

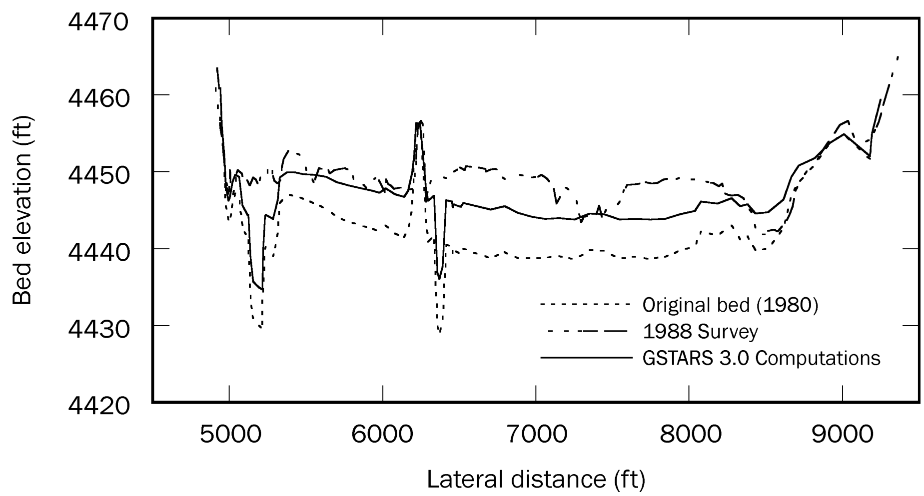


Figure 6.9 Computed and measured cross sections at rangeline 48, which is located at a distance of approximately 88,577 ft from the downstream boundary.

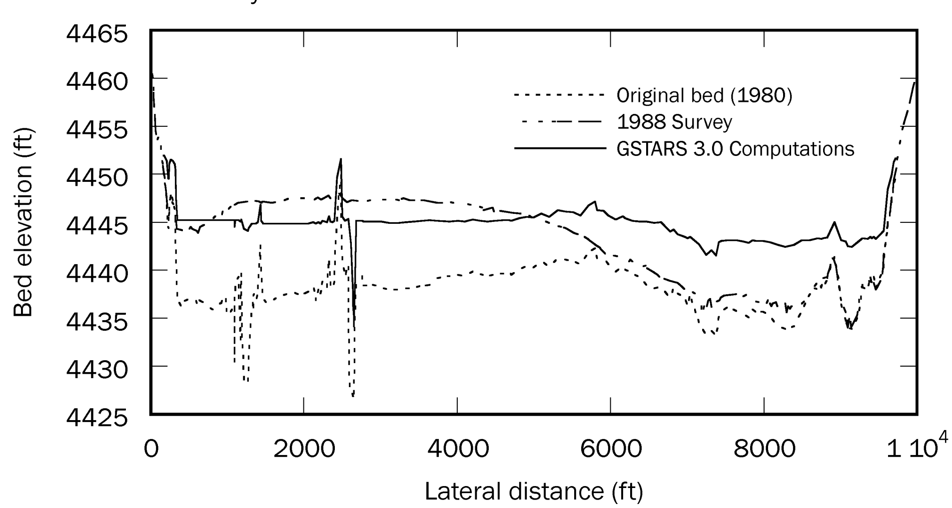


Figure 6.10 Computed and measured cross sections at rangeline 39, which is located at a distance of approximately 63,722 ft from the downstream boundary.

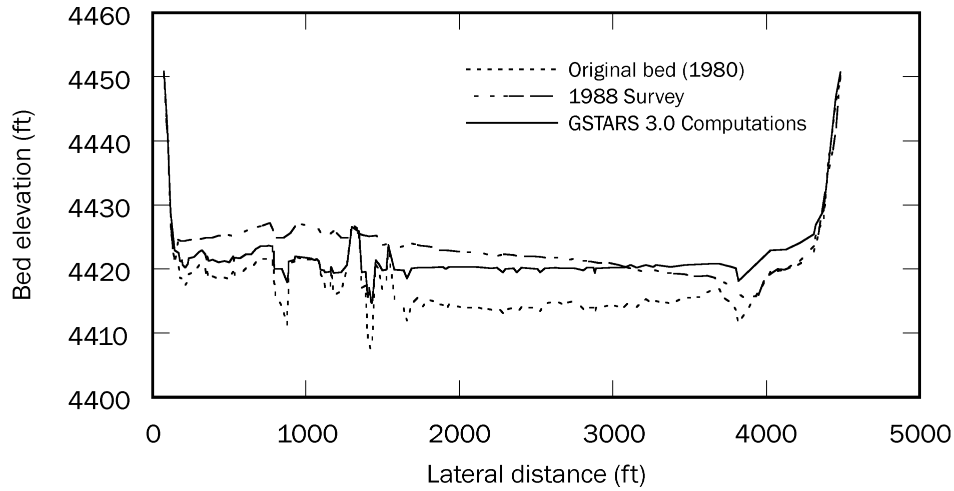
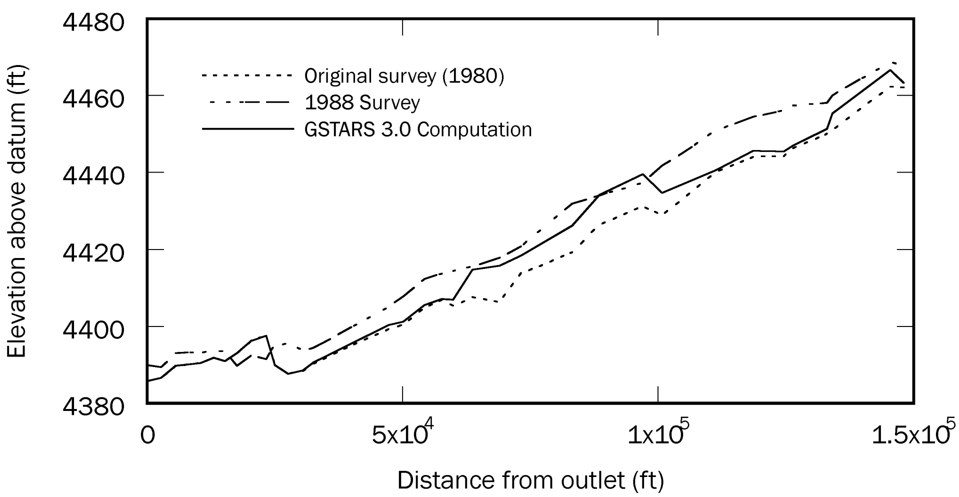


Figure 6.11 Thalweg elevations for the simulated reach.



6.4 References

Yang, C.T., Treviño, M.A., and Simões, F.J.M. (1998). *User's manual for GSTARS 2.0 (Generalized Stream Tube model for Alluvial River Simulation version 2.0)*. U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

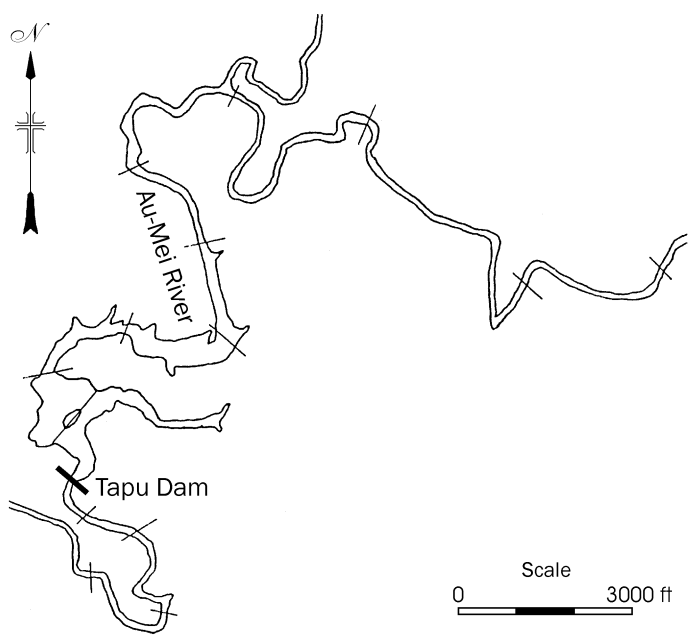
Yang, C.T., and Simões, F.J.M. (2000). *User's manual for GSTARS 2.1 (Generalized Stream Tube model for Alluvial River Simulation version 2.1)*. U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

EXAMPLE 7

TAPU RESERVOIR, TAIWAN

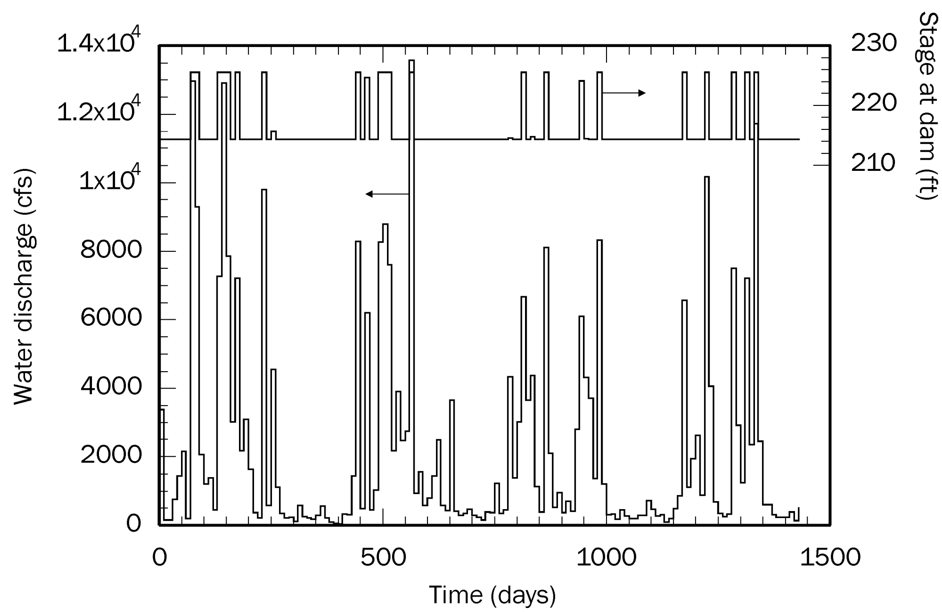
This example is similar to example 6. Tapu reservoir is a run-of-the-river type of reservoir (except for a small lake-like area near the dam) located in the Au-Mei River, in the northern part of Taiwan, with a natural drainage area of 24,710 acres. Tapu is a multipurpose reservoir for irrigation, flood control, and water supply. Its concrete gravity dam was completed in 1960. The map of the reservoir is shown in figure 7.1.

Figure 7.1 Tapu dam and reservoir in northern Taiwan.



Data collected in 1987 is used in the present study. 17 cross sections are used, comprising a reach with 41,561 ft in length. The run simulates a four-year period, ranging between 1987 and 1990. 144 10-day time steps are used in this run, with the corresponding hydrology shown in figure 7.2. River inflow discharge and stage at the dam are defined using TABLE OF DISCHARGE in record QQ and STAGE DISCHARGE TABLE in record SS, in which case the hydrology is supplied using TL and SQ records.

Figure 7.2 Hydrology for Tapu reservoir in the period of 1987 to 1990.



Bed composition comprises very fine material, as shown in figure 7.3, and is specified using sets of NB/BG records. Due to the presence of silt and clay fractions, it is necessary to use CS and CH records to define the appropriate cohesive sediment transport parameters. Inflow sediment distribution is defined using IQ/IS records, with an inflow sediment rating curve defined in a QR record:

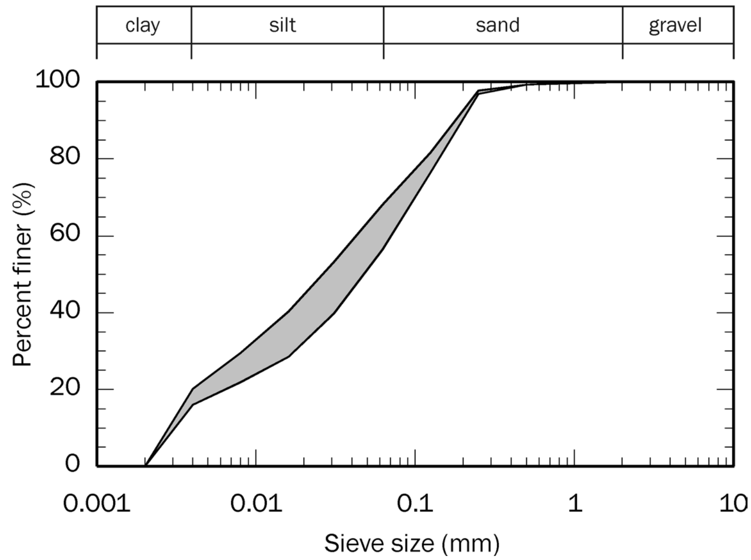
$$Q_s = 12.153 Q^{0.5738}$$

where Q_s = sediment discharge (ton/day) and Q = water discharge (ft^3/s). Sediment transport is computed using Yang (1973) and (1984) sediment transport equations using quarter-day time steps and 5 stream tubes.

7.1 Input Data File

The files shown in this and the next sections are part of the main GSTARS3 distribution package. They can be found under directory Example7.

Figure 7.3 Range of particle sizes for the bed sediment composition in the reach of interest.




```
TT          Simulation of the Tapu Reservoir from 1987 to 1990
TT

********************************************************************************
***  NOTE: this is a datafile to be used as an example of input data as it   ***
***  might be used in a GSTARS version 3.0 simulation.  It should not be     ***
***  used for any other purpose without appropriate verification and        ***
***  validation.                                                             ***
***                                                                          ***
********************************************************************************

NS    17
YX

ST 41561      15       0       0       0
ND     1   220.8
XS 265.7    0.00   264.4   42.65   256.1   45.28   248.7   46.29   242.9   56.76
XS 242.0   85.31   239.0   109.9   236.0   127.3   237.3   140.1   235.6   154.2
XS 237.0   169.3   258.7   174.5   264.4   176.5   264.7   187.0   266.6   220.8
RH 0.035

ST 39887      21       0       0       0
ND     1   255.9
XS 241.9    0.00   257.0   8.203   258.0   52.50   250.3   54.79   244.8   55.78
XS 241.7   80.23  236.18   90.56   236.9   104.3   235.2   133.9   234.8   152.9
XS 233.7   183.7   235.2   192.6   241.9   200.8   244.1   214.6   250.3   215.6
XS 257.9   216.5   258.2   223.1   257.7   234.6   251.4   239.5   248.2   244.4
XS 248.2   255.9
RH 0.035

ST 36643      13       0       0       0
ND     1   203.4
XS 241.8    0.00   246.8   62.34   239.2   63.65   235.5   65.62   235.5   68.90
XS 227.1   79.73   226.2   101.7   225.4   114.8   224.9   141.1   229.8   150.9
XS 233.0   160.8   246.8   180.5   247.9   203.4
```

```
RH 0.035

ST 34365      13       0       0       0
ND     1   295.3
XS 255.7    0.00   257.1   42.65   239.2   45.93   228.7   49.22   226.6   69.89
XS 222.2   125.3   224.7   168.0   226.5   195.2   232.9   207.4   232.6   268.1
XS 240.8   287.4   257.2   289.4   257.2   295.3
RH 0.035

ST 31262      19       0       0       0
ND     1     269
XS 232.0    0.00   236.3   2.625   236.6   16.73   242.8   65.95   242.8   70.21
XS 232.9   73.17   232.3   81.70   226.0   85.96   221.3   118.8   222.6   164.4
XS 225.9   188.3   233.5   207.4   243.5   210.0   243.5   212.9   243.7   218.8
XS 238.7   247.7   239.2   258.9   237.8   264.8   235.1   269.0
RH 0.035

ST 28430      18       0       0       0
ND     1   429.8
XS 259.7    0.00   256.2   39.37   236.0   43.31   239.8   59.39   237.0   71.53
XS 242.3   99.74   241.9   135.5   236.4   154.2   232.0   183.7   226.1   250.0
XS 222.1   269.0   214.4   312.7   220.1  344.20   247.8  378.30   256.3  383.90
XS 256.5  389.10   257.0  400.00   259.2  429.80
RH 0.035

ST 25965      19       0       0       0
ND     1   328.1
XS 259.9    0.00  256.90   8.203   256.3   13.12   241.9   35.76   240.3   47.25
XS 229.6   69.89   226.5   161.8   223.1   168.3   215.8   182.4   209.1   212.0
XS 207.0   234.3   221.0   281.5   229.5   282.8   240.5   295.0   241.2   298.9
XS 241.8   302.8   251.7   304.5   252.6   310.4   265.8  328.10
RH 0.035

ST 22780      14       0       0       0
ND     1   358.6
XS 277.4    0.00   228.8   37.40   221.5   72.18   220.3   89.90   214.9   111.6
XS 211.5   142.7   210.8   180.8   213.5   212.6   222.2   229.7   224.7   254.3
XS 225.9   265.8   233.5   270.4   249.0   298.6   296.4  358.60
RH 0.035

ST 20695      15       0       0       0
ND     1   465.6
XS 295.4    0.00   281.2   31.83   262.5   55.45   232.0   114.8   226.4   130.6
XS 219.2  160.77  216.55  180.13  197.06  208.67  200.14  238.20  219.56  272.32
XS 229.7   306.8   238.7  328.10   246.4  370.80   275.3  418.00   295.9  465.60
RH 0.035

ST 18113      16       0       0       0
ND     1   462.6
XS 240.6    0.00   239.7   9.843   222.4   21.65  194.80   53.48   196.1   93.51
XS 208.7   145.0   214.9   168.0   225.0   221.8   231.4   260.8   239.1   262.5
XS 239.6   315.6   233.4  345.80   234.7  360.36   241.3  368.50   240.9  382.20
XS 239.4  462.60
RH 0.035

ST 15199      15       0       0       0
ND     1     962
XS 262.9    0.00   232.8   82.68   230.0   213.6   230.2   316.9   226.1  372.70
XS 223.1  443.60   217.9  469.80   204.1  555.50   210.3  641.10   218.5  730.70
XS 219.5  771.70   223.1  835.00   229.3  876.00   262.8  922.00   278.9  962.00
RH 0.035
```

```
ST 12440      20       0       0       0
ND     1   334.7
XS 285.5    0.00   251.3   8.203   249.4   16.41   247.7   20.01   234.8   43.31
XS 230.3   47.25   224.1   82.03   224.5   114.8   221.5   147.6   218.9   180.5
XS 217.4   213.3   219.7   246.1   227.5   270.7   237.1   273.6   242.2   283.8
XS 274.5   289.1   249.5   295.3   250.3   301.9   258.5   305.1   259.9  334.70
RH 0.035

ST  9009      14       0       0       0
ND     1    1087
XS 277.1    0.00   262.6   91.21   231.6   158.1   225.1   246.1   223.8  400.30
XS 222.5  557.80   219.8  602.40   210.0  675.90   215.2  787.40   219.8  908.80
XS 228.7  933.10   236.6  1004.0   249.4  1076.0   257.9  1087.0
RH 0.035

ST  6893      15       0       0       0
ND     1   505.9
XS 257.6    0.00   250.6   66.28   249.6   93.51  213.50   105.6   203.3   133.5
XS 204.3   168.3   210.7   238.2   222.6   316.9   226.2  418.00   227.9  427.80
XS 239.5  429.80   239.5  434.40   250.7  437.00   252.9  472.80   256.8  505.90
RH 0.035

ST  3830      15       0       0       0
ND     1    1092
XS 274.8    0.00   268.3   49.22   225.9   108.9   224.1   242.8   223.6   319.9
XS 219.2  374.00   208.7  470.20   206.6  553.20   205.4  616.80   207.4  699.80
XS 214.5  805.20   217.4  854.00   224.4  971.20   226.4  1000.0   233.0  1092.0
RH 0.035

ST  2815      20       0       0       0
ND     1    2077
XS 268.1    0.00  219.20   86.62   218.4   201.8   208.2   322.9   207.7  557.80
XS 214.9  774.60   256.0  887.80   270.6  954.80   269.5  984.30   250.7  1049.0
XS 249.5  1111.0   271.7  1214.0   263.1  1324.0   221.4  1417.0   219.4  1542.0
XS 212.3  1723.0   217.6  1814.0   230.0  1867.0   262.6  1996.0   292.2  2077.0
RH 0.035

ST     0      14       1       1       0
ND     1   323.8
XS 236.8    0.00   226.7    10.5   195.5   44.95   191.6   75.13   193.5   92.20
XS 194.3   107.3   190.7   139.4   191.1   171.6   180.3   203.8   181.6   236.2
XS 214.4   269.0   221.3   304.5   226.7   309.1   236.2   323.8
RH 0.035

NT     5

IT   144      40      10 DAY
QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE
TL    17

SQ3380.1 214.410
SQ151.88 214.410
SQ158.94 214.410
SQ762.91 214.410
SQ1441.1 214.410
SQ2168.6 214.410
SQ201.32 214.410
SQ 12976 225.570
SQ9292.6 225.570
```

```
SQ2069.7 214.410
SQ1204.4 214.410
SQ  1381 214.410
SQ 441.5 214.410
SQ7282.9 225.570
SQ 12919 225.570
SQ7858.7 225.570
SQ3019.8 214.410
SQ7222.9 225.570
SQ2186.3 214.410
SQ3104.6 214.410
SQ1631.7 214.410
SQ370.86 214.410
SQ208.39 214.410
SQ9804.9 225.570
SQ586.31 214.410
SQ4552.7 215.659
SQ1119.6 214.410
SQ 353.2 214.410
SQ208.39 214.410
SQ233.11 214.410
SQ109.49 214.410
SQ586.31 214.410
SQ243.71 214.410
SQ215.45 214.410
SQ 176.6 214.410
SQ300.22 214.410
SQ558.06 214.410
SQ215.45 214.410
SQ102.42 214.410
SQ 52.98 214.410
SQ 35.32 214.410
SQ335.54 214.410
SQ321.41 214.410
SQ  1434 214.410
SQ  8279 225.570
SQ480.35 214.410
SQ6202.2 224.674
SQ448.56 214.410
SQ1031.3 214.410
SQ8275.5 225.570
SQ8798.2 225.570
SQ  7615 225.570
SQ2182.8 214.410
SQ3906.4 214.410
SQ2479.5 214.410
SQ2740.8 214.410
SQ 13577 225.570
SQ932.45 214.410
SQ1557.6 214.410
SQ575.72 214.410
SQ 794.7 214.410
SQ1437.5 214.410
SQ2486.5 214.410
SQ579.25 214.410
SQ427.37 214.410
SQ3655.6 214.410
SQ406.18 214.410
SQ300.22 214.410
SQ356.73 214.410
SQ473.29 214.410
```

```
SQ286.09 214.410
SQ229.58 214.410
SQ 155.4 214.410
SQ384.99 214.410
SQ381.46 214.410
SQ1225.6 214.410
SQ360.26 214.410
SQ 441.5 214.410
SQ4333.8 214.540
SQ  1381 214.410
SQ3016.3 214.410
SQ6668.4 225.570
SQ3662.7 214.410
SQ4376.1 214.755
SQ1123.2 214.410
SQ384.99 214.410
SQ8109.5 225.570
SQ  2098 214.410
SQ 529.8 214.410
SQ957.17 214.410
SQ367.33 214.410
SQ709.93 214.410
SQ416.78 214.410
SQ2804.4 214.410
SQ6099.8 224.087
SQ4316.1 214.450
SQ3715.7 214.410
SQ1363.4 214.410
SQ8324.9 225.570
SQ1211.5 214.410
SQ310.82 214.410
SQ335.54 214.410
SQ   166 214.410
SQ445.03 214.410
SQ268.43 214.410
SQ 187.2 214.410
SQ201.32 214.410
SQ286.09 214.410
SQ296.69 214.410
SQ   717 214.410
SQ462.69 214.410
SQ275.49 214.410
SQ317.88 214.410
SQ102.43 214.410
SQ 187.2 214.410
SQ490.95 214.410
SQ865.34 214.410
SQ6573.1 225.570
SQ1116.1 214.410
SQ1949.7 214.410
SQ2634.9 214.410
SQ875.94 214.410
SQ 10168 225.570
SQ4065.3 214.410
SQ678.14 214.410
SQ360.26 214.410
SQ250.77 214.410
SQ328.48 214.410
SQ7497.8 225.570
SQ  2928 214.410
SQ1253.9 214.410
```

```
SQ7208.8 225.570
SQ2345.2 214.410
SQ 11733 225.570
SQ2461.8 214.410
SQ600.44 214.410
SQ600.44 214.410
SQ321.41 214.410
SQ233.11 214.410
SQ240.18 214.410
SQ229.58 214.410
SQ392.05 214.410
SQ134.22 214.410
SQ505.08 214.410

SE    10
NE  0.25       1
QR12.153  0.5738
TM   144      65
SF    10
SG 0.002   0.004
SG 0.004   0.008
SG 0.008   0.016
SG 0.016   0.031
SG 0.031  0.0625
SG0.0625   0.125
SG 0.125    0.25
SG  0.25     0.5
SG   0.5       1
SG     1       2

NB     0
BG  0.16    0.06  0.0652  0.1127   0.166     0.2   0.206  0.0243  0.0032  0.0026

NB  3830
BG0.2015  0.0948   0.107   0.128   0.149  0.1366  0.1613  0.0148  0.0051  0.0019

CS  0.02     0.1    0.15      60     1.5     0.1
CH 1.0e8   2.0e8              -1      -1      -1

IQ     5  388.52  1483.4  4944.8  8829.9 31787.9
IS        0.1068  0.1136  0.1136  0.1136  0.1136
IS        0.0747  0.1533  0.1533  0.1533  0.1533
IS        0.0747  0.1136  0.1136  0.1136  0.1136
IS        0.0747  0.0795  0.0795  0.0795  0.0795
IS        0.2028  0.2044  0.2044  0.2044  0.2044
IS        0.1966  0.1264  0.1264  0.1264  0.1264
IS        0.2357  0.1871  0.1871  0.1871  0.1871
IS        0.0236  0.0137  0.0137  0.0137  0.0137
IS        0.0038   0.006   0.006   0.006   0.006
IS        0.0005  0.0004  0.0004  0.0004  0.0004


PR     3     144
PX   144
PW   144
END
```

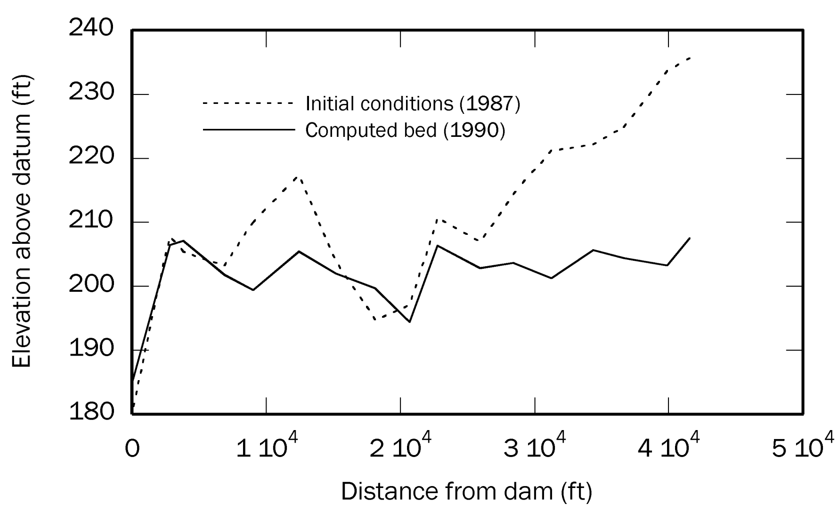
7.2 Output Data Files

All the output data files for this example are given, in electronic format, in the GSTARS3 distribution package in directory Example7.

7.3 Results and Discussion

At the time of writing of this manual there wasn't enough information to write a detailed analysis of the results for this example, which will be done at a later time. Here, the thalweg resulting from the GSTARS3 computations is presented in figure 7.4. Figure 7.4 was plotted using the data in the GSTARS3 main output data file (.OUT) and a typical plotting software package.

Figure 7.4 Initial (measured) and computed thalweg profiles for a four-year GSTARS3 simulation of Tapu reservoir.



EXAMPLE 8

TARBELA RESERVOIR, PAKISTAN

This is yet another example of reservoir sedimentation. Here, GSTARS3 is applied to Tarbela Dam and Reservoir to compute reservoir sedimentation and delta movement. Tarbela Dam, located in northern Pakistan along the Indus River, is the largest earth-filled dam in the world. The reservoir, with a gross storage capacity of 506.4 billion cubic feet, is a 60 mile long run of the river type of reservoir with two major tributaries, the Siran and the Brandu. Tarbela's main function is of providing water for irrigation, releasing 388 million cubic feet of irrigation water annually. Additionally, the hydropower capacity of the power station totals 3478 MW and produces 32% of Pakistan's needs. The reservoir's storage capacity has been continuously depleted since the dam has been built, in 1974, with an annual inflow rate of 265 million tons of sediment, most of which in the silt and clay range. This loss in capacity threatens the resources and revenue associated with the dam and reservoir.

In this example, GSTARS3 is used to simulate 22 years of reservoir sedimentation (from 1974 through 1996) for a reach that spans nearly 58 miles upstream from the dam (see figure 8.1). The hydrology of the system is given in figure 8.2, together with the dam operation. The tributaries have a relatively small contribution when compared with the main stem discharge, therefore they are not included in figure 8.2 (but they are included in the computations).

This case has three interesting differences from the Rio Grande study presented in example 6. First, there is a large percentage of silt and clay in the sediments in transport, but there is no data to simulate them using the Krone/Ariathurai methods. Second, analysis of 1996 cross-sectional data suggests that deposition occurs in the form of a uniform fill, such as that described in figure 5.4 of chapter 5, as can be observed in figure 8.3 below. Finally, there exists a rating curve derived much in the same way as that in example 6, but during the calibration runs it was observed that the amount of deposition was severely underpredicted. That rating curve was adjusted to correctly reproduce the reservoir deposition volume. For that, it was also used the fact that the first cross section was observed not to change much during the 1974-1994 period concerning this study. The distribution of the incoming sediment load was also subject of calibration. More details on how these factors were taken into account are presented in the discussion that follows.

Figure 8.1 Tarbela dam and reservoir. The points (+) mark the thalweg and the locations of the cross sections used in this study.

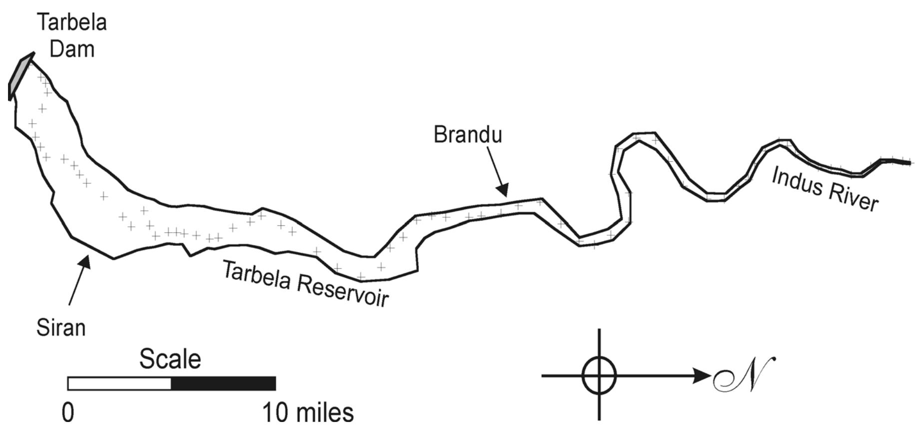
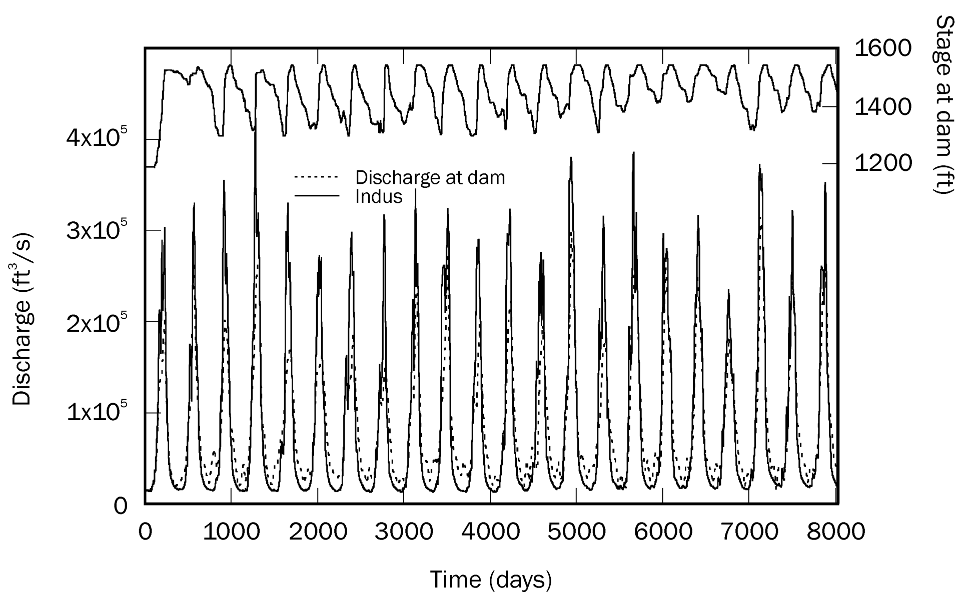
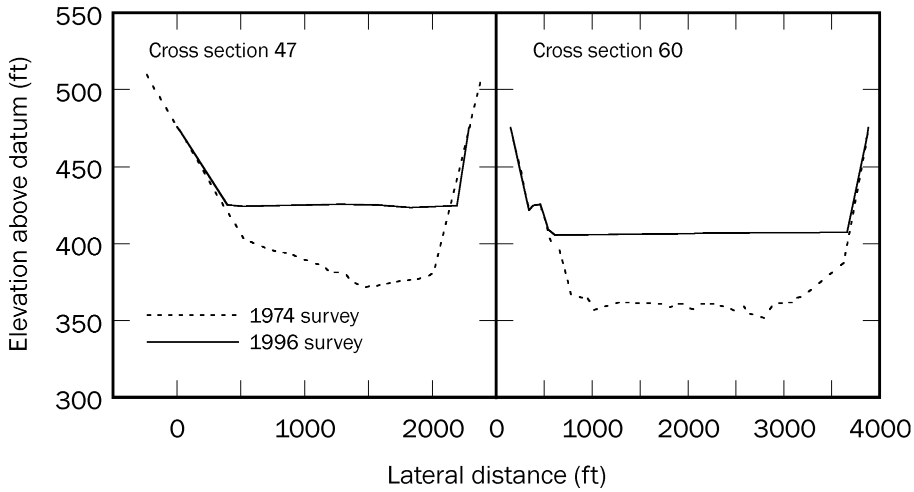


Figure 8.2 Hydrology and dam operation for Tarbela in the period of 1974 to 1996.



The Tarbela reservoir's bathymetry was discretized using existing surveyed cross sections, which are marked in figure 8.1. The uniform fill observed in figure 8.3 indicates that there is not much transverse variation in the sedimentation processes, therefore the GSTARS3 simulations were carried out using one stream tube. Uniform fill is indicated setting *RFILL* equal to 1 in record SE.

Figure 8.3 Two reservoir cross sections showing uniform sedimentation.



Yang's (1973) equation was used for this study. Because there is no information concerning the deposition characteristics of the silt and clay fractions, it is difficult to use the Krone/Ariathurai methods effectively. Instead, the Yang (1973) was extrapolated for these size ranges by setting *STDEP* equal to -1 in record CS (the particle size distributions are in the range of 0.002 to 2.0 mm). Under this circumstance, record CH should not be used. This approach can sometimes yield good results, especially in mainly depositional processes such as those occurring in large reservoirs. However, care should be exercised, and the results of the simulations should always be confirmed by careful validation using field data.

Daily time steps for the hydraulic computations and 4.8 hours for sediment routing computations (8,040 time steps for hydraulics, 40,200 time steps for sediment) are used (see record IT). Using these parameters, computer runs on a fairly modern PC-compatible desktop workstation running Microsoft Windows XP took less than 20 minutes.

8.1 Input Data File

Due to the length of this data file, the full extent of records SQ and TM is not included. The complete data file is bundled in the GSTARS3 distribution files in directory Example8. Also, the tributary input datafiles are not included here, but they can be found under directory Example8. All the files shown in this and the next sections are included in the main GSTARS3 distribution package.

```
TT GSTARS version 3.0  -  Example data file for Appendix B of user's manual
TT Tarbela Reservoir, simulation run for the period of 1975-1996

********************************************************************************
***                                                                          ***
***  NOTE: this is a simplified version of the datafile used to simulate     ***
```

```
***  the delta formation at the Tarbela Reservoir duriong the period of      ***
***  1975 to 1996.  It may not contain an accurate representation of the     ***
***  actual flow and geological conditions at the site.  This data file      ***
***  should be viewed only as an example of input data as it might be used   ***
***  in a GSTARS version 3.0 simulation.  This file was constructed for      ***
***  didactic purposes only.                                                 ***
***                                                                          ***
********************************************************************************

NS    76

ST289093      13
ND     1  600.00
XS                10.01 1560.01   64.99 1550.00   89.99 1527.49
XS               270.01 1504.99  289.99 1496.00  343.50 1491.01
XS               395.01 1487.50  414.99 1487.50  464.99 1539.99
XS               520.01 1521.00  539.99 1519.00  585.01 1550.00
XS               600.00 1560.01
RH 0.020

ST287254      13
ND     1  704.99
XS               118.01 1570.01  149.02 1560.01  179.99 1550.00
XS               339.99 1510.99  350.00 1502.00  370.01 1502.99
XS               400.00 1495.01  439.99 1496.00  500.00 1510.99
XS               560.01 1512.99  654.99 1550.00  679.99 1560.01
XS               704.99 1570.01
RH 0.020

ST284725      11
ND     1  479.99
XS              -374.80 1641.60  -87.17 1576.21   29.99 1550.00
XS               179.99 1519.00  229.99 1471.00  285.01 1468.50
XS               310.01 1473.00  350.00 1472.01  379.99 1485.01
XS               450.00 1550.00  479.99 1643.86
RH 0.020

ST281630      11
ND     1  535.01
XS                39.99 1560.01   60.01 1550.00  175.00 1523.00
XS               185.01 1510.99  210.01 1506.99  279.99 1471.00
XS               310.01 1469.00  439.99 1535.01  475.00 1527.00
XS               514.99 1550.00  535.01 1560.01
RH 0.020

ST278777      13
ND     1 1365.12
XS              -397.24 1647.57  179.99 1550.00  314.99 1529.00
XS               450.00 1501.51  600.00 1496.00  639.99 1497.51
XS               739.99 1493.50  800.00 1485.99  870.01 1493.01
XS               900.00 1508.01  939.99 1503.51 1070.01 1550.00
XS              1365.12 1647.57
RH 0.020

ST275973      11
ND     1  960.01
XS               114.99 1560.01  150.00 1537.01  220.01 1537.01
XS               370.01 1508.99  420.01 1506.99  450.00 1491.99
XS               639.99 1491.99  770.01 1524.02  800.00 1525.00
XS               920.01 1550.00  960.01 1560.01
RH 0.020
```

```
ST273235      15
ND     1  810.01
XS               70.01 1560.01   79.99 1550.00  150.00 1479.99
XS              189.99 1479.99  225.00 1475.00  245.01 1464.99
XS              275.00 1461.52  314.99 1464.50  389.99 1460.99
XS              539.99 1510.01  639.99 1520.01  700.00 1537.99
XS              795.01 1541.01  800.00 1550.00  810.01 1560.01
RH 0.020

ST270364      14
ND     1 1110.01
XS               70.01 1560.01  100.00 1550.00  150.00 1533.99
XS              220.01 1527.00  250.00 1514.99  289.99 1514.01
XS              350.00 1516.99  450.00 1518.01  639.99 1514.99
XS              729.99 1506.99  929.99 1504.00 1000.00 1510.01
XS             1089.99 1550.00 1110.01 1560.01
RH 0.020

ST268052      12
ND     1 1269.19
XS               65.72 1643.86  129.99 1550.00  139.99 1539.01
XS              420.01 1537.99  520.01 1527.49  704.99 1487.01
XS              829.99 1466.01  889.99 1463.48  979.99 1510.01
XS             1020.01 1514.99 1100.00 1550.00 1269.19 1643.86
RH 0.020

ST264701      19
ND     1  860.01
XS               85.01 1560.01   89.99 1550.00  120.01 1500.98
XS              150.00 1498.00  189.99 1450.98  220.01 1439.01
XS              250.00 1443.01  300.00 1445.01  350.00 1458.01
XS              400.00 1491.99  510.01 1512.01  585.01 1506.00
XS              670.01 1527.00  714.99 1527.99  750.00 1535.99
XS              800.00 1535.99  829.99 1541.01  839.99 1550.00
XS              860.01 1560.01
RH 0.020

ST261807      11
ND     1 1425.00
XS              137.30 1697.18  149.11 1550.00  150.00 1472.51
XS              185.01 1471.00  214.99 1464.99  250.00 1435.99
XS              575.00 1469.00  629.99 1490.49  660.01 1487.99
XS              985.01 1550.00 1425.00 1655.97
RH 0.020

ST258204      14
ND     1 1014.99
XS              106.99 1560.01  110.01 1550.00  120.01 1496.00
XS              179.99 1493.01  189.99 1479.99  425.00 1495.51
XS              485.01 1494.00  550.00 1487.01  589.99 1496.00
XS              639.99 1496.49  700.00 1512.01  789.99 1525.00
XS              950.00 1550.00 1014.99 1560.01
RH 0.020

ST255382      19
ND     1 1900.00
XS              250.00 1560.01  400.00 1543.50  429.99 1539.99
XS              475.00 1538.48  520.01 1529.99  529.99 1510.01
XS              564.99 1489.50  600.00 1486.52  700.00 1487.01
XS              729.99 1489.99  820.01 1489.01 1279.99 1502.99
```

```
XS               1560.01 1506.99 1720.01 1525.00 1739.99 1522.51
XS               1800.00 1537.99 1879.99 1539.99 1889.99 1550.00
XS               1900.00 1560.01
RH 0.020

ST253042      13
ND     1 1463.35
XS                  2.03 1648.03   75.00 1550.00  110.01 1500.00
XS                177.99 1481.00  379.99 1462.01  650.00 1454.00
XS                814.99 1450.00  839.99 1468.01  879.99 1479.00
XS                989.99 1510.01 1160.01 1535.99 1200.00 1550.00
XS               1463.35 1648.03
RH 0.020

ST249004      18
ND     1 1400.00
XS                 68.01 1560.01   70.01 1550.00  114.99 1441.99
XS                181.99 1431.99  204.99 1429.99  350.00 1426.51
XS                439.99 1425.49  489.99 1425.49  660.01 1425.98
XS                820.01 1437.01  900.00 1450.00 1079.99 1458.99
XS               1239.99 1470.01 1320.01 1481.99 1335.01 1485.99
XS               1350.00 1494.00 1389.99 1550.00 1400.00 1560.01
RH 0.020

ST245092      17
ND     1 1627.95
XS                -36.35 1697.18   20.01 1550.00   39.99 1489.99
XS                160.01 1481.99  200.00 1477.99  300.00 1450.98
XS                379.99 1441.99  500.00 1435.01  620.01 1431.99
XS                779.99 1429.99  960.01 1431.99 1200.00 1439.01
XS               1260.01 1444.00 1279.99 1448.00 1425.00 1539.99
XS               1439.99 1550.00 1627.95 1697.18
RH 0.020

ST241273      12
ND     1 1404.99
XS               -125.00 1560.01 -114.99 1550.00 -100.00 1539.99
XS                 64.99 1431.99  200.00 1424.02  439.99 1422.01
XS                760.01 1429.99  879.99 1439.01 1279.99 1479.99
XS               1360.01 1494.00 1395.01 1550.00 1404.99 1560.01
RH 0.020

ST238300       8
ND     1 2162.43
XS               -238.32 1696.46   79.99 1550.00  345.01 1416.99
XS                479.99 1414.01  739.99 1469.00  950.00 1502.00
XS               1300.00 1550.00 2162.43 1670.51
RH 0.020

ST234014      10
ND     1 1810.01
XS                  0.00 1560.01   20.01 1550.00  164.99 1419.00
XS                329.99 1389.01  500.00 1460.01  879.99 1470.01
XS                920.01 1475.98 1360.01 1531.99 1650.00 1550.00
XS               1810.01 1560.01
RH 0.020

ST229488      16
ND     1 1866.86
XS                -75.95 1622.93   79.99 1550.00  339.99 1441.99
XS                360.01 1425.98  400.00 1408.01  500.00 1394.00
```

```
XS              539.99 1394.00  760.01 1429.99 1039.99 1458.01
XS             1139.99 1474.02 1260.01 1485.99 1389.99 1494.00
XS             1400.00 1498.00 1679.99 1539.99 1720.01 1550.00
XS             1866.86 1622.93
RH 0.020

ST223195      10
ND     1 2727.95
XS               -8.10 1630.74   14.99 1550.00   39.99 1447.01
XS              360.01 1373.00  700.00 1452.00 1000.00 1462.01
XS             1620.01 1475.98 2135.01 1510.01 2400.00 1550.00
XS             2727.95 1630.74
RH 0.020

ST216194      20
ND     1 2560.01
XS              150.00 1560.01  175.00 1550.00  285.01 1500.00
XS              370.01 1429.99  400.00 1420.01  529.99 1399.02
XS              560.01 1398.00  789.99 1398.00 1139.99 1420.01
XS             1620.01 1431.00 1800.00 1450.00 1979.99 1429.99
XS             1989.99 1441.01 2079.99 1450.00 2120.01 1441.01
XS             2300.00 1439.99 2400.00 1450.00 2479.99 1520.01
XS             2539.99 1550.00 2560.01 1560.01
RH 0.020

ST210919      15
ND     1 3036.91
XS            -1275.72 1687.14 -531.89 1593.83  500.00 1550.00
XS              920.01 1533.99 1360.01 1516.99 1620.01 1489.99
XS             1889.99 1412.99 2139.99 1383.99 2239.99 1377.99
XS             2300.00 1379.99 2479.99 1393.01 2550.00 1425.98
XS             2560.01 1450.98 2760.01 1550.00 3036.91 1704.79
RH 0.020

ST205917      15
ND     1 2160.01
XS                0.00 1560.01   50.00 1550.00  100.00 1539.99
XS              360.01 1491.01  610.01 1400.98  800.00 1364.99
XS              920.01 1360.01 1100.00 1391.99 1200.00 1416.01
XS             1629.99 1479.00 1739.99 1487.99 1860.01 1512.99
XS             1939.99 1520.01 2100.00 1550.00 2160.01 1560.01
RH 0.020

ST201014      14
ND     1 2426.21
XS             -213.78 1630.74   79.99 1550.00  200.00 1519.00
XS              339.99 1499.02  539.99 1483.99  610.01 1472.01
XS             1039.99 1441.99 1160.01 1429.00 1279.99 1385.01
XS             1404.00 1364.01 1600.00 1366.99 1960.01 1489.99
XS             2179.99 1550.00 2426.21 1630.74
RH 0.020

ST195283      11
ND     1 2379.99
XS              560.01 1560.01  600.00 1550.00  710.01 1520.01
XS             1279.99 1416.01 1610.01 1370.01 1720.01 1370.01
XS             1939.99 1374.02 2075.00 1383.99 2179.99 1454.99
XS             2360.01 1550.00 2379.99 1560.01
RH 0.020

ST189956      19
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ND     1 3592.95
XS              -217.36 1802.53  120.01 1550.00  200.00 1510.99
XS               279.99 1400.00  439.99 1362.01  560.01 1345.01
XS               660.01 1348.00  770.01 1370.01 1039.99 1402.00
XS              1239.99 1439.99 1289.99 1460.01 1400.00 1479.00
XS              1439.99 1481.99 2000.00 1489.99 2760.01 1512.99
XS              3100.00 1519.00 3200.00 1529.00 3300.00 1650.00
XS              3592.95 1802.76
RH 0.020

ST183812      15
ND     1 2370.01
XS                29.99 1560.01   39.99 1550.00  239.99 1360.01
XS               389.99 1335.99  529.99 1322.01  650.00 1333.99
XS               939.99 1419.00 1139.99 1439.99 1289.99 1450.00
XS              1550.00 1500.00 2100.00 1510.01 2200.00 1531.99
XS              2300.00 1541.01 2339.99 1550.00 2370.01 1560.01
RH 0.020

ST178802      19
ND     1 3241.57
XS              -351.15 1638.81  200.00 1550.00  600.00 1498.00
XS               860.01 1427.00  960.01 1349.02 1010.01 1329.99
XS              1039.99 1324.02 1200.00 1314.01 1279.99 1316.01
XS              1679.99 1389.99 1879.99 1410.01 2110.01 1420.01
XS              2300.00 1439.99 2500.00 1450.00 2639.99 1462.01
XS              2660.01 1470.01 2800.00 1489.01 3000.00 1550.00
XS              3241.57 1638.81
RH 0.020

ST174680      19
ND     1 2010.01
XS                50.00 1560.01   52.00 1550.00   60.01 1460.01
XS               100.00 1437.99  145.01 1429.99  250.00 1339.99
XS               310.01 1333.99  329.99 1320.01  389.99 1314.01
XS               460.01 1310.01  679.99 1302.99  800.00 1302.00
XS              1200.00 1310.01 1204.00 1320.01 1600.00 1360.01
XS              1760.01 1394.00 1879.99 1439.99 2000.00 1550.00
XS              2010.01 1560.01
RH 0.020

ST170206      11
ND     1 2142.19
XS               -50.46 1647.51   70.01 1550.00  264.99 1422.01
XS               479.99 1397.01 1000.00 1308.01 1129.99 1300.00
XS              1660.01 1400.00 1700.00 1450.00 1920.01 1500.00
XS              1989.99 1550.00 2142.19 1647.51
RH 0.020

ST163908      25
ND     1 3305.77
XS                89.30 1647.51  189.99 1550.00  250.00 1475.98
XS               439.99 1450.00  600.00 1429.99  870.01 1410.01
XS               920.01 1389.99 1079.99 1370.01 1120.01 1360.01
XS              1239.99 1339.99 1270.01 1329.99 1620.01 1310.01
XS              1679.99 1289.99 1720.01 1285.99 1920.01 1281.99
XS              2100.00 1287.99 2200.00 1300.00 2429.99 1360.01
XS              2679.99 1360.01 2850.00 1370.01 2939.99 1379.99
XS              2970.01 1389.99 3020.01 1446.00 3179.99 1550.00
XS              3305.77 1647.51
RH 0.020
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ST156915      15
ND     1 4127.53
XS             -418.34 1655.94  160.01 1550.00  400.00 1500.00
XS             1000.00 1444.00 1379.99 1420.01 1920.01 1368.01
XS             2120.01 1329.99 2389.99 1310.01 2429.99 1300.00
XS             3120.01 1262.01 3220.01 1262.01 3650.00 1298.00
XS             3820.01 1450.00 3979.99 1550.00 4127.53 1655.94
RH 0.020

ST151965      20
ND     1 2600.00
XS                0.00 1560.01   10.01 1550.00   79.99 1500.00
XS              339.99 1398.00  500.00 1370.01  579.99 1329.99
XS              700.00 1339.99  960.01 1329.99 1039.99 1320.01
XS             1439.99 1302.00 1700.00 1266.99 1739.99 1269.00
XS             1920.01 1350.00 1989.99 1350.00 2100.00 1302.00
XS             2200.00 1344.00 2220.01 1400.00 2400.00 1450.00
XS             2579.99 1550.00 2600.00 1560.01
RH 0.020

ST147429      17
ND     1 2773.13
XS              -16.47 1655.94   60.01 1550.00   79.99 1447.01
XS              139.99 1389.99  239.99 1358.01  300.00 1289.99
XS              439.99 1264.99  520.01 1264.01  660.01 1268.01
XS             1170.01 1310.99 1220.01 1323.00 1320.01 1335.99
XS             1760.01 1360.01 2279.99 1379.99 2360.01 1400.00
XS             2589.99 1550.00 2773.13 1655.94
RH 0.020

*** Lateral tributary: Brandu
LI Brandu.dat

ST142248      18
ND     1 3189.99
XS              104.99 1560.01  110.01 1550.00  114.99 1450.00
XS              339.99 1379.99  479.99 1362.01  679.99 1291.99
XS              750.00 1279.00  889.99 1295.01 1125.00 1322.01
XS             1279.99 1329.99 1400.00 1339.99 1860.01 1350.00
XS             2389.99 1370.01 2760.01 1379.99 2979.99 1400.00
XS             3160.01 1516.01 3179.99 1550.00 3189.99 1560.01
RH 0.020

ST139071      19
ND     1 3338.45
XS               76.64 1643.14  204.99 1550.00  314.99 1350.00
XS              439.99 1287.01  600.00 1269.00  760.01 1266.01
XS              960.01 1266.01 1150.00 1279.99 1220.01 1300.00
XS             1639.99 1320.01 1720.01 1329.99 1839.99 1339.99
XS             1879.99 1350.00 2250.00 1360.01 2460.01 1379.99
XS             2800.00 1400.00 3079.99 1450.00 3200.00 1550.00
XS             3338.45 1655.94
RH 0.020

ST133600      11
ND     1 4056.36
XS               41.34 1655.94  220.01 1550.00  400.00 1400.00
XS             2000.00 1310.99 2400.00 1258.99 2600.00 1250.98
XS             2889.99 1260.01 3070.01 1256.00 3650.00 1348.00
XS             3929.99 1550.00 4056.36 1655.94
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RH 0.020

ST129961      14
ND     1 4379.99
XS              170.01 1560.01  179.99 1550.00  479.99 1391.01
XS              750.00 1379.00 2100.00 1350.00 2600.00 1329.99
XS             2720.01 1320.01 3450.00 1300.00 3560.01 1279.99
XS             3679.99 1256.00 3720.01 1254.99 3800.00 1258.01
XS             4370.01 1550.00 4379.99 1560.01
RH 0.020

ST126499      17
ND     1 5776.25
XS             -192.22 1655.94  129.99 1550.00  439.99 1452.00
XS              789.99 1418.01 1039.99 1400.00 2639.99 1379.00
XS             3539.99 1341.01 3860.01 1310.01 3979.99 1300.00
XS             4079.99 1322.01 4170.01 1322.01 4400.00 1262.01
XS             4560.01 1254.00 4860.01 1254.00 5039.99 1272.01
XS             5600.00 1550.00 5776.25 1655.94
RH 0.020

ST122032      21
ND     1 6370.01
XS              239.99 1560.01  320.01 1550.00  660.01 1502.99
XS              879.99 1489.99 1600.00 1433.99 1710.01 1427.99
XS             2300.00 1420.01 2460.01 1410.01 2620.01 1381.00
XS             3479.99 1360.99 4120.01 1260.99 4260.01 1254.00
XS             4600.00 1300.00 4720.01 1300.00 4820.01 1277.99
XS             4970.01 1279.00 5129.99 1300.98 5760.01 1320.01
XS             6160.01 1420.01 6360.01 1550.00 6370.01 1560.01
RH 0.020

ST117863      35
ND     110090.68
XS            -3720.14 1654.66 -720.01 1550.00  600.00 1500.00
XS              860.01 1491.01 1000.00 1479.99 1410.01 1470.01
XS             1510.01 1450.00 1700.00 1450.00 1920.01 1441.99
XS             1989.99 1433.99 2100.00 1427.99 2239.99 1420.01
XS             2400.00 1420.01 2479.99 1429.99 2560.01 1429.99
XS             2820.01 1410.01 3810.01 1410.01 4110.01 1400.00
XS             5000.00 1350.00 5260.01 1350.00 5489.99 1420.01
XS             5760.01 1420.01 6070.01 1408.01 6439.99 1400.00
XS             6660.01 1387.99 7189.99 1310.01 7720.01 1300.00
XS             8400.00 1264.01 8720.01 1258.01 8900.00 1258.99
XS             9329.99 1275.98 9479.99 1298.00 9800.00 1400.00
XS             9989.99 1550.0010090.68 1655.94
RH 0.020

ST112080      13
ND     1 6932.22
XS             -655.61 1655.94 1600.00 1372.01 2060.01 1327.99
XS             2779.99 1302.00 3200.00 1260.01 3300.00 1252.00
XS             3479.99 1250.98 3660.01 1250.98 4039.99 1258.01
XS             6110.01 1337.01 6439.99 1352.99 6779.99 1550.00
XS             6932.22 1655.94
RH 0.020

ST106871      13
ND     1 5979.99
XS              350.00 1560.01  360.01 1550.00  370.01 1479.99
XS              679.99 1300.00  960.01 1237.99 2200.00 1250.00
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XS              2529.99 1250.00 5000.00 1379.99 5150.00 1400.00
XS              5639.99 1431.99 5810.01 1450.00 5970.01 1550.00
XS              5979.99 1560.01
RH 0.020

ST101269      20
ND     1 5731.10
XS                89.30 1672.05  189.99 1550.00  200.00 1493.01
XS               489.99 1297.01  670.01 1247.01 1010.01 1231.99
XS              1200.00 1229.99 2339.99 1229.99 2679.99 1237.01
XS              2800.00 1244.00 2879.99 1252.99 3279.99 1341.01
XS              3439.99 1354.99 4339.99 1391.99 5200.00 1450.00
XS              5239.99 1472.01 5479.99 1493.01 5560.01 1548.00
XS              5570.01 1550.00 5731.10 1672.05
RH 0.020

ST94542.      12
ND     1 5195.08
XS              -221.78 1672.05   50.00 1550.00  579.99 1300.00
XS               920.01 1237.99  979.99 1229.99 1300.00 1218.01
XS              2200.00 1220.01 3410.01 1250.00 4300.00 1250.00
XS              4800.00 1370.01 5039.99 1550.00 5195.08 1672.05
RH 0.020

ST87562.      16
ND     1 7821.13
XS              -774.48 1671.49   20.01 1560.01  110.01 1550.00
XS              1710.01 1323.00 2400.00 1299.02 2920.01 1291.01
XS              3800.00 1262.99 3920.01 1250.00 4300.00 1250.00
XS              4460.01 1233.01 4760.01 1220.01 5000.00 1221.00
XS              6400.00 1239.01 6589.99 1250.00 7479.99 1550.00
XS              7821.13 1672.05
RH 0.020

ST84327.      18
ND     1 9060.01
XS                 0.00 1560.01   29.99 1550.00  579.99 1329.99
XS              1200.00 1383.01 1400.00 1389.99 2000.00 1320.01
XS              2760.01 1300.00 4560.01 1279.99 4820.01 1250.00
XS              4879.99 1260.01 5560.01 1250.98 6679.99 1214.01
XS              7100.00 1218.01 8520.01 1310.01 8789.99 1356.00
XS              9029.99 1548.00 9039.99 1550.00 9060.01 1560.01
RH 0.020

ST79498.      13
ND     1 9044.00
XS              -279.69 1672.05   39.99 1550.00  270.01 1446.00
XS               339.99 1454.99  479.99 1337.01  939.99 1318.01
XS              6039.99 1239.99 6400.00 1212.99 7120.01 1206.00
XS              7600.00 1275.98 8400.00 1327.99 8820.01 1550.00
XS              9044.00 1672.05
RH 0.020

ST76511.      16
ND     1 6960.01
XS                 0.00 1560.01   20.01 1550.00  379.99 1314.01
XS               520.01 1308.01  900.00 1306.00 2300.00 1279.99
XS              3400.00 1271.00 3539.99 1260.01 5050.00 1250.00
XS              5200.00 1220.01 5300.00 1210.01 5800.00 1210.01
XS              6479.99 1248.00 6760.01 1335.99 6939.99 1550.00
XS              6960.01 1560.01
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RH 0.020

ST72402.      16
ND     1 7850.00
XS              -151.12 1672.05   29.99 1550.00  439.99 1329.99
XS               760.01 1268.01 1100.00 1239.99 2620.01 1229.99
XS              3700.00 1202.99 4100.00 1200.00 4300.00 1200.00
XS              5600.00 1231.00 6070.01 1239.99 6800.00 1239.99
XS              7039.99 1270.01 7639.99 1550.00 7660.01 1560.01
XS              7850.00 1670.83
RH 0.020

ST69310.      18
ND     1 9029.99
XS               250.00 1560.01  320.01 1550.00  700.00 1489.99
XS               810.01 1485.99 1279.99 1239.99 1360.01 1216.99
XS              1570.01 1206.00 2160.01 1206.00 2579.99 1189.99
XS              2760.01 1170.01 3350.00 1172.01 4260.01 1202.00
XS              4970.01 1200.00 5279.99 1216.01 7879.99 1248.00
XS              8579.99 1320.01 9000.00 1550.00 9029.99 1560.01
RH 0.020

ST66946.      18
ND     1 9200.00
XS               320.01 1570.01  339.99 1560.01  360.01 1550.00
XS               770.01 1439.01  979.99 1466.01 1279.99 1429.99
XS              2229.99 1158.01 2370.01 1185.99 2839.99 1198.00
XS              3639.99 1175.00 4000.00 1198.00 7160.01 1258.01
XS              7629.99 1258.01 8400.00 1287.01 8800.00 1366.99
XS              9120.01 1550.00 9139.99 1560.01 9200.00 1572.01
RH 0.020

ST63272.      21
ND     111570.01
XS              -120.01 1560.01  -89.99 1550.00  700.00 1439.01
XS              2320.01 1316.99 2539.99 1349.02 2679.99 1354.00
XS              4400.00 1183.01 4800.00 1162.99 5029.99 1187.99
XS              5300.00 1179.99 5420.01 1179.99 5600.00 1189.99
XS              6360.01 1200.98 6500.00 1200.00 9900.00 1275.98
XS             10300.00 1456.0010839.99 1324.0211079.99 1325.98
XS             11239.99 1344.0011560.01 1550.0011570.01 1560.01
RH 0.020

ST59957.      16
ND     1 9200.00
XS               300.00 1620.01  400.00 1560.01  420.01 1550.00
XS              1189.99 1198.00 1400.00 1200.00 1839.99 1189.99
XS              1970.01 1198.00 2400.00 1171.00 4600.00 1204.00
XS              4900.00 1197.01 7900.00 1266.01 8679.99 1489.01
XS              8779.99 1433.99 9100.00 1550.00 9120.01 1560.01
XS              9200.00 1589.99
RH 0.020

ST57772.      21
ND     1 8760.01
XS               360.01 1560.01  370.01 1558.01  400.00 1550.00
XS               879.99 1375.98 1000.00 1360.01 1120.01 1246.00
XS              1400.00 1191.01 1760.01 1202.00 2000.00 1196.00
XS              2479.99 1172.01 2839.99 1171.00 3200.00 1185.99
XS              3560.01 1189.99 3900.00 1200.98 4560.01 1181.00
XS              4720.01 1196.00 6600.00 1214.01 8560.01 1254.00
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XS               8720.01 1550.00 8739.99 1554.99 8760.01 1560.01
RH 0.020

ST55650.      18
ND     1 8779.99
XS                379.99 1572.01  389.99 1570.51  400.00 1570.01
XS               1320.01 1187.99 1839.99 1183.99 2639.99 1156.00
XS               2800.00 1179.99 3300.00 1200.98 3439.99 1194.00
XS               4300.00 1175.98 5200.00 1198.00 6439.99 1239.99
XS               6779.99 1256.00 8000.00 1287.99 8439.99 1300.00
XS               8760.01 1560.01 8770.01 1560.99 8779.99 1562.01
RH 0.020

ST52767.      26
ND     1 9939.99
XS                220.01 1560.01  260.01 1550.00  529.99 1497.01
XS                879.99 1344.00 1220.01 1260.01 1420.01 1250.00
XS               1600.00 1250.00 2000.00 1187.99 2150.00 1181.99
XS               2250.00 1187.99 2400.00 1185.01 2560.01 1162.01
XS               3079.99 1172.01 3300.00 1185.99 5000.00 1177.99
XS               6039.99 1194.00 6450.00 1185.99 7520.01 1202.00
XS               7660.01 1223.00 7800.00 1206.00 8000.00 1206.00
XS               8200.00 1197.01 9300.00 1231.00 9479.99 1260.01
XS               9929.99 1550.00 9939.99 1560.01
RH 0.020

ST51020.      24
ND     111160.01
XS                -39.99 1560.01    0.00 1550.00  800.00 1406.99
XS               1100.00 1300.98 1320.01 1279.99 1450.00 1279.99
XS               1839.99 1229.99 2000.00 1239.99 2300.00 1181.00
XS               2820.01 1169.00 3160.01 1191.01 3879.99 1168.01
XS               4660.01 1181.00 5239.99 1154.99 6100.00 1189.99
XS               7000.00 1177.99 7839.99 1194.00 8689.99 1195.01
XS               8839.99 1187.0110439.99 1258.9911039.99 1469.00
XS              11139.99 1539.9911150.00 1550.0011160.01 1560.01
RH 0.020

ST48856.      35
ND     112729.99
XS                479.99 1560.01  520.01 1550.00  600.00 1529.99
XS               1129.99 1383.01 1250.00 1393.01 1510.01 1396.00
XS               1629.99 1375.00 1779.99 1329.99 1879.99 1318.01
XS               2160.01 1298.00 2550.00 1204.00 2950.00 1197.01
XS               3079.99 1200.98 3350.00 1171.00 4200.00 1187.01
XS               5750.00 1183.01 5950.00 1175.98 6239.99 1183.01
XS               6500.00 1183.01 6620.01 1174.02 6750.00 1173.00
XS               6929.99 1183.99 7500.00 1183.99 8229.99 1168.01
XS               8479.99 1177.99 8600.00 1164.01 9160.01 1154.00
XS               9500.00 1183.9910179.99 1185.9910300.00 1197.01
XS              10500.00 1199.0211900.00 1270.0112700.00 1539.99
XS              12720.01 1550.0012729.99 1560.01
RH 0.020

ST46154.      38
ND     115820.01
XS               3279.99 1560.01 3289.99 1550.00 3300.00 1454.99
XS               4279.99 1302.00 4439.99 1262.01 4920.01 1223.00
XS               5800.00 1206.00 5960.01 1150.98 6039.99 1179.00
XS               6410.01 1158.99 6589.99 1170.01 6979.99 1179.00
XS               8000.00 1179.99 8300.00 1185.01 8760.01 1181.99
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XS              9020.01 1168.01 9279.99 1171.00 9600.00 1164.01
XS             10679.99 1181.0011300.00 1173.0011410.01 1177.99
XS             11560.01 1169.0011670.01 1172.0111779.99 1160.01
XS             11920.01 1158.9912639.99 1175.9813320.01 1175.98
XS             13529.99 1169.0013770.01 1175.0013939.99 1160.01
XS             14320.01 1206.9914700.00 1212.0115000.00 1212.99
XS             15200.00 1225.0015439.99 1252.9915800.00 1470.01
XS             15810.01 1550.0015820.01 1560.01
RH 0.020

ST43417.      35
ND     115029.99
XS               860.01 1560.01  870.01 1550.00  879.99 1466.99
XS               889.99 1468.01  900.00 1469.00 1000.00 1462.01
XS              1750.00 1404.00 1929.99 1402.99 2329.99 1362.99
XS              2579.99 1312.99 2960.01 1354.00 3560.01 1254.00
XS              3960.01 1241.99 4600.00 1198.00 6279.99 1170.01
XS              6800.00 1175.98 7460.01 1174.02 7600.00 1162.99
XS              7889.99 1166.01 8010.01 1143.01 8479.99 1162.01
XS              9760.01 1162.99 9920.01 1141.9910560.01 1154.99
XS             11079.99 1166.9912120.01 1154.0012379.99 1173.00
XS             12520.01 1162.0113260.01 1170.0114100.00 1175.98
XS             14900.00 1289.9915000.00 1320.0115010.01 1320.31
XS             15020.01 1550.0015029.99 1560.01
RH 0.020

ST35803.      28
ND     116239.99
XS              1800.00 1560.01 1810.01 1550.00 1820.01 1321.00
XS              2229.99 1252.99 2479.99 1312.99 2620.01 1327.99
XS              2960.01 1372.01 3600.00 1214.99 3960.01 1223.00
XS              4600.00 1193.01 8679.99 1162.9911000.00 1148.00
XS             11360.01 1160.9911560.01 1150.0011760.01 1156.00
XS             12260.01 1131.0012660.01 1212.9913200.00 1187.99
XS             14420.01 1262.9914560.01 1254.9915239.99 1348.00
XS             15639.99 1320.0115839.99 1272.0116200.00 1293.01
XS             16210.01 1296.0016220.01 1304.9916229.99 1550.00
XS             16239.99 1560.01
RH 0.020

*** Lateral tributary: Siran
LI Siran.dat

ST29765.      28
ND     114539.99
XS              -100.00 1560.01  -89.99 1550.00  -79.99 1360.01
XS              1000.00 1179.99 1900.00 1171.00 2620.01 1175.00
XS              2839.99 1183.01 3120.01 1158.99 5479.99 1162.99
XS              6160.01 1154.00 6400.00 1162.99 7860.01 1164.01
XS              8420.01 1150.00 8889.99 1166.9910079.99 1147.01
XS             10900.00 1167.4911700.00 1152.9912079.99 1250.00
XS             12779.99 1291.0113120.01 1241.9913329.99 1279.99
XS             13510.01 1289.0113720.01 1279.9913939.99 1279.99
XS             14220.01 1329.9914520.01 1339.0114529.99 1550.00
XS             14539.99 1560.01
RH 0.020

ST27285.      38
ND     112570.01
XS                39.99 1560.01   50.00 1550.00  200.00 1248.00
XS               350.00 1187.01  539.99 1172.01  660.01 1179.99
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XS               1979.99 1162.99 4200.00 1162.99 4360.01 1154.00
XS               4720.01 1156.00 4900.00 1162.01 5600.00 1150.00
XS               6079.99 1146.00 6520.01 1156.99 6700.00 1150.00
XS               6900.00 1158.99 7139.99 1158.01 7420.01 1166.01
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XS               8439.99 1218.01 9639.99 1250.98 9660.01 1279.99
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XS               8060.01 1179.99 8160.01 1220.01 9000.00 1260.01
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XS               2360.01 1144.00 4100.00 1154.99 4320.01 1135.99
XS               5200.00 1139.99 7000.00 1158.01 7520.01 1143.01
XS               7850.00 1154.00 8379.99 1152.99 8800.00 1254.99
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XS              11350.00 1560.01
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```

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XS              7200.00 1152.00 7460.01 1144.00 7750.00 1148.00
XS              8139.99 1139.01 8560.01 1279.99 8660.01 1279.99
XS              8800.00 1200.00 8860.01 1200.00 9029.99 1270.01
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RH 0.020

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RH 0.020

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XS              3950.00 1141.01 5150.00 1139.99 5229.99 1125.00
XS              7079.99 1118.01 7279.99 1139.99 8239.99 1137.99
XS              8360.01 1129.99 9179.99 1123.00 9600.00 1154.00
XS             10879.99 1181.9911160.01 1183.0111860.01 1229.99
XS             12060.01 1260.0112200.00 1264.0112479.99 1250.00
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RH 0.020

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XS              4700.00 1133.01 4950.00 1141.99 5520.01 1131.99
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XS              6450.00 1150.00 6600.00 1135.01 8039.99 1124.02
XS              8520.01 1125.98 8800.00 1141.99 9579.99 1124.02
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XS             13079.99 1560.01
RH 0.020

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XS              3700.00 1135.01 4050.00 1145.01 4400.00 1152.00
XS              4600.00 1160.01 4739.99 1174.02 5200.00 1129.99
XS              5920.01 1139.99 6439.99 1133.99 7039.99 1139.99
XS              7350.00 1154.00 7479.99 1149.02 7720.01 1152.00
XS              7860.01 1137.99 8020.01 1137.99 8200.00 1131.99
XS              8600.00 1189.99 8960.01 1172.01 9160.01 1122.01
```

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XS              9800.00 1120.0110200.00 1152.9910520.01 1158.01
XS             10939.99 1354.0011039.99 1360.0111239.99 1400.00
XS             11400.00 1550.0011410.01 1560.01
RH 0.020

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XS               879.99 1183.01  970.01 1145.01 1279.99 1146.00
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XS              2360.01 1129.99 2560.01 1129.99 2679.99 1131.99
XS              3160.01 1131.99 3400.00 1129.99 3539.99 1127.00
XS              3760.01 1129.99 3929.99 1139.01 4379.99 1129.99
XS              4520.01 1135.99 5400.00 1135.01 5700.00 1139.99
XS              5810.01 1154.00 5979.99 1135.99 6139.99 1133.01
XS              6520.01 1143.01 6600.00 1170.01 6679.99 1170.01
XS              6879.99 1144.00 7000.00 1139.99 7439.99 1133.01
XS              7679.99 1154.99 7839.99 1156.00 7889.99 1158.01
XS              8029.99 1143.01 8389.99 1139.01 8420.01 1133.01
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XS              9279.99 1185.01 9460.01 1227.99 9850.00 1550.00
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RH 0.020

ST2397.7      41
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XS              2500.00 1141.99 2720.01 1141.99 2779.99 1144.00
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XS              3520.01 1145.01 3720.01 1144.00 3960.01 1146.00
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XS              7479.99 1124.02 7700.00 1122.01 7760.01 1120.01
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RH 0.020

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XS              3872.07 1156.00 3929.83 1156.00 3934.67 1149.02
XS              4074.31 1149.02 4430.71 1141.99 4623.35 1141.99
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XS              7667.06 1121.00 7763.38 1154.00 7898.22 1170.01
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XS              8620.62 1550.00 8639.90 1560.01
RH 0.020
```

```
RE     1MANNING

NT     1

IT  8030       5       1

QQ      TABLE OF DISCHARGES
SS      STAGE DISCHARGE TABLE

TL    76

SQ 15407 1190.94
SQ 15407 1190.94
...
SQ 19358 1456.02
SQ 19249 1455.81

SE     6       8       1
N0     0    0.80    0.10
N0130000    0.09    0.10

*** Sediment rating curve at Besham.
  QR4.4e-8    2.51
  QR8.8e-8    2.51
QR1.8e-7    2.51
  QR EQUILIBRIUM

*** Synthesized temperatures.
TM    31    40.0
TM    28    40.0
...
TM    30    40.0
TM    31    40.0

SF     7
SG 0.002   0.004    30.0
SG 0.004   0.008    30.0
SG 0.008   0.016    65.0
SG 0.016   0.031    65.0
SG 0.031  0.0625    65.0
SG0.0625    0.25    93.0
SG  0.25     2.0    93.0

NB   0.0
BG   0.0    0.00    0.00    0.00    0.10    0.10    0.80

CS    -1

IQ     1 10000.0
IS          0.05
IS          0.05
IS          0.25
IS          0.25
IS          0.25
IS          0.15
IS          0.00

AR  -1.0    -1.0

LM  1100   99999
LM  1100   99999
```

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LM  1100   99999
LM  1100   99999
LM  1100   99999
LM  1100   99999
LM  1100   99999
LM  1100   99999
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LM  1100   99999
LM  1100   99999
LM  1100   99999
LM  1100   99999

PR     3    8030
PX  8030
PW  8030

END
```

8.2 Output Data Files

All the output data files for this example can be found, in electronic format, in the main GSTARS3 distribution package in directory Example8.

8.3 Results and Discussion

Here, the results of the GSTARS3 run of this example are presented and briefly analyzed. The results of a 1996 survey carried out in Tarbela reservoir, corresponding to the conclusion of the period of the simulation, are used here. That data are used for comparison purposes. Note that this example does not constitute an exhaustive and definitive study of the sedimentation processes in Tarbela reservoir for the 1974-1996 period. Rather, it is presented here for didactic purposes only.

The simulation results for the thalwegs are shown in figure 8.4. They are in good agreement with measurements, especially as in what concerns the location of the frontset of the delta and its slope. This is important to determine capacity loss, the useful life of the reservoir, and the impact that dam operations have on the reservoir's deposition pattern.

Cross-sectional geometries were better predicted in the downstream reservoir region than in the upstream region. That is because the upstream part is has mostly riverine characteristics, and uniform deposition is not the most appropriate technique for this circumstance (recall figure 3.3, which shows the depositional pattern in a river, versus figure 5.4, which shows the depositional pattern in a reservoir). However, this region is limited to the first 21 cross sections, which represents less than one fourth of the entire simulated reach. Even then, deposition volumes are in general well predicted, even if thalweg elevations are not very accurate. Two representative cross section in this region are shown in figure 8.5 for comparison purposes.

Figure 8.4 Results of the simulation of the Tarbela delta advancement over a period of 22 years.

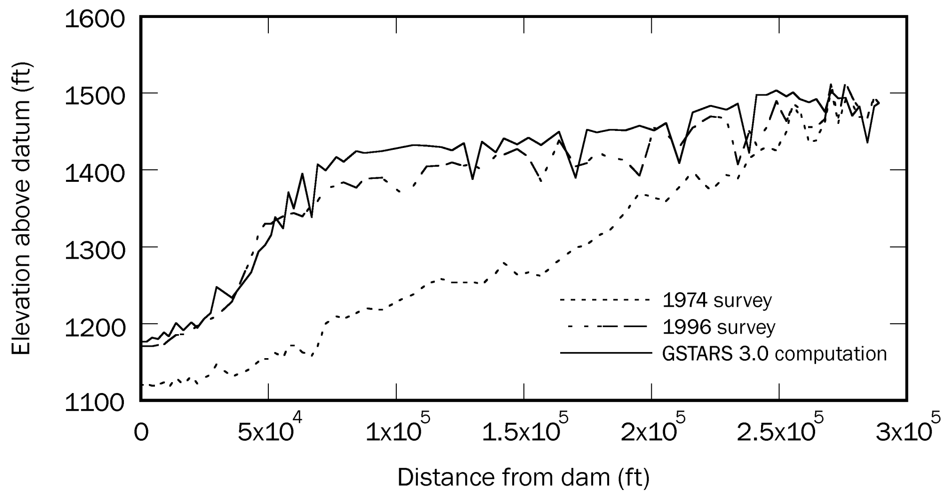
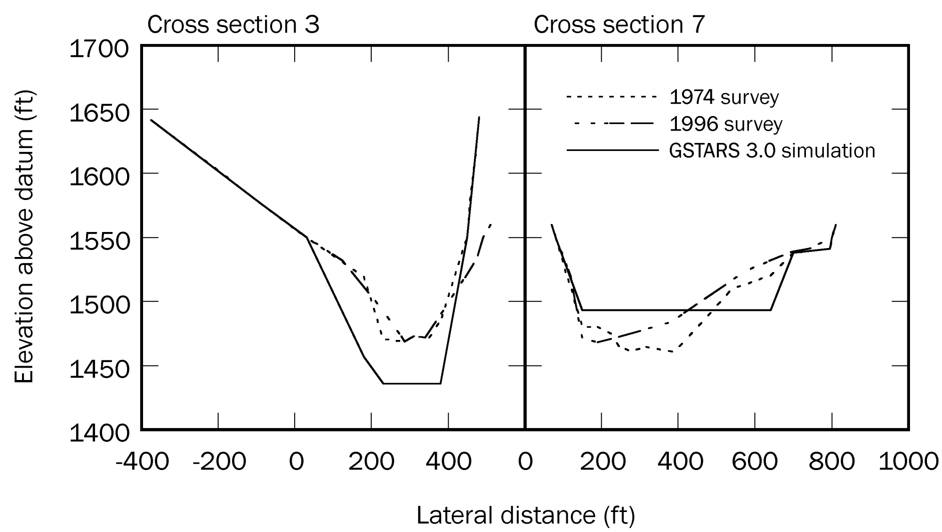


Figure 8.5 Comparison of measurements and GSTARS3 computation for two cross sections in the upstream region of Tarbela reservoir.



In the reservoir region, which constitutes the focus of the study, deposition volumes are well predicted, in spite of a small tendency to overpredict the thalweg elevations. Four representative cross sections are shown in figures 8.6 and 8.7. These cross sections were taken from the full breath of the reservoir region.

Figure 8.6 Comparison of measurements and GSTARS3 computation for two cross sections in the reservoir region of the study reach.

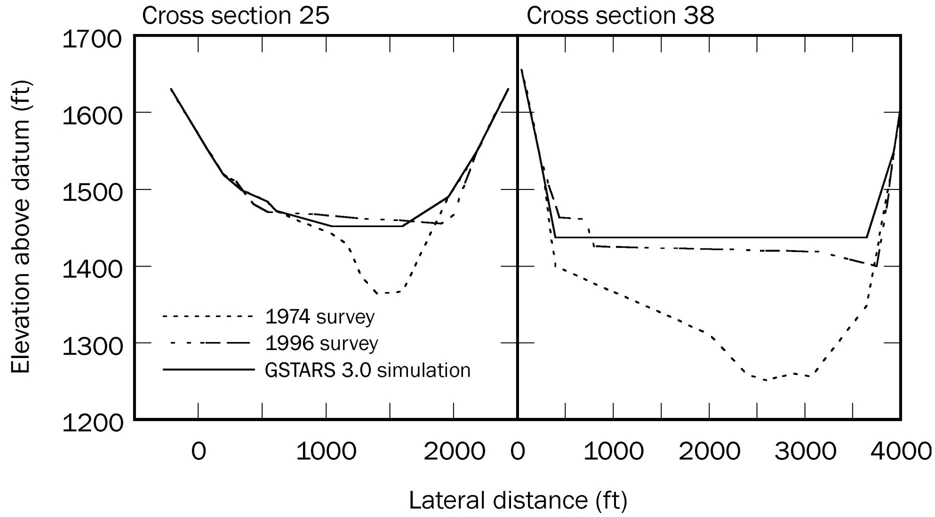
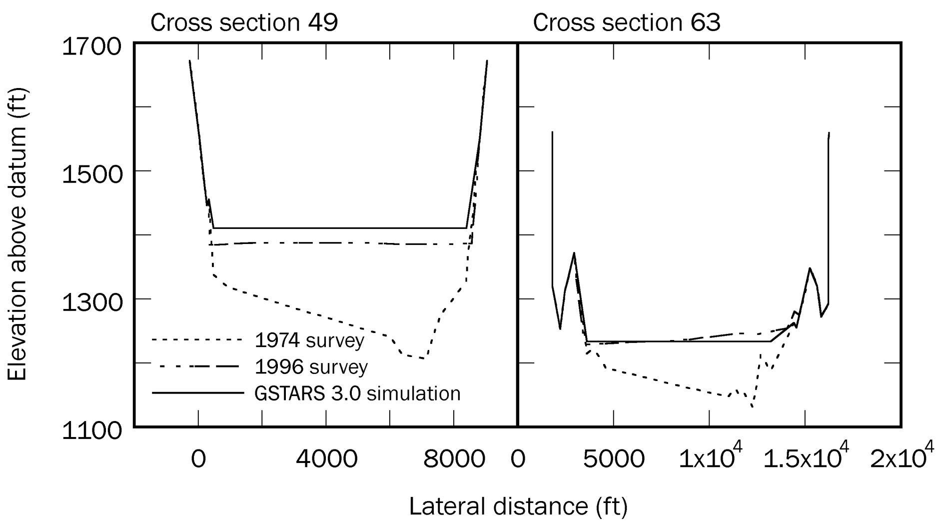
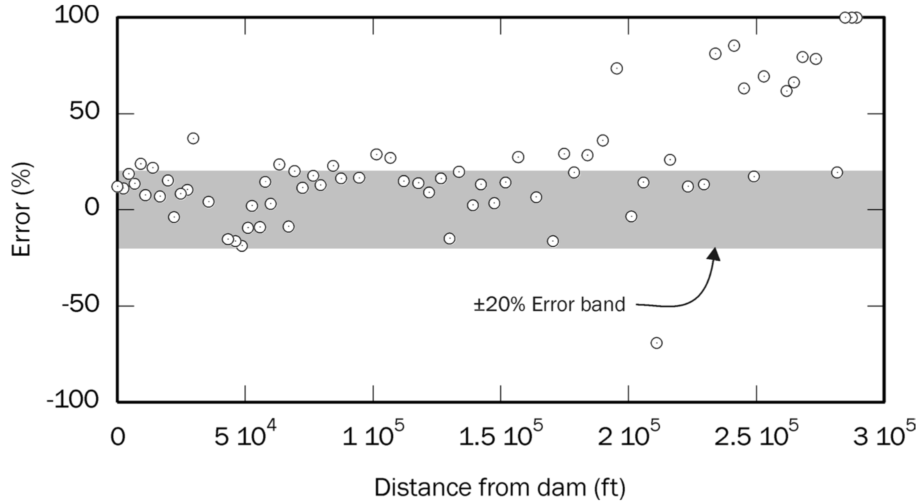


Figure 8.7 More comparisons of measurements and GSTARS3 computations, for two cross sections in the reservoir region of the study reach downstream from those in figure 8.6.



The error associated with the predicted thalwegs is shown in figure 8.8. Most data is inside the 20% error band, which is a very good result for this type of simulation (22 years of sedimentation spanning a 58-mile reach). However, this study could easily be improved with the use of little additional data. Such data would comprise more accurate bed-sediment size distributions, as well as more information about the inflowing sediment sizes travelling through the Indus. Further improvements would be attained from a study of the cohesive-sediment fraction properties within the reach.

Figure 8.8 Relative error of the thalweg elevation predictions. Note the larger magnitude of the errors upstream, in the riverine part of the reach, compared to the lower magnitude of the errors in the reservoir reach.



APPENDIX C

Reprint of the paper by A. Molinas and C. T. Yang, "Generalized water surface profile computation," ASCE Journal of Hydraulic Engineering, Vol. 111, No. 3, March 1985, pages 381–387.

Generalized Water Surface Profile Computations

By Albert Molinas,[1] A. M. ASCE and Chih Ted Yang,[2] M. ASCE

Abstract: A computer model based on both the energy and momentum equations is developed. This generalized model can be used for the computation of water surface profiles through hydraulic jumps. It also allows computation of water surface profiles regardless of whether the bed slope is steep, mild, horizontal, adverse or a combination of these. The control section can be a lake, weir, gate or a natural river section. The Manning, Chezy or Darcy-Weisbach equations can be used for head loss computation. A detailed description of methods used and a step-by-step computation procedure is given. Examples are used to demonstrate the applications of this generalized model for water surface profile computations.

Introduction

Most of the computer programs for water surface profile computations are based on the application of energy equations for gradually varied open-channel flows. These types of programs cannot be directly applied to open-channel flows with hydraulic jumps. The most commonly used model of this type is the HEC-2 Water Surface Profiles Computer Program developed by the U.S. Army Corps of Engineers (3). The generalized computer program introduced in this paper employs both the energy and momentum equations so the computation of water surface profile can go through hydraulic jumps without interruption. This capability allows computation of water surface profiles through a study reach, regardless of whether the bed slope is steep, mild, horizontal, adverse or a combination of these. The control section can be a lake, weir, gate or a natural river section. This paper provides a step-by-step description of the methods and procedures used in the generalized water surface profile computation program. Examples of computations are used to demonstrate the capability of the generalized program.

Basic Equations

The basic equation used in most of the water surface profile computations is the energy equation (1):

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V^2}{2g} + h_t \qquad (1)$$

in which z = bed elevation; y = water depth; V = velocity; α = velocity distribution coefficient; h_t = total energy loss between sections 1 and 2;

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[2]Civ. Engr., U.S. Dept. of the Interior, Bureau of Reclamation, Engrg. and Research Center, Denver, Colo.

Note.—Discussion open until August 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 23, 1983. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 111, No. 3, March, 1985. ©ASCE, ISSN 0733-9429/85/0003-0381/$01.00. Paper No. 19554.

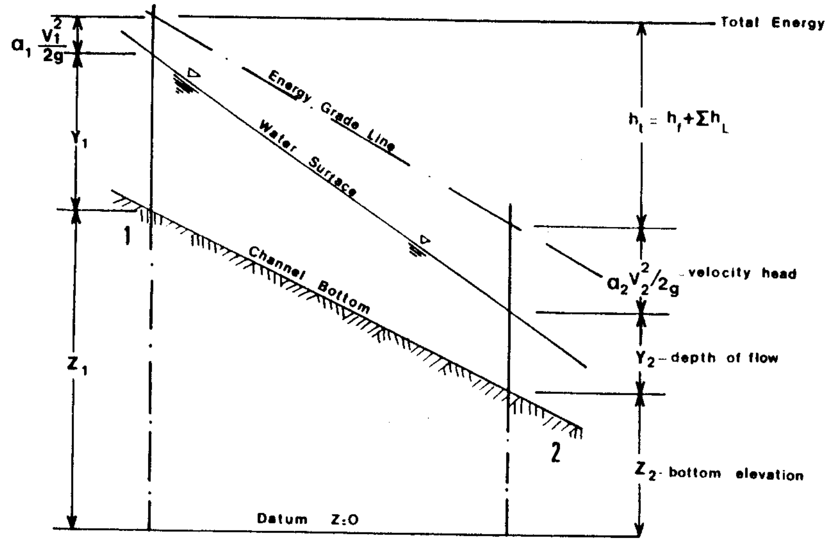

FIG. 1.—Definition of Variables

g = gravitational acceleration; and subscripts 1 and 2 denote sections 1 and 2, respectively. Fig. 1 shows these definitions.

The standard procedure for water surface profile computation is a trial-and-error procedure to balance Eq. 1. The computer program used in this paper utilizes the method described by Henderson (2) for making estimated guesses to shorten the trial-and-error procedure. This procedure, after the initial water surface elevation is guessed, computes the next guessed water surface elevation for faster convergence according to the equation

$$(Z_{ass})_{new} = (Z_{ass})_{old} - \frac{(H_{ass} - H_{comp})}{1 - F_{ass}^2(1 \mp 0.5C_L) \mp \left(\frac{3}{2}\right)\left(\frac{h_f}{R}\right)} \quad \text{(2)}$$

in which $(Z_{ass})_{old}$, $(Z_{ass})_{new}$ = initial and improved assumed water surface elevations, respectively; $(F)_{ass}$, $(R)_{ass}$, $(h_f)_{ass}$, H_{ass} = Froude number, hydraulic radius, friction loss, and total head, respectively, computed by use of the initial assumed depth; H_{comp} = total head computed by subtraction or addition of head losses to the total head of the cross section at which flow conditions are known; and C_L = energy loss coefficient. The total head at a given cross section is

$$H = \frac{\alpha V^2}{2g} + y + z \quad \text{(3)}$$

For irregular channels, the Froude number can be computed by

$$(F)_{ass} = \frac{Q}{A_{ass}\left(\frac{g y_d \cos\theta}{\alpha}\right)^{1/2}} \quad \text{(4)}$$

in which Q = water discharge; A = cross-sectional area; y_d = hydraulic depth = area/top width; and θ = angle of inclination of channel bed.

Before starting water surface profile computations, the normal and critical depths for different reaches along the study reach are computed to determine whether the flow conditions are supercritical, subcritical or critical. The computation is carried out in the upstream direction for subcritical flow; while for supercritical flows, it is in the downstream direction. In the case of horizontal or adverse slope reach, the normal depth is set equal to a very large value. The preceeding method is valid for gradually varied open-channel flows without hydraulic jump.

Whenever the flow condition changes from supercritical to subcritical, the occurrence of hydraulic jumps must be considered. The governing equation for hydraulic jumps is the momentum equation (1), i.e.

$$\frac{Q\gamma}{g}(\beta_2 V_2 - \beta_1 V_1) = P_1 - P_2 + W \sin\theta - F_f \qquad (5)$$

in which γ = unit weight of water; β = momentum coefficient; P = pressure acting on a given cross section; W = weight of water enclosed between sections 1 and 2; and F_f = total external friction force acting along the channel boundary. Assuming the value of θ is small and $\beta_1 = \beta_2 = 1$, Eq. 5 can be reduced to

$$\frac{Q^2}{A_1 g} + A_1 \bar{y}_1 = \frac{Q^2}{A_2 g} + A_2 \bar{y}_2 \qquad (6)$$

in which $\bar{y}$ = depth measured from water surface to the centroid of cross section, A, containing flow. For an irregular channel cross section consisting of m subsections, $\bar{y}$ can be computed by

$$\bar{y} = \frac{\sum_{i=1}^{m} A_i \bar{y}_i}{A} \qquad (7)$$

and the specific force is defined as

$$SF = \frac{Q^2}{Ag} + A\bar{y} \qquad (8)$$

Since the sequent depths of a hydraulic jump are the depths before and after the jump with the same specific force, a trial-and-error computation can be made to satisfy Eq. 6. Thus, a combined utilization of Eqs. 2 and 6 should enable us to carry out water surface profile computations to and through hydraulic jumps.

Computation Methods

Normal, Critical and Sequent Depth Computations.—Before water surface profile computations are started, the normal and critical depths for different reaches along the study reach are computed to determine whether the flow conditions are supercritical, subcritical or critical. For supercritical flows, the computations are progressed in the downstream direction. For subcritical flows, the computations are progressed in the upstream direction. The normal depth computation is made in conjunction with conveyance by satisfying the equation

$$g(d) = Q - K(d)\sqrt{S_0} = 0 \qquad (9)$$

in which $K(d)$ = conveyance which is a function of depth, d; and S_0 = bottom slope. For adverse and horizontal slopes, a normal depth value of 999.9 ft is assigned.

Critical depth is the depth of minimum specific energy with a Froude number of 1 for a given discharge. Thus, the critical depth can be computed by satisfying the equation

$$f(d) = 1 - \alpha(d)\frac{Q^2 T(d)}{gA^3(d)} = 0 \qquad (10)$$

in which $T(d)$ = top channel width at a given elevation or depth, d; and $A(d)$ = channel cross-sectional area at a given elevation or depth, d. The computational procedure for critical depth is similar to that just described for normal depth by satisfying Eq. 10.

Sequent depths for a given discharge are the depths with equal specific forces. Sequent depth in the present program is computed if the flow changes from supercritical to subcritical and results in a hydraulic jump. The specific force of a natural channel can be expressed by

$$SF(d) = \frac{Q^2}{A_t g} + A_m \bar{y} \qquad (11)$$

in which $SF(d)$ = specific force corresponding to a water surface elevation or depth, d; A_t = total flow area; A_m = flow area in which there is motion; and $\bar{y}$ = distance from water surface to the centroid of the cross section, i.e.

$$\bar{y} = \frac{\sum_{i=1}^{m} A_i \bar{y}_i}{A_t} \qquad (12)$$

In this program, it is assumed that $A_t = A_m$, and Eq. 12 is solved in the channel geometry subroutine.

Sequent water surface elevation computations for a given supercritical water surface elevation are started with two initial guesses. The first one is the critical water surface elevation with the theoretical minimum specific force. The second guess is the maximum bottom elevation for the cross section. The subcritical sequent water surface elevation should be within these two limitations. Once the interval for the sequent depth is defined, the bisection method is used to get the elevation, d_b, for which

$$SF(d_a) - SF(d_b) = 0 \qquad (13)$$

in which d_a = computed supercritical water surface elevation; and d_b = desired subcritical sequent water surface elevation. The accuracy level of Eq. 13 is a user defined value.

Geometric Computations.—For natural channels, the channel is divided into subchannels. The geometric variables are computed for each subchannel. Later on, these values are summed to obtain the total area,

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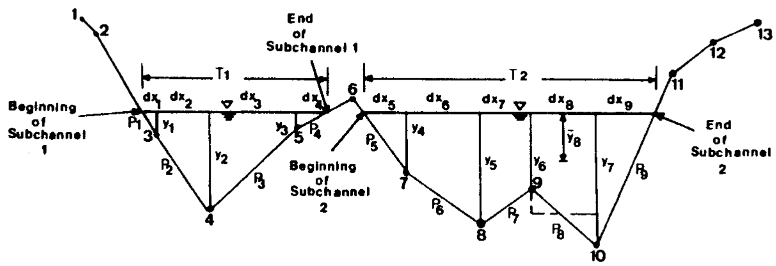

FIG. 2.—Assumed Natural Channel Cross Section

wetted perimeter and top width. The hydraulic radius, hydraulic depth and the centroid of the cross section are determined from these values. For the channel cross section shown in Fig. 2, these values are computed with the following equations:

$$A_i = 0.5(y_i + y_{i+1})dX_i \qquad (14)$$

$$p_i = [dX_i^2 + (y_i - y_{i+1})^2]^{1/2} \qquad (15)$$

$$R_i = \frac{A_i}{p_i} \qquad (16)$$

$$\bar{y}_i = 0.25(y_i + y_{i+1}); \quad \text{if not adjacent to channel wall} \qquad (17)$$

$$\bar{y}_i = \frac{1}{3} y_i; \quad \text{if adjacent to channel wall} \qquad (18)$$

$$A_t = \sum_{i=1}^{m} A_i, \quad i = 1, 2, \ldots, m \qquad (19)$$

$$p_t = \sum_{i=1}^{m} p_i, \quad i = 1, 2, \ldots, m \qquad (20)$$

$$R = \frac{A_t}{p_t} \qquad (21)$$

$$T = \sum_{j=1}^{N} T_j \qquad (22)$$

$$\bar{y} = \frac{\sum_{i=1}^{m} A_i \bar{y}_i}{A_t} \qquad (23)$$

in which A_i, p_i, R_i, $\bar{y}_i$ = area, wetted perimeter, hydraulic radius, and centroid of a subsection, respectively; T_j = top width of a subchannel; A_t, p_t, R, T, $\bar{y}$ = area, wetted perimeter, hydraulic radius, top width, and centroid of the whole cross section; m = number of subsections; and N = number of subchannels. The beginning of a subchannel is identified when the bottom elevation of the channel drops below the water surface. The end of a subchannel is identified when the bottom elevation emerges above the water surface elevation.

Conveyance and Friction Slope Computations.—The conveyance, K, is a measure of a channel's flow-carrying capacity. Any one of the following three formulas can be used in this program for discharge computation:

Manning's formula

$$Q = KS_f^{1/2} = \left(\frac{CM}{n} AR^{2/3}\right) S_f^{1/2} \qquad (24)$$

Chezy's formula

$$Q = KS_f^{1/2} = (CAR^{1/2})\, S_f^{1/2} \qquad (25)$$

or Darcy-Weisbach's formula

$$Q = KS_f^{1/2} = \left[\left(\frac{8gR}{f}\right)^{1/2} A\right] S_f^{1/2} \qquad (26)$$

in which n, C, f = roughness coefficient in Manning, Chezy, and Darcy-Weisbach's formula, respectively; A = cross-sectional area; R = hydraulic radius, and S_f = friction slope; and CM = coefficient in Manning's formula. It is equal to 1.0 for SI units and 1.486 for U.S. units. The conveyance of each subsection is computed first and the sum of them is the total conveyance of the cross section. The total conveyance is used for the determination of friction slope, S_f, of a given discharge, Q, i.e.

$$S_f = \left(\frac{Q}{K}\right)^2 \qquad (27)$$

α Value Computation.—The velocity distribution coefficient, α, is a measure of flow uniformity across a channel. For uniform flow across a channel, $\alpha = 1$. For nonuniform flow across a channel

$$\alpha = \frac{\sum_{i=1}^{m} V_i^3 A_i}{A_t \bar{V}^3}, \quad i = 1, 2, \ldots, m \qquad (28)$$

in which V_i, A_i = velocity and area of subsection, i, respectively; and $\bar{V}$ = average velocity for the total cross-sectional area, A_t. The velocity in each subsection can be computed by

$$V_i = \frac{K_i S_f^{1/2}}{A_i} \qquad (29)$$

Thus, the velocity distribution coefficient can be computed by

$$\alpha = \frac{\sum_{i=1}^{m} \left(\frac{\alpha_i K_i^3}{A_i^2}\right)}{\left(\frac{K_t^3}{A_t^2}\right)} \qquad (30)$$

in which α_i, K_i = velocity distribution coefficient and conveyance of each substation, respectively; and K_t = total conveyance of the cross section. If the subsection is small enough, α_i can be assumed to be 1. The velocity distribution coefficients are computed automatically in this program when the conveyance and area are computed in the channel geometry subroutine.

Energy Loss Computation.—The friction loss, h_f, through a reach is the product of energy slope, S_f, and reach length, L. There are different ways to determine average friction slope based on the friction slopes at the two ends of a given reach. Any one of the following equations can be used in this program for the computation of energy loss:

$$h_f = \left[\frac{(S_f)_1 + (S_f)_2}{2}\right] L \quad (31)$$

$$h_f = [\sqrt{(S_f)_1 (S_f)_2}]\, L \quad (32)$$

$$h_f = \left[\frac{Q}{\frac{CM}{n}\frac{(A_1 + A_2)}{2}\left(\frac{R_1 + R_2}{2}\right)^{2/3}}\right]^2 L \quad (33)$$

$$h_f = \left(\frac{2Q}{K_1 + K_2}\right)^2 L \quad (34)$$

in which K_1, K_2 = conveyance at the beginning and end of the reach, respectively.

Local loss due to channel expansion and contraction, h_E, is computed according to the equation:

$$h_E = C_E \left|\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right| \quad (35)$$

in which C_E = energy loss coefficient due to channel expansion or contraction. C_E is set equal to 0.1 for contractions, and to 0.3 for expansions.

Local loss occurring due to channel bends, h_B, is computed using the equation

$$h_B = C_b \frac{V_2^2}{2g} \quad (36)$$

in which C_b = energy loss coefficient due to channel bends. C_b is a user supplied coefficient and can be defined as a function of Froude number. Total energy loss is the sum of friction loss and the local losses.

Computation Procedures

There are six possible transitions from one type of flow to another. These are:

1. From subcritical to supercritical.
2. From supercritical to subcritical.
3. From subcritical to critical.

4. From critical to subcritical.
5. From critical to supercritical.
6. From supercritical to critical.

The program checks for these transitions during the water surface profile computations at each each cross section. If a water surface profile at the transition can change rapidly, it is called a rapidly varied flow profile. To obtain more accurate profiles for rapidly varied flows, shorter length computations are required. However, in the program, irrespective of the reach length, computations are not interrupted for the sake of continuity.

The transitions from subcritical to supercritical flow and from subcritical to critical flow are handled in the same way. The cross section where the change occurs is set as a control section with critical depth/w.s.e. (water surface elevation) as a control depth/w.s.e. Subcritical water surface profile computations are performed in the upstream direction, and supercritical flow profile computations are performed in the downstream direction.

The transition from supercritical to subcritical flow and from critical to subcritical flow are handled the same way when the variable indicating the existence of a hydraulic jump (HYDJUMP) is set equal to "YES" and hydraulic jump computations are started. These computations are explained in the following paragraph in greater detail. However, here we will mention the fact that in case of a transition from critical to subcritical flow, the computations are carried out starting from the next downstream control, proceeding in the upstream direction to obtain a Cl type profile with no hydraulic jump. The transition from critical to supercritical does not cause an interruption in the computations. Supercritical water surface profile computations are started from the cross section where this transition occurs.

If during the supercritical flow computations proceeding in the downstream direction, a mild, adverse or horizontal reach is encountered, the variable indicating the existence of a hydraulic jump (HYDJUMP) is set equal to "YES." The supercritical water surface computations are continued until either the critical depth/w.s.e. or the next subcritical or critical downstream control is met. If in the course of computations, the critical depth/w.s.e. is reached before the next control section, the variable to initiate the search for a control section (SEARCH) is set equal to "YES" to stop further computation. The next natural or artificial control section in the downstream direction is located. If in the course of computations, the computed depths/w.s.e. remain below the critical depths/w.s.e., depending on the downstream controls, a possibility for an M3, A3 or H3 type profile exists. As soon as the variable "HYDJUMP" becomes "YES," the sequent depth computations are initiated.

Sequent depth computations continue until either the variable "SEARCH" becomes equal to "YES" or the variable "HYDJUMP" is reset to "NO."

The steps followed in location of the hydraulic jump can be summarized as:

1. Compute the upstream supercritical water surface profile up to the

junction where the transition from supercritical to subcritical flow occurs.

2. Continue the supercritical water surface profile computations downstream from the junction. At the same time, compute the corresponding sequent water surface profile.

3. Starting from the subcritical or critical downstream control, compute the subcritical water surface profile in the upstream direction.

4. While computing the subcritical water surface profile at each cross section, compare the subcritical depth/w.s.e. with the sequent depth/w.s.e.

a. If the sequent depth/w.s.e. is greater than the subcritical depth/w.s.e., the toe of the hydraulic jump is between the current cross section and the next cross section in the downstream direction.

b. If the sequent depth/w.s.e. is equal to the subcritical depth/w.s.e., the toe of the hydraulic jump is located at the current cross section.

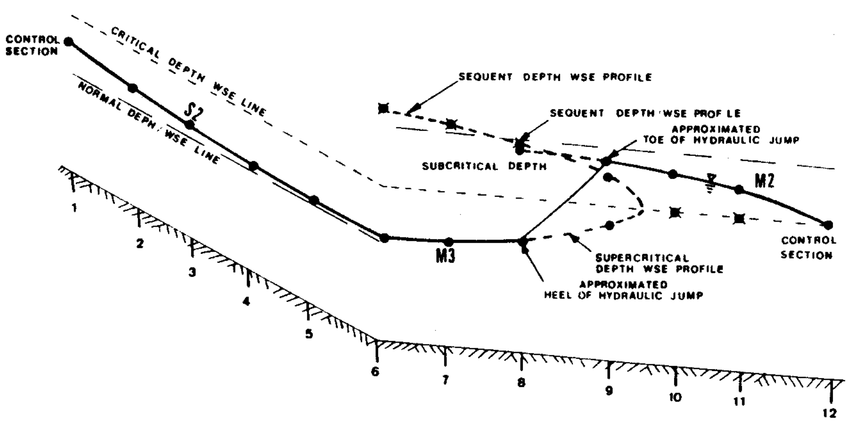

FIG. 3.—Locating Hydraulic Jump on Subcritical Slope

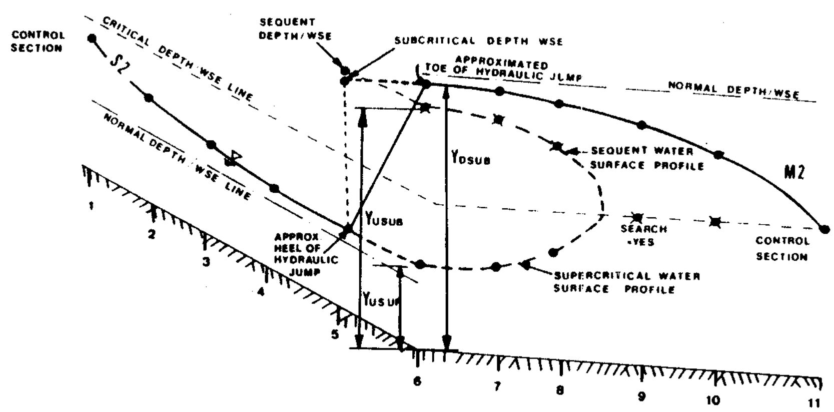

FIG. 4.—Locating Hydraulic Jump on Supercritical Slope

c. If the sequent depth/w.s.e. if less than the subcritical depth/w.s.e., subcritical water surface profile computations should be continued in the upstream direction. If the sequent depth/w.s.e. is greater than or equal to subcritical depth/w.s.e., the hydraulic jump computations are ended and the variables "HYDJUMP" and "SEARCH" are reset to "NO." If not, subcritical water sur-

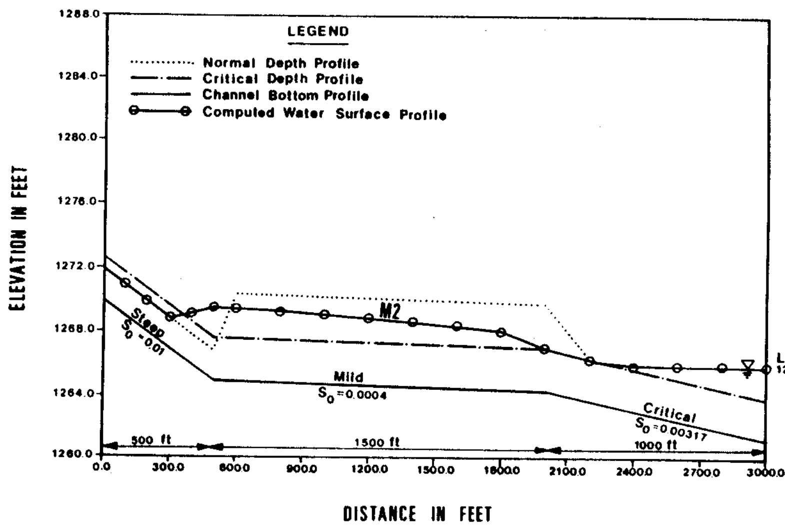

FIG. 5.—Computed Water Surface Profile with Transitions from Steep to Mild Slope and from Mild to Critical Slope in Sequence

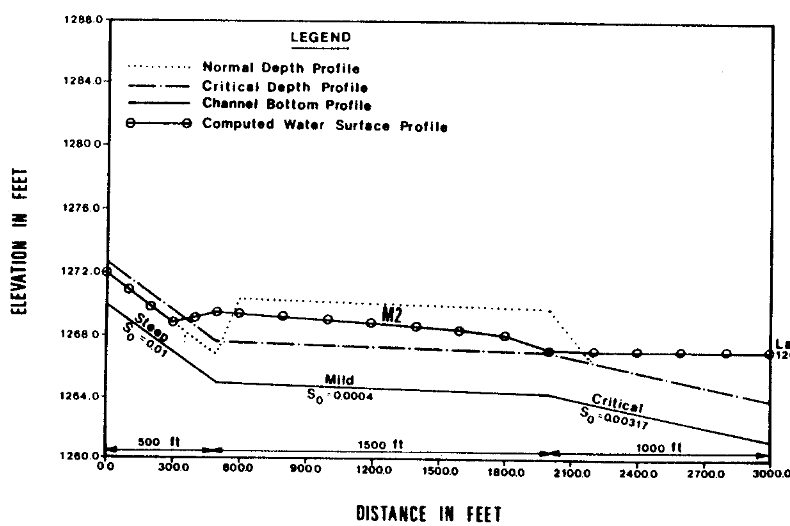

FIG. 6.—Computed Water Surface Profile with Transitions Stated in Fig. 5, Except Lake Level Is Raised from 1,266 ft to 1,267 ft

face computations are continued until the junction is reached.

5. At the junction of subcritical and supercritical slopes, the sequent depth/w.s.e. to the depth/w.s.e. determined from the supercritical water surface profile computations is compared with the subcritical depth/w.s.e. determined from the subcritical water surface profile computations.

a. If $Y_{usub} > Y_{dsub}$, the hydraulic jump takes place downstream from

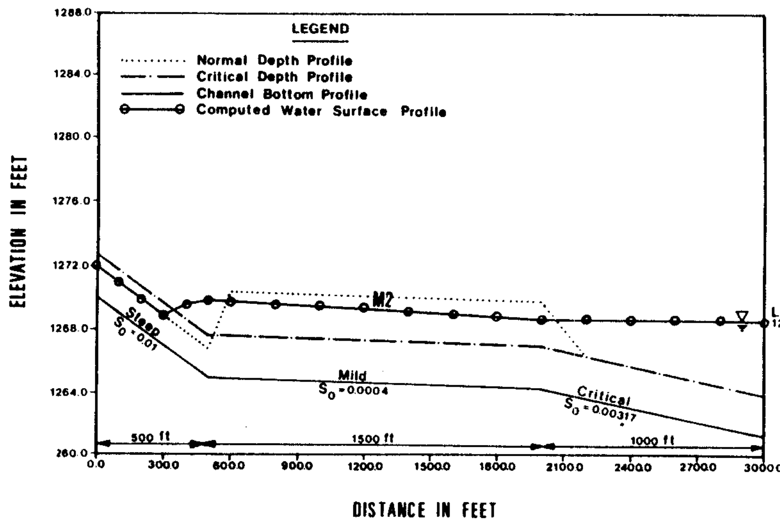

FIG. 7.—Computed Water Surface Profile with Transitions Stated in Fig. 5, Except Lake Level is Raised to 1,269 ft

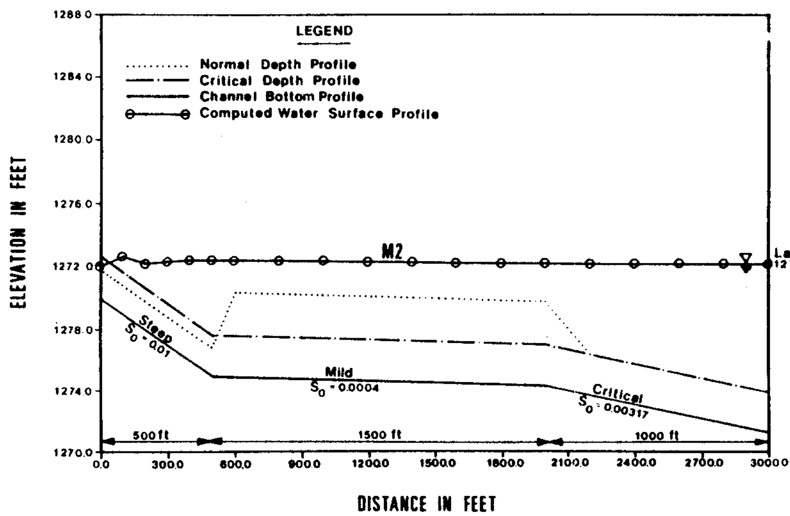

FIG. 8.—Computed Water Surface Profile with Transitions Stated in Fig. 5, Except Lake Level is Raised to 1,272 ft

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the junction. The heel of the jump is set to be located at the junction, and the toe at the next downstream cross section.

b. If $Y_{usub} = Y_{dsub}$, the hydraulic jump takes place at the junction.

c. If $Y_{usub} < Y_{dsub}$, the hydraulic jump takes place upstream from the junction.

Here, Y_{usub} = sequent depth/w.s.e. for the supercritical depth/w.s.e., determined from the supercritical water surface profile computations upstream from the junction; Y_{dsub} = subcritical depth/w.s.e. determined from the subcritical water surface profile computations downstream from the junction.

If Y_{usub} is greater than or equal to Y_{dsub}, the heel of the hydraulic jump is set at the junction and the toe at the next downstream cross section. This approximation is to give the user an idea where the jump would be located. For better results, intermediary cross sections computed from measured cross sections should be utilized.

If Y_{usub} is less than Y_{dsub}, subcritical water surface computations are continued in the upstream direction for a possible S1 profile. At each cross section upstream from the junction, the sequent depth/w.s.e. is computed, and a comparison between Y_{usub} and Y_{dsub} is done. The computations are terminated when either $Y_{usub} \geq Y_{dsub}$ or Y_{dsub} becomes less than critical depth/w.s.e. Theoretically, Y_{dsub} becomes less than critical depth/w.s.e. in the case of $Y_{dsub} \leq Y_{usub}$. However, due to reasons explained in the sequent water surface elevation computations, there might be cases where the computed Y_{usub} is less than critical depths/w.s.e.

Fig. 3 shows an example of computed results of locating the hydraulic jump on a subcritical slope. At cross section 8, the subcritical depth/w.s.e. is less than the sequent depth/w.s.e. So the heel of the jump is

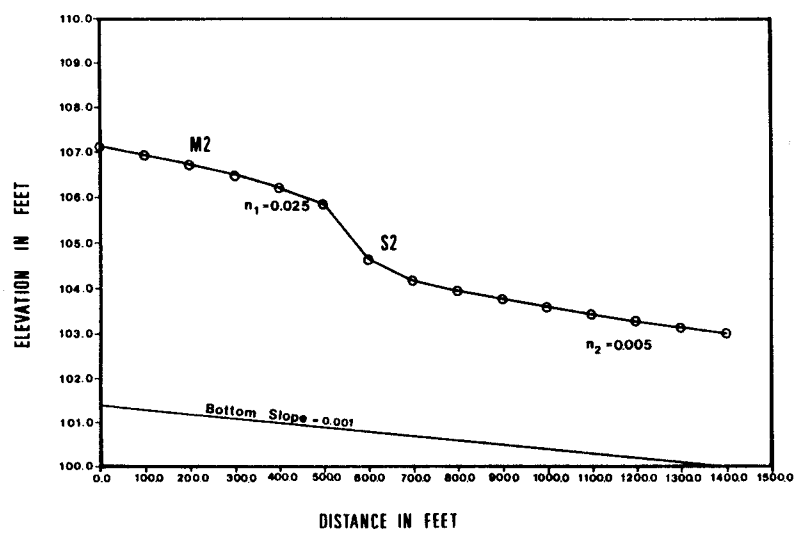

FIG. 9.—Computed Water Surface Profile with Transition from Subcritical to Supercritical by Changing Channel Bottom Roughness

at section 8 and the toe is at section 9. Fig. 4 shows an example of locating the hydraulic jump on a steep slope. At section 6, $Y_{dsub} > Y_{usub}$. At section 5, the subcritical depth/w.s.e. is less than the sequent depth/w.s.e. The heel of the jump is at section 5 and the toe at section 6.

Examples

To show the capability of the generalized water surface computation program, problem 9-8 in the "Open-Channel Hydraulics," by Chow (1) is slightly modified and used as an example. The example problem is a rectangular channel, 20-ft wide, and consists of steep, mild and critical slopes as shown in Figs. 5–8. The entrance flow has a normal depth on a supercritical slope. The channel has a Manning's roughness coefficient of $n = 0.015$ and carries a discharge of 500 ft^3/sec. The normal depth water surface elevation at station "0" on the supercritical slope is 1,272 ft. The downstream control is a lake. In order to demonstrate the change of water surface profile, the lake water surface is allowed to change between elevation 1,266 and 1,272 ft. With the lake level at 1,266 ft, as shown in Fig. 5, the profile goes through supercritical flow, critical depth,

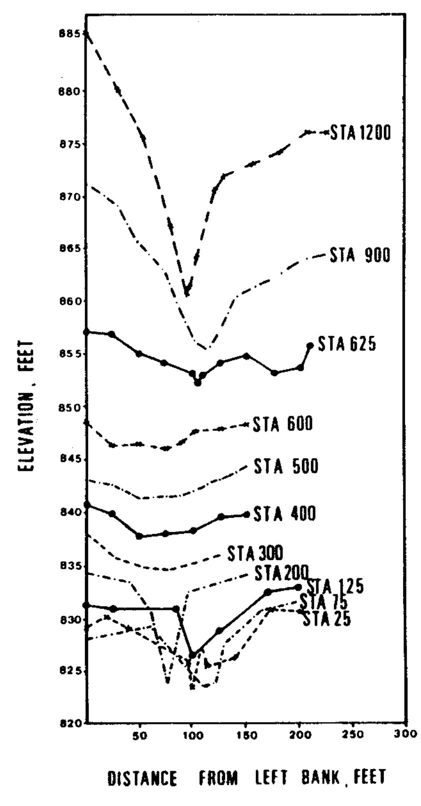

FIG. 10.—Channel Cross Sections of Different Stations Along Priest Rapids Lateral and Wasteway, Columbia River Basin, Wash.

hydraulic jump, M2 curve and critical depth, and ends up with a horizontal profile at the lake level of 1,266 ft. As the lake level is raised to 1,267 ft, as shown in Fig. 6, the critical depth profile after the M2 profile disappears. With lake level at 1,269 ft, as shown in Fig. 7, the hydraulic jump is directly influenced by the backwater effect due to high lake level. With the lake level further raised to 1,272 ft, as shown in Fig. 8, the hydraulic jump moves toward the upstream gate control and basically eliminates the hydraulic jump.

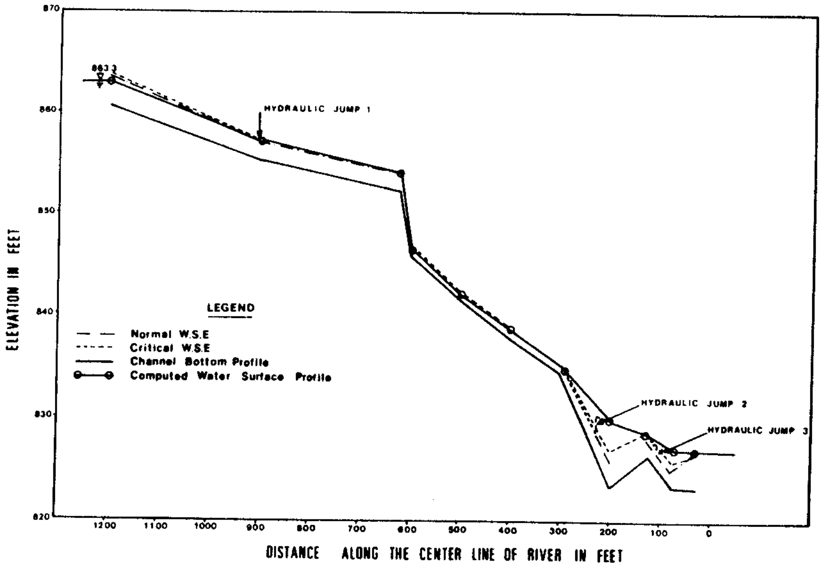

FIG. 11.—Computed Water Surface Profile Along Priest Rapids Lateral and Wasteway, Columbia River Basin, Wash.

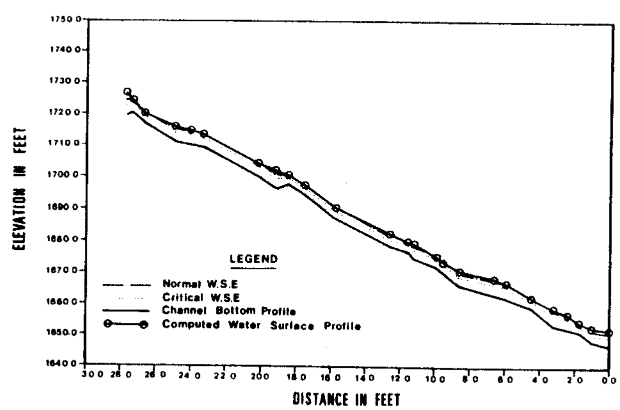

FIG. 12.—Computed Water Surface Profile Along Trinity River Below Grass Valley Creek, Calif.

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The change from one type to another type of water surface profile can occur not only due to the change of channel bottom slope or upstream or downstream controls; it could also be caused by the change of roughness along the course of flow. Fig. 9 shows the computed water surface profile for a rectangular channel with a channel bottom slope of 0.001. A change of Manning's roughness coefficient from 0.025 to 0.005 can change the water surface from an M2 to an S2 profile.

To demonstrate the application of the program to a natural river with mild, steep and adverse slopes, the Priest Rapids Lateral and Wasteway, Columbia Basin Project, Washington, is utilized. The channel cross sections at different stations along the Priest Rapids are shown in Fig. 10. The water discharge used in the computation is 200 ft^3/sec. The Manning's roughness coefficient is 0.035. The accuracy level for backwater computations and sequent water surface elevation computations are 0.001 ft and 0.01 ft, respectively. The upstream and downstream controls are set at elevation 863.3 ft and 827.0 ft, respectively. The computed water surface profile is shown in Fig. 11. The computed profile has three hy-

TABLE 1.—Comparison Between Generalized Computer Program and U.S. Bureau of Reclamation's (USBR) Program for Gradually Varied Flows: Trinity-River Below Grass Valley Creek

Station identification	Q = 300 Cubic Feet per Second			Q = 1,000 Cubic Feet per Second			Q = 3,000 Cubic Feet per Second		
	USBR	Generalized	Difference	USBR	Generalized	Difference	USBR	Generalized	Difference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1		1,724.75		1,726.6	1,726.65	−0.1	1,729.4	1,729.56	−0.2
2	1,722.9	1,722.85	0.0	1,724.2	1,724.08	+0.1	1,726.2	1,726.00	−0.2
3	1,718.8	1,718.75	0.0	1,720.1	1,720.04	+0.1	1,722.4	1,722.32	+0.1
4	1,714.3	1,714.17	+0.1	1,715.9	1,715.85	+0.0	1,718.4	1,718.33	0.0
5	1,713.4	1,713.29	+0.1	1,714.7	1,714.64	+0.1	1,717.0	1,716.95	0.0
6	1,712.1	1,711.98	+0.1	1,713.4	1,713.43	0.0	1,715.7	1,715.69	0.0
7	1,702.9	1,702.76	+0.1	1,704.5	1,704.39	+0.1	1,707.1	1,706.99	+0.1
8	1,700.9	1,700.90	0.0	1,702.2	1,702.12	+0.1	1,704.5	1,704.41	+0.1
9	1,699.6	1,699.57	0.0	1,700.9	1,700.85	0.0	1,702.8	1,702.80	0.0
10	1,696.4	1,696.38	0.0	1,697.7	1,697.63	+0.1	1,699.5	1,699.46	0.0
11	1,689.3	1,689.29	0.0	1,690.6	1,690.60	0.0	1,692.8	1,692.81	0.0
12	1,681.3	1,681.49	−0.2	1,682.6	1,682.64	0.0	1,685.2	1,685.17	0.0
13		1,678.73		1,680.3	1,680.17	+0.1	1,682.6	1,682.49	+0.1
14		1,677.26		1,679.7	1,678.66	+0.0	1,682.0	1,682.05	−0.1
15		1,674.37		1,675.5	1,675.47	0.0	1,677.4	1,677.28	+0.1
16	1,672.5	1,672.45	0.0	1,673.7	1,673.61	0.1	1,675.9	1,675.80	+0.1
17	1,669.2	1,669.09	+0.1	1,670.9	1,670.90	0.0	1,674.1	1,674.05	0.0
18	1,666.8	1,666.60	+0.2	1,668.5	1,668.41	+0.1	1,671.1	1,671.02	+0.1
19	1,666.0	1,665.88	+0.1	1,667.2	1,667.07	+0.1	1,669.1	1,668.96	+0.1
20	1,661.3	1,661.17	+0.1	1,662.4	1,662.42	0.0	1,664.7	1,664.66	0.0
21	1,657.0	1,656.88	+0.1	1,658.9	1,658.85	0.0	1,661.9	1,661.83	+0.1
22		1,656.01		1,657.3	1,657.34	0.0	1,659.6	1,659.52	+0.1
23	1,653.3	1,653.24	+0.1	1,654.7	1.654.80	+0.1	1.657.2	1,657.02	+0.2
24	1,650.9	1,650.96	0.0	1,652.8	1,652.75	0.0	1,655.7	1,655.70	0.0
25	1,650.1	1,640.10	0.0	1,651.9	1,651.88	0.0	1,654.8	1,654.80	0.0
	Average: +0.045 feet			Average: +0.040 feet			Average: +0.028 feet		

draulic jumps and goes through steep, mild and adverse bed slope profiles without any interruptions.

A comparison between the generalized computer program with the Bureau of Reclamation's Water Surface Profile Computer Program (4) is made on the Trinity River below the Grass Creek Valley. The computed results by the Bureau program were verified by field measurements and observations. A comparison of the computed results from these two programs is summarized in Table 1. The computed water surface by generalized program along the Trinity River is shown in Fig. 12. The results shown in Table 1 indicate that the results computed by these two programs are in close agreement.

Summary and Conclusion

A generalized computer program for the computation of water surface profiles of natural rivers is introduced in this paper. A step-by-step description of the methods and procedures used in the program is made. Examples are used to show the capability of the program. This study has reached the following conclusions:

1. The energy equation can be used in conjunction with the momentum equation for the computation of water surface profiles through gradually varied, as well as rapidly varied open-channel flows.
2. The computer program developed in this paper can be used to compute water surface profiles through hydraulic jumps or the change from subcritical to supercritical flows without any interruptions.
3. The generality of the theories used and the field conditions considered in the computer program make it a powerful and useful tool for engineering computations of water surface profiles in natural rivers and man-made channels.

Acknowledgment

The writers appreciate the financial support of the U.S. Bureau of Reclamation which made this study possible.

Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

A = cross-sectional area;
$A(d)$ = channel cross-sectional area at given elevation or depth, d;
A_m = flow area in which there is motion;
A_t = total flow area;
C_L, C_E, C_b = energy loss coefficient due to velocity variation, expansion or contraction, and bend, respectively;
CM = coefficient in Manning's formula; it is equal to 1.0 for SI units and 1.486 for U.S. units;
d_a = computed supercritical water surface elevation;
d_b = desired subcritical sequent water surface elevation;
$(\mathsf{F})_{ass}, (R)_{ass}, (h_f)_{ass}, H_{ass}$ = Froude number, hydraulic radius, friction loss, and total head, respectively, computed by use of initial assumed depth;
F_f = total external friction force;
H_{comp} = total head computed by subtraction or addition of head losses to total head of cross section at which flow conditions are known;
h_f, h_t = friction loss and total energy loss, respectively;
$K(d)$ = conveyance which is a function of depth, d;
n, C, f = roughness coefficient in Manning, Chezy, and Darcy Weisbach's formula, respectively;
P = pressure;
p = wetted perimeter;
Q = water discharge;
R = hydraulic radius;
S_f = friction slope;
S_0 = bottom slope;
$SF(d)$ = specific force corresponding to water surface elevation or depth, d;
$T(d)$ = top channel width at given elevation or depth, d;
V = velocity;
W = weight of water;
Y_d = hydraulic depth;
y = water depth;
$\bar{y}$ = depth measured from water surface to centroid of cross section;
Z = bed elevation;
$(Z_{ass})_{old}, (Z_{ass})_{new}$ = initial and improved assumed water surface elevations, respectively;
α = velocity distribution coefficient;
β = momentum coefficient;
γ = unit weight of water; and
θ = angle of inclination of channel bed.

APPENDIX D

Reprint of the paper by C. T. Yang and C. Huang, “Applicability of sediment transport formulas,” International Journal of Sediment Research, Vol. 16, No. 3, 2001, pages 335–353. (With correction.)

APPLICABILITY OF SEDIMENT TRANSPORT FORMULAS

Chih Ted YANG[1] and Caian HUANG[2]

ABSTRACT

The paper provides a comprehensive testing of the applicability of 13 sediment transport formulas under different flow and sediment conditions. The dimensionless parameters used for testing the reliability and sensitivity of formulas are dimensionless particle diameter, relative depth, Froude number, relative shear velocity, dimensionless unit stream power, and sediment concentration. A total of 3,391 sets of laboratory and river data are used in the tests. Engineers may find the test results useful to their selection of formulas under different flow and sediment conditions.

Key Words: Accuracy, Dimensionless parameter, Sediment transport formula, Stream power, Unit stream power

1 INTRODUCTION

The selection of appropriate sediment transport formulas under different flow and sediment conditions is important to the sediment transport and river morphologic studies of a river. There are numerous formulas published in professional journals and summarized in sediment transport textbooks. Most textbooks shy away from direct comparisons of the accuracies of transport formulas. Computed results based on different transport formulas may differ significantly from each other and from measurements. Students and engineers often face the dilemma of selecting the correct formula for solving river engineering and sediment-related problems. In his review of Yang's (1996) book, Fang (1998) stated "If we take into account the fact that there are too many sediment transport formulae, I believe it is better to seriously evaluate and compare existing commonly used sediment transport formulae than to give a new formula."

Comparisons of accuracies of sediment transport formulas were published by Schulits and Hill (1968), White, et al. (1975), Yang (1976, 1979), Alonso (1980), Brownlie (1981), Yang and Molinas (1982), ASCE Task Committee (1982), Yang (1984), Vetter (1989), German Association for Water and Land Improvement (1990), Yang and Wan (1991), among others. The ranking of the accuracy of formulas in the above comparisons are not consistent because they were based on different sets of data. Some of the comparisons are not strictly valid because data outside of the range of application recommended by the authors of the formulas were used in the comparison. Although there is no lack of data for comparison, the accuracies of data, especially field data, may be questionable.

This paper provides a comprehensive comparison of 13 sediment transport formulas to determine their limits of application. Published reliable data by different authors are used to give unbiased comparisons. Different amounts of data may be used for different formulas because only the data within the applicable range of a formula are used to test its accuracy. Dimensionless parameters are used to determine the sensitivities of formulas to these parameters. Engineers may use this paper as a reference in their selection of formulas under different flow and sediment conditions.

2 SEDIMENT TRANSPORT FORMULAS

There are numerous sediment transport formulas proposed by different investigators. Stevens and Yang (1989) published FORTRAN and BASIC computer programs for 13 commonly used sediment transport formulas in river engineering. The complete source codes in both FORTRAN and BASIC and a floppy diskette of the programs are included in Yang's (1996) book Sediment Transport Theory and Practice. The 13 formulas are those proposed by Schoklitsch (1934), Kalinske (1947), Meyer-Peter and

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Note: The manuscript of this paper was received in Nov. 2000. The revised version was received in March 2001. Discussion open until Sept. 2002.

Müller (1948), Einstein (1950) for bedload, Einstein (1950) for bed material load, Laursen (1958), Rottner (1959), Engelund and Hansen (1967), Toffaleti (1968), Ackers and White (1973), Yang (1973) for sand transport with incipient motion criteria, Yang (1979) for sand transport without incipient motion criteria, and Yang (1984) for gravel transport. These formulas are selected for detailed comparisons because the computer program used in comparison is readily available to the writers and other engineers. Many of these formulas have been incorporated in sediment transport models, such as the U.S. Army Corps of Engineers'HEC-6 computer model Scour and Deposition in Rivers and Reservoirs (1993), and the U.S. Bureau of Reclamation's Generalized Stream Tube model for Alluvial River Simulation (GSTARS) by Molinas and Yang (1986) and its revised and improved versions of GSTARS 2.0 (Yang, et al., 1998) and GSTARS 2.1 (Yang and Simoes, 2000). A brief description of the formulas tested in this paper are summarized in Appendix II.

3 DIMENSIONLESS PARAMETERS

The accuracy of a sediment transport formula may vary with varying flow and sediment conditions. To determine the sensitivities of a transport formula to varying flow and sediment conditions, seven dimensionless parameters are selected for comparison.

3.1 Dimensionless Particle Diameter

Different transport formulas were developed for sediment transport in different size ranges. The dimensionless particle diameter used in this paper is defined as:

$$D_* = d\left[\frac{\gamma_s - \gamma}{\gamma} g / v^2\right]^{1/3} \tag{1}$$

where d = sediment particle diameter; γ_s, γ = specific weight of sediment and water, respectively; g = gravitational acceleration; and v = kinetic viscosity of water.

3.2 Relative Depth

The relative depth is defined as the ratio between average water depth D and sediment particle diameter d. The inverse of relative depth is the relative roughness, which has been considered by many investigators as an important parameter for the determination of sediment transport rate and resistance to flow. One major difference between laboratory and river data is that the former has much smaller value of relative depth. If the relative depth is small, say less than 50, the water surface wave and the size of bed form may affect accuracy of measurements.

3.3 Froude Number

Froude number is one of the most important parameters for open channel flow studies. Most sediment transport formulas were developed for subcritical flows.

3.4 Relative Shear Velocity

Relative shear velocity is defined as the ratio between shear velocity U_* and sediment particle fall velocity ω. Many researchers consider U_*/ω as an index of flow intensity for sediment transport. For example, Julien (1995) believes that there is no sediment movement if $U_*/\omega < 0.2$; sediment transport is in the form of bed load if $0.2 < U_*/\omega < 0.4$; sediment transport is in the form of both bed load and suspended load if $0.4 < U_*/\omega < 2.5$; sediment transport is in the form of suspended load if $U_*/\omega > 2.5$.

3.5 Dimensionless Unit Stream Power

Yang (1973) defined the dimensionless unit stream power as VS/ω, where V = cross sectional average flow velocity; S = energy or water surface slope; and ω = sediment particle fall velocity. Yang (1973, 1996) considered VS/ω the most important parameter for the determination of sediment concentration or sediment transport rate.

3.6 Sediment Concentration

Sediment concentration is defined as the ratio between sediment transport rate and water discharge by weight.

3.7 Discrepancy Ratio

Discrepancy ratio is defined as the ratio between computed sediment concentration and measured sediment concentration, i.e.,

$$R = C_c / C_m \tag{2}$$

where C_c = computed sediment concentration in parts per million by weight; C_m = measured total bed-material concentration in parts per million by weight. The average discrepancy ratio is defined as:

$$\overline{R} = \frac{\sum_{i=1}^{j} R_i}{j} \tag{3}$$

where i = data set number; and j = total number of data used in the comparison.

4 DATA ANALYSES

A total of more than 6,200 sets of sediment transport and hydraulic data were available to the writers for preliminary comparison and analysis. One of the difficulties in the selection of data for final comparison and analysis is the determination of accuracies of data published by different investigators. The following criteria are used to eliminate data of questionable accuracy.

1. Only those data published by an investigator with more than 50 percent in a range of discrepancy ratio between 0.5 and 2 based on two or more of the 13 formulas are included. Data with less than 10 sets are excluded. A total of 3,391 sets of data meet this requirement. These data were compiled by Yang (2001).

2. To avoid the uncertainties related to incipient motion, measured sediment concentrations less than 10 ppm by weight are excluded.

3. Most of the laboratory data are fairly uniform in size. The median particle diameter is used for all sediment transport formula computations. The gradation coefficient is defined as:

$$\sigma = \frac{1}{2}\left(\frac{d_{84.1}}{d_{50}} + \frac{d_{50}}{d_{15.9}}\right) \tag{4}$$

where $d_{15.9}$, d_{50}, $d_{84.1}$ = sediment particle size corresponding to 15.9 percent, 50 percent, and 84.1 percent finer, respectively. Data with $\sigma \geq 2.0$ are excluded from further analysis.

4. To avoid the inclusion of wash load, data with median particle diameters of less than 0.0625 mm are excluded.

5. All the laboratory data must be collected under steady equilibrium conditions. Natural river sediment and hydraulic data must be collected within a day, and flow conditions must be fairly steady to ensure a close relationship between sediment and flow conditions for a given set of river data.

Based on the above criteria, a total of 3,225 sets of laboratory data and 166 sets of river data are selected for final analysis and comparison. These data are summarized in Table 1.

Some of the transport formulas were intended for sand transport and some for gravel transport. The second step of comparison is to determine the range of application of sediment particle size based on discrepancy ratio for each formula. The results are shown in Table 2. Based on the results shown in Table 2, the ranges of application of the 13 formulas are given in Table 3. Only those data within the range of application of each formula as shown in Table 3 are used for further comparison and analysis in this paper.

The sensitivity of the accuracy of formulas as a function of relative depth is summarized in Table 4. The relatively large variations of discrepancy ratio for 13 formula with 4 < D/d < 50 suggest that the influence of water surface wave and bed form may be significant. If we exclude the data with 4 < D/d < 50, Yang's 1979 sand formula is least sensitive to the variation of relative depth, followed by Yang's 1973 sand formula, and Yang's 1984 gravel formula. The most sensitive formulas are the Rottner formula and the Kalinske formula. The Ackers and White formula has a tendency to overestimate sediment concentration with increasing flow depth while the Engelund and Hansen formula has the reverse tendency.

The sensitivity of the accuracy of formulas as a function of Froude number is summarized in Table 5 and Figure 1. The Rottner formula is most sensitive to the variation of Froude number, followed by Einstein's bed load and bed-material load formulas and the Kalinske formula. Yang's 1979 and 1973 sand formulas are least sensitive to the variation of Froude number. Table 5 also shows that Yang's 1973, 1979, and 1984 formulas can be applied to subcritical, supercritical, and transitional flow regimes, while other formulas should be applied to subcritical flow only. The sensitivity of the accuracy of formulas as a function of relative shear velocity is summarized in Table 6. The Rottner and Kalinske formulas are most sensitive to the variation of relative shear velocity. Yang's 1973, 1979, and 1984 formulas are least sensitive to the variation of relative shear velocity.

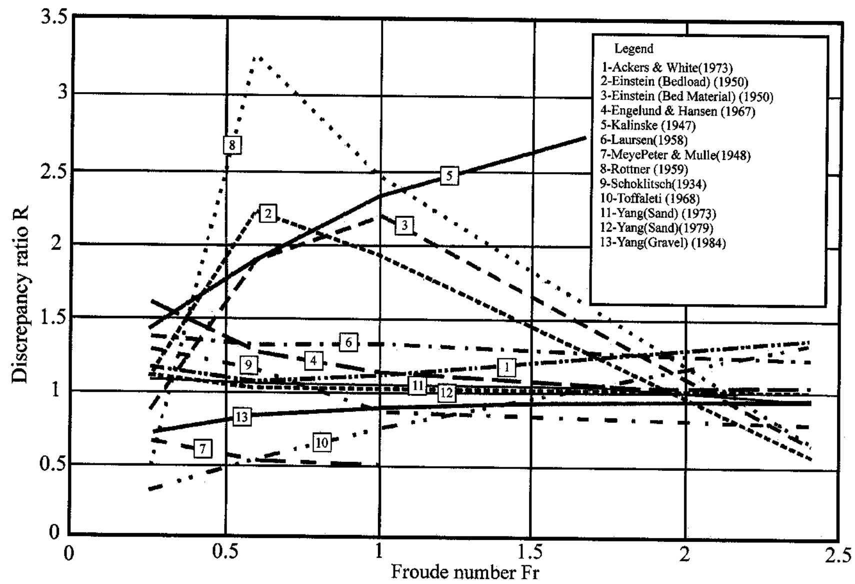

Fig 1 Comparison of discrepancy ratio based on Froude number

Yang considered the dimensionless unit stream power the most important parameter in his 1973, 1979, and 1984 formulas. Table 7 shows that Yang's three formulas consistently and reliably predict sediment concentration or transport rates. The formulas by Ackers and White and by Engelund and Hansen also can give accurate estimation of sediment concentration or load for a wide range of dimensionless unit stream power. The least reliable ones are the Rottner, Kalinske, Einstein's bed load and bed material load formulas. While the Kalinske and Laursen formulas consistently overestimate sediment concentration and transport rate, the Meyer-Peter and Müller formula consistently underestimates sediment concentration and transport rate.

The accuracies of transport equations as a function of measured sediment concentration are summarized in Table 8 and Figure 2. There is an apparent increase of accuracy for all formulas when the measured sediment concentration is greater than 100 ppm by weight. This may be related to the fact that it is more difficult to measure accurately when the concentration is low. If we limit our comparisons with concentration greater than 100 ppm by weight, the most accurate formulas are those proposed by Yang in 1973, 1979, and 1984. The Ackers and White and the Engelund and Hansen formulas can also give reasonable estimations. The least accurate ones are the Kalinske, Rottner, Einstein bed load and bed-material load, Taffoletti, and the Meyer-Peter and Müller formulas.

The difference between Yang's 1973 and 1979 formulas is that the 1973 formula includes incipient motion criteria, while the 1979 formula does not have incipient motion criteria. Consequently, the 1973 formula should be used where measured total bed-material concentration is less than 100 ppm by weight. The 1979 formula should give slightly more accurate results at high concentrations because the

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uncertainty and the importance of incipient motion criteria decrease with increasing sediment concentration. The comparison between Yang's 1973 and 1979 formulas is summarized in Tables 8 and 9 and Figure 3. It is apparent that the 1973 formula should be used where total bed material concentration is less than 100 ppm by weight, while the 1979 formula is slightly more accurate where the concentration is greater than 100 ppm by weight.

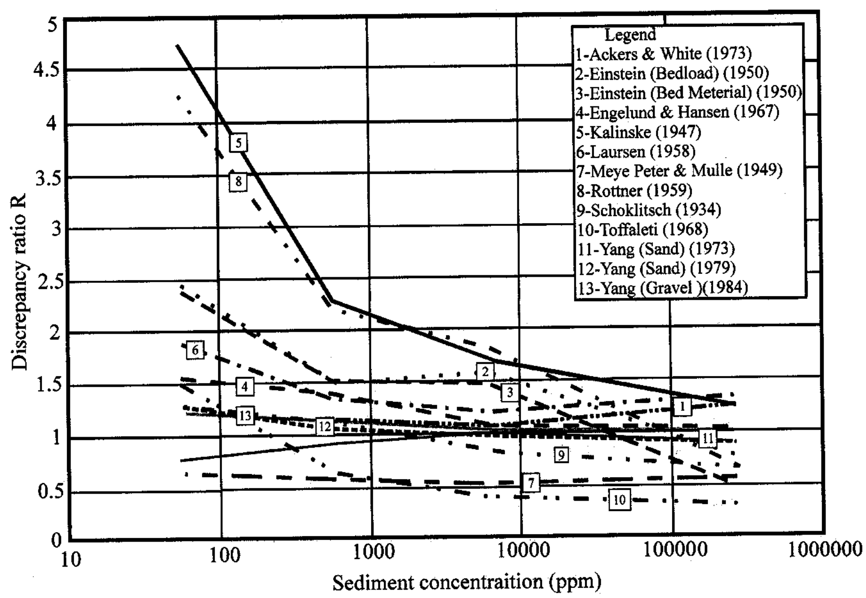

Fig. 2 Comparison of discrepancy ratio based on concentration.

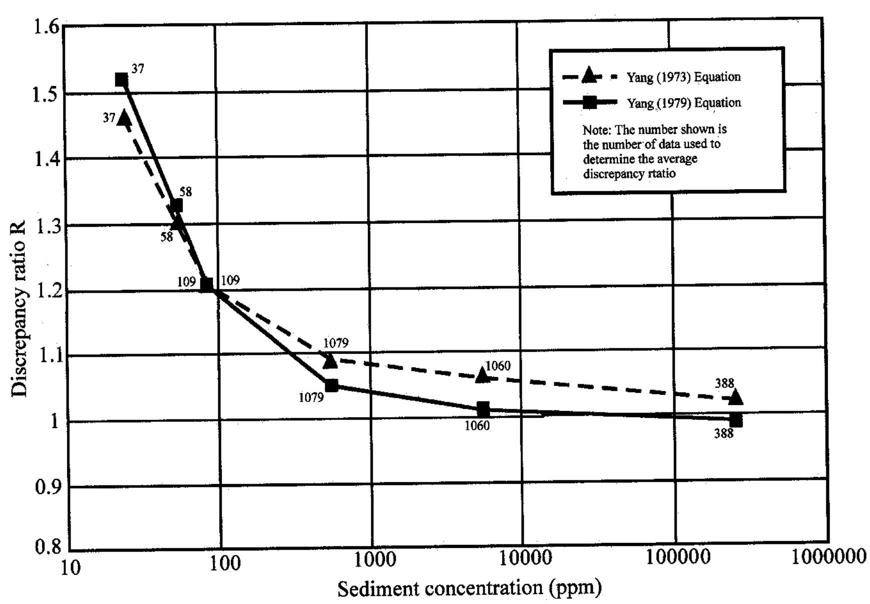

Fig 3 Comparison of equations of Yang (1973) & Yang (1979) for sand transport

The Meyer-Peter and Müller and the Yang 1984 formulas should be used for bed materials in the very coarse sand to coarse gravel range. Figure 4 shows that the Yang 1984 formula gives more reasonable prediction than that of the Meyer-Peter and Müller formula.

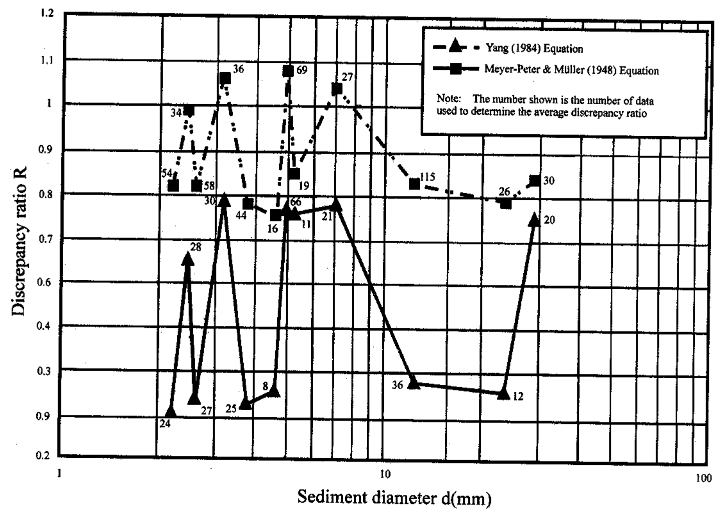

Fig. 4 Comparisons of equations of Meyer-Peter & Müller (1948) & Yang (1984) for gravel transport

Table 10 summarizes the recommended ranges of application and the accuracy of 13 formulas. It is apparent that formulas based on energy dissipation rate either directly or indirectly, such as those by Yang, Ackers and White, and Engelund and Hansen, outperform those based on other approaches. The Einstein transport functions were based on probability concepts. In spite of the sophisticated theories and the complicated computational procedures used, the accuracy of Einstein's bed load and bed-material transport formulas are less accurate than others for engineering applications. This is mainly due to the lack of generality of Einstein's assumptions, such as step length, hiding factor, and lifting factor (Yang and Wan, 1991). Einstein's formulas should not be used in any computer model if sediment routing based on size fractions is performed. Yang and Wan (1991) pointed out that if computation is based on size fraction using Einstein's formulas, sediment in transportation would be coarser than the original bed-material gradation, and coarser materials would be transported further in the downstream direction at a higher rate than the finer materials.

The Rottner formula is a pure regression equation without much theoretical basis. The results shown in table 10 indicate that the Rottner formula is less reliable than others based on discrepancy ratio. Formulas purely based on regression analysis should not be applied to those places other than where the data were used in the original regression analyses.

Table 10 also indicates that the classical approach based on shear stress, such as the Kalinske and the Meyer-Peter and Müller formulas, are less accurate than those based on the energy dissipation rate theories used by Yang directly and by Ackers and White, and Engelund and Hansen indirectly. Yang's approach was based on his unit stream power theory, while Ackers and White and Engelund and Hansen's applied Bagnold's (1966) stream power concept to obtain their transport functions (Yang, 1996, 2002).

Most of the river sediment transport studies involve sediments in the coarse silt to coarse gravel size range. Table 10 indicates that the priority of selection should be Yang (1979) for $d_{50} < 2$ mm plus Yang (1984) for $d_{50} > 2$ mm, followed by Yang (1973) for $d_{50} < 2$ mm plus Yang (1984) for $d_{50} > 2$ mm, and then followed by Ackers and White (1973) and Engelund and Hansen (1967). If the local conditions on the range of variations of dimensionless particle diameter, relative depth, Froude number, relative shear velocity, dimensionless unit stream power, and measured bed-material load concentration are available, tables 2 to 9 should be used as references to finalize the selection of the most appropriate formula for engineers to use.

5 SUMMARY AND CONCLUSIONS

A comprehensive and systematic analysis of 3,391 sets of laboratory and river sediment transport data were used to test the accuracies of 13 commonly used sediment transport formulas. Only those sets of data applicable to a given formula are used to determine its accuracy and sensitivities to the variations of five dimensionless parameters. These dimensionless parameters are relative depth, Froude number, dimensionless shear velocity, dimensionless unit stream power, and sediment concentration in parts per million by weight. The analyses reached the following conclusions:

1. Sediment transport formulas based on energy dissipation rate or power concept are more accurate than those based on other concepts. Yang's (1973, 1979, 1984) formulas were derived directly from the unit stream power theory while the formulas by Engelund and Hansen (1967) and by Ackers and White (1973) were obtained indirectly from Bagnold's (1966) stream power concept.

2. Among the 13 formulas compared, Yang's 1973, 1979, and 1984 formulas are most robust and their accuracies are least sensitive to the variation of relative depth, Froude number, dimensionless shear velocity, dimensionless unit stream power, and sediment concentration.

3. With the exception of Yang's (1973, 1979, 1984) dimensionless unit stream power formulas and Engelund and Hansen's (1967) formula, the application of other sediment transport formulas should be limited to subcritical flows.

4. Table 10 should be used by engineers as a reference for the preliminary selection of appropriate formulas for different size ranges of sediment particle diameter. Tables 4 to 8 should be used to determine whether a formula is suitable for a given range of dimensionless parameters before the final selection of formula is made.

5. Yang's 1973 and 1979 sand transport formulas have about the same degree of accuracy. However, the 1973 formula with incipient motion criteria is slightly more accurate when the sand concentration is less than 100 ppm, while the 1979 formula without incipient motion criteria is slightly more accurate for concentrations higher than 100 ppm.

6. The Einstein bed-material load (1950) and bed load (1950) formulas and those by Toffaleti (1968) and Meyer-Peter and Müller (1948) are not as accurate as those formulas based on the power approach. Some engineers use the Meyer-Peter and Müller formula for bed load, and the Einstein bed-material or Toffaleti formula for suspended load for the estimate of total load. This kind of combined use may not be justified from a theoretical point of view nor from the accuracies of these equations based on the results shown in this paper.

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Appendix I

Table 1 Summary of basic data

Author	D*	σ	D/d	Fr	U_*/ω	VS/ω	C	N.
(a) Laboratory data								
Gilbert (1914)	7.63-175.3	1.06-1.34	5.74-295.9	0.292-3.540	0.240-1.998	0.0057-0.6628	77-35340	886
Guy et al. (1996)	4.75-30.0	1.25-1.67	109.2-1701	0.220-1.698	0.235-7.236	0.0014-0.6533	10-50000	272
Willis et al. (1972)	2.50	1.30	1036-3780	0.218-1.005	4.217-10.427	0.0167-0.3810	87-19400	96
Willis (1979)	13.5	1.12	191.9-276.6	0.272-1.155	0.437-1.276	0.0035-0.1248	15-6670	32
Willis (1983a)	13.8	1.60	698.3-2810	0.163-0.643	0.776-2.392	0.0024-0.0693	27-4620	42
Willis (1983b)	13.8	1.60	310.3-642.9	0.284-1.159	0.395-1.533	0.0021-0.1603	61-6180	27
Barton & Lin (1955)	4.50	1.26	508.0-1321	0.161-0.872	1.428-3.428	0.0119-0.1141	19-3776	28
Stein (1965)	10.0	1.50	228.6-777.2	0.243-1.664	0.747-2.467	0.0045-0.3118	93-39293	57
Nordin (1976)	6.25	1.44	951.0-3438	0.222-1.128	1.308-3.722	0.0041-0.2744	18-17200	45
Foley (1975)	7.25	1.37	102.0-162.9	0.656-1.375	0.953-1.554	0.0393-0.2193	845-11693	12
Taylor (1971)	5.70	1.52	346.2-701.8	0.278-0.988	1.106-2.653	0.0111-0.1146	14-2270	13
Williams (1970)	33.8	1.20	20.1-164.8	0.343-3.504	0.216-1.490	0.0020-0.5207	10-34575	175
Kennedy (1961)	5.83-13.7	1.14-1.47	41.1-465.7	0.499-1.964	0.639-4.137	0.0355-0.7779	490-58500	41
Brooks (1957)	2.20-3.63	1.11-1.17	325.8-983.7	0.274-0.799	2.545-8.507	0.0425-0.2759	190-5300	21
Vanoni & Brooks (1957)	3.43	1.38	527.3-1230	0.252-0.810	2.061-4.377	0.0078-0.1613	37-3000	14
Nomicos (1956)	3.80	1.76	483.3-508.7	0.287-0.956	2.246-3.755	0.0323-0.2136	300-5600	12
Laursen (1958)	2.75	1.20	692.7-2757	0.243-0.863	4.440-6.626	0.0224-0.1580	140-5150	16
Davis (1971)	3.75	1.17	508.0-2032	0.190-0.623	2.083-3.844	0.0073-0.1024	11-1760	70
Pratt (1970)	12.0	1.11	159.4-956.5	0.210-0.502	0.407-1.074	0.0016-0.0195	12-560	29
Singh (1960)	15.5	1.16	23.6-329.4	0.313-1.244	0.269-0.954	0.0041-0.1355	19-9200	286
Znamenskaya (1963)	20.0	1.60	62.5-254.9	0.422-1.213	0.298-0.862	0.0055-0.0478	126-3000	26
Straub (1954)	4.78	1.40	218.6-1232	0.399-1.299	1.800-2.626	0.0222-0.2788	423-12600	18
Krishnappan & Engel (1988)	30.0	1.00	118.1-137.9	0.459-0.765	0.283-0.745	0.0040-0.0451	88-2087	15
Wang et al. (1998)	2.78	1.94	845.8-1229	0.329-1.128	6.894-13.716	0.1045-0.9641	13750-118180	35
Ansely (1963)	5.83	1.33	58.9-157.0	2.301-3.362	2.042-3.446	1.0312-2.2163	29576-198664	26
Chyn (1935)	19.5-21.0	1.23-1.58	59.4-106.0	0.514-0.764	0.261-0.440	0.0043-0.0152	123-751	22
MacDougal (1933)	16.5-31.5	1.29-1.71	29.6-190.3	0.433-0.799	0.218-0.507	0.0038-0.0212	123-1237	74
USACE (1935)	4.50-12.5	1.31-1.94	46.6-1021	0.253-0.735	0.208-3.260	0.0043-0.00786	10-833	279
USACE (1936)	23.8	1.44	30.5-206.9	0.324-0.674	0.206-0.506	0.0032-0.0102	16-379	101
Sato et al. (1958)	26.0-114.5	1.00	60.2-421.1	0.189-0.754	0.210-0.626	0.0010-0.0115	10-500	219
Casey (1935)	61.5	1.16	11.0-89.1	0.425-0.880	0.179-0.286	0.0034-0.0173	10-960	36
Meyer-Peter & Müller (1948)	130.3-716.3	1.00	11.1-47.7	0.623-1.414	0.222-0.440	0.0092-0.0787	10-7000	51
Graf & Suszka (1987)	307.5-587.5	1.23-1.24	3.99-20.9	0.772-1.264	0.205-0.293	0.0114-0.0552	12-2910	101
Song et al. (1998)	307.5	1.37	6.84-17.1	0.698-0.991	0.227-0.288	0.0113-0.0316	11-2519	48
							Total	3225
(b) River data								
Cobly & Hem- bree (1955)	7.08	1.76	1465-2036	0.304-0.535	1.763-3.264	0.0205-0.0716	392-2220	25
Hubbell & Matejka (1959)	4.50-6.00	1.58-2.54	1365-2019	0.326-0.723	2.165-4.425	0.0263-0.0919	632-2440	15
Nordin (1964)	4.75-9.75	1.44-1.89	1107-5045	0.258-0.735	1.055-3.607	0.0112-0.0591	260-3787	42
Jordan (1965)	4.75-19.5	1.43-1.98	9735-45078	0.100-0.158	0.710-4.579	0.0005-0.0064	13.1-226	23
Einstein (1944)	25.0	1.84	61.0-399.3	0.394-0.497	0.251-0.710	0.0047-0.0106	40-664	61
							Total	166

Total number of laboratory and river data = 3,391.

Note: D* = Dimensionless Diameter; σ = Gradation; D/d = Relative depth; Fr = Froude number; U_*/ω = Ratio of shear velocity to fall velocity; VS/ω Dimensionless unit stream power; C = Concentration (ppm by weight); N = Number of data set.

Table 2 Applicability test of formulas according to dimensionless diameter D_* (all data)

Author of formula	D_*=1.56-6.25 (d=0.0625-0.25 mm)			D_*=6.25-20.0 (d=0.25-0.8 mm)			D_*=20.0-50.0 (d=0.8-2.0 mm)			D_*=50.0-720.0 (d=2.0-28.8 m)			N_T
	R		N	R		N	R		N	R		N	
	$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		
Ackers & White (1973)	1.31	77%	505	1.06	95%	1700	1.07	89%	491	1.26	74%	535	3231
Einstein (Bedload) (1950)	0.23	30%	505	1.38	52%	1703	1.77	53%	523	2.45	25%	553	3284
Einstein (Bed Material) (1950)	0.55	46%	505	1.42	64%	1703	1.83	52%	523	2.49	21%	553	3284
Engelund & Hansen (1967)	0.87	82%	505	1.22	88%	1703	1.31	83%	523	1.63	72%	553	3284
Kalinske (1947)	1.23	49%	505	1.88	33%	1703	3.62	9%	523	5.84	4%	553	3284
Laursen (1958)	1.26	82%	495	1.29	85%	1690	1.48	67%	491	2.11	43%	473	3149
Meyer-Peter & Müller (1948)	0.16	11%	502	0.61	60%	1617	0.44	36%	374	0.58	63%	308	2801
Rottner (1959)	0.63	58%	505	1.84	47%	1703	3.77	11%	523	8.34	3%	553	3284
Schoklitsch(1934)	0.43	39%	488	0.82	83%	1242	1.25	73%	224	1.31	85%	284	2238
Toffaleti (1968)	0.21	26%	505	0.38	35%	1703	0.79	54%	523	1.68	48%	553	3284
Yang–Sand (1973)	1.06	90%	505	1.04	93%	1703	1.24	86%	523	9.86	6%	528	3259
Yang–Sand (1979)	0.99	94%	505	1.01	96%	1703	1.21	85%	523	8.85	7%	528	3259
Yang –Gravel (1984)	0.03	1%	505	0.29	24%	1703	0.66	53%	523	0.89	81%	528	3259

Note: R = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 3 Range of application of median sediment particle size

Author of formula	Median particle diameter (mm)
Ackers & White (1973)	0.065-32 (coarse silt - coarse gravel)
Einstein Bed Load (1950)	0.25-32 (medium sand - coarse gravel)
Einstein Bed Material (1950)	0.0625-32 (coarse silt - coarse gravel)
Engelund & Hansen (1967)	0.0625-32 (coarse silt -coarse gravel)
Kalinske (1947)	0.0625-2 (coarse silt - coarse sand)
Laursen (1958)	0.0625-2 (coarse silt - coarse sand)
Meyer-Peter & Müller (1948)	2.0-32 (very coarse sand - coarse gravel)
Rottner (1959)	0.0625-2 (coarse silt - very coarse sand)
Schoklitsch (1934)	0.25-32 (median sand - very coarse gravel)
Toffaleti (1968)	0.25-32 (median sand - coarse gravel)
Yang (Sand) (1973)	0.0625-2.0 (coarse silt - very coarse sand)
Yang (Sand) (1979)	0.0625-2.0 (coarse silt - very coarse sand)
Yang (Gravel) (1984)	2.0-32 (very coarse sand - coarse gravel)

Table 4 Applicability test of formulas according to relative depth D/d (using applicable data)

Author of formula	D/d=4.0-50			D/d=50-200			D/d=200-1000			D/d=1000-50000			N_T
	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	
Ackers & White (1973)	1.27	75%	589	1.08	94%	1561	1.05	90%	646	1.28	79%	436	3232
Einstein (Bed Load) (1950)	2.10	32%	624	1.66	52%	1521	1.46	50%	448	0.76	46%	186	2779
Einstein (Bed Material) (1950)	2.17	31%	624	1.60	52%	1577	1.41	62%	647	0.55	68%	436	3284
Engelund & Hansen (1967)	1.68	73%	624	1.23	85%	1577	1.17	91%	647	0.82	83%	436	3284
Kalinske (1947)	3.76	11%	289	2.20	28%	1385	1.65	38%	621	1.28	46%	436	2731
Laursen (1958)	1.74	68%	266	1.31	81%	1356	1.23	84%	618	1.22	86%	436	2676
Meyer-Peter & Müller (1948)	0.63	71%	136	0.52	55%	150	0.68	68%	22	-	-	0	308
Rottner (1959)	4.46	9%	289	2.06	33%	1385	1.57	59%	621	0.70	69%	436	2731
Schoklitsch (1934)	1.25	81%	237	1.02	86%	931	0.74	80%	401	0.71	68%	181	1750
Toffaleti (1968)	1.56	49%	624	0.52	42%	1521	0.37	32%	448	0.32	30%	186	2779
Yang-Sand (1973)	1.24	86%	289	1.10	90%	1385	1.06	93%	621	1.02	95%	436	2731
Yang-Sand (1979)	1.25	85%	289	1.04	93%	1385	1.01	96%	621	1.00	97%	436	2731
Yang –Gravel (1984)	0.83	79%	264	0.96	83%	238	0.82	84%	26	-	-	0	528

Note: R = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 5 Applicability test of formulas according to Froude number Fr (using applicable data)

Author of formula	Fr=0.10-0.40			Fr=0.40-0.80			Fr=0.80-1.20			Fr=1.20-3.60			N_T
	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	R: $\bar{R}$	R: 0.5-2.0	N	
Ackers & White (1973)	1.09	88%	641	1.08	94%	1349	1.11	84%	644	1.33	78%	597	3231
Einstein (Bed Load) (1950)	1.12	62%	421	2.23	42%	1237	1.93	49%	564	0.56	44%	557	2779
Eistein (Bed Material) (1950)	0.88	47%	647	1.90	50%	1387	2.22	49%	653	0.63	66%	597	3284
Engelund & Hansen (1967)	1.61	80%	647	1.27	83%	1387	1.14	87%	653	0.93	85%	597	3284
Kalinske (1947)	1.44	44%	639	1.91	35%	1162	2.34	24%	424	3.13	13%	506	2731
Laursen (1958)	1.39	69%	611	1.33	84%	1138	1.32	88%	421	1.21	84%	506	2676
Meyer-Peter & Müller (1948)	-	-	0	0.68	72%	94	0.54	60%	174	0.52	55%	40	308
Rottner (1959)	0.51	31%	659	3.25	39%	1142	2.48	44%	424	0.64	62%	506	2731
Schoklitsch (1934)	1.29	80%	47	1.16	85%	611	0.87	82%	537	0.78	79%	555	1750
Toffaleti (1968)	0.34	32%	421	0.55	40%	1237	0.76	47%	564	1.32	45%	557	2 779
Yang-Sand (1973)	1.18	88%	659	1.07	91%	1142	1.04	92%	424	1.02	95%	506	2 731
Yang-Sand (1979)	1.14	90%	659	1.03	93%	1142	1.01	96%	424	0.99	97%	506	2731
Yang-Gravel (1984)	0.74	75%	8	0.86	79%	216	0.91	82%	263	0.94	87%	41	528

Note: R_D = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 6 Applicability test of formulas according to relative shear velocity U_*/ω (using applicable data)

Author of formula	U_*/ω =0.18-0.40			U_*/ω =0.40-1.00			U_*/ω =1.00-2.50			U_*/ω =2.50-15.0			N_T
	R		N	R		N	R		N	R		N	
	$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		
Ackers & White (1973)	1.30	80%	1030	0.97	96%	1237	1.06	90%	552	1.32	80%	412	3231
Einstein (Bed Load) (1950)	2.00	35%	1081	1.42	58%	1229	1.53	43%	461	0.65	45%	28	2799
Einstein (Bed Material) (1950)	2.07	33%	1081	1.47	57%	1239	1.33	74%	552	0.57	58%	412	3284
Engelund & Hansen (1967)	1.64	76%	1081	1.08	89%	1239	1.11	86%	552	0.92	84%	412	3284
Kalinske (1947)	3.38	11%	640	1.97	31%	1127	1.51	40%	552	1.21	52%	412	2731
Laursen (1958)	1.49	74%	601	1.28	82%	1115	1.26	84%	548	1.25	85%	412	2676
Meyer-Peter & Müller (1948)	0.60	65%	212	0.55	60%	93	-	-	0	-	-	0	305
Rottner (1959)	3.54	13%	640	2.20	44%	1127	0.82	73%	552	0.55	41%	412	2731
Schoklitsch (1934)	1.27	82%	372	0.91	85%	910	0.80	77%	441	0.63	65%	27	1750
Toffaleti (1968)	1.12	49%	1081	0.48	38%	1229	0.39	30%	461	0.30	28%	28	2799
Yang-Sand (1973)	1.17	88%	640	1.06	92%	1127	1.05	93%	552	1.01	94%	412	2731
Yang-Sand (1979)	1.14	90%	640	1.03	94%	1127	1.01	96%	552	0.98	95%	412	2731
Yang-Gravel (1984)	0.88	80%	386	0.92	84%	142	-	-	0	-	-	0	528

Note: R_D = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 7 Applicability test of formulas according to dimensionless unit stream power VS/ω

Author of formula	VS/ω =0.0005-0.01			VS/ω =0.01-0.05			VS/ω =0.05-0.1			VS/ω =0.1-2.5			N_T
	R		N	R		N	R		N	R		N	
	$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		
Ackers &White (1973)	1.18	87%	847	1.09	90%	1141	1.02	94%	505	1.23	81%	738	3231
Einstein (Bed load) (1950)	2.21	43%	897	1.69	43%	1105	1.39	60%	361	0.67	54%	416	2779
Eistein (bed material) (1950)	2.22	42%	897	1.70	49%	1144	1.38	67%	505	0.54	59%	738	3284
Engelund &Hansen (1967)	1.57	73%	897	1.23	87%	1144	1.18	90%	505	0.94	87%	738	3284
Kalinske (1947)	3.63	11%	513	2.15	29%	986	1.57	36%	494	1.30	46%	738	2731
Laursen (1958)	1.65	72%	476	1.25	83%	971	1.27	82%	491	1.23	84%	738	2676
Meyer-Peter & Müller (1948)	0.63	68%	176	0.53	59%	121	0.46	37%	8	-	-	0	305
Rottner (1959)	4.18	11%	513	2.17	41%	986	1.44	62%	494	0.58	52%	738	2731
Schoklitsch (1934)	1.29	83%	121	1.09	87%	904	0.82	82%	314	0.66	71%	411	1750
Toffaleti (1968)	1.31	47%	897	0.50	40%	1105	0.37	37%	361	0.31	32%	416	2779
Yang (Sand) (1973)	1.21	85%	513	1.08	91%	986	1.05	92%	494	1.02	95%	738	2731
Yang (Sand) (1979)	1.22	84%	513	1.02	96%	986	1.01	95%	494	0.98	97%	738	2731
Yang (Gravel) (1984)	0.85	78%	334	0.96	86%	1891	0.92	91%	11	-	-	0	528

Note: R_D = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 8 Applicability test of formulas according to sediment concentration C (using applicable data)

Author of formula	C=10.0-100ppm			C=100-1000ppm			C=1000-10000ppm			C=10000-200000			N_T
	R		N	R		N	R		N.	R		N.	
	$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		$\bar{R}$	0.5-2.0		
Ackers &White (1973)	1.22	78%	480	1.14	87%	1211	1.05	94%	1152	1.26	85%	388	3231
Einstein (Bed Load) (1950)	2.39	28%	505	1.49	47%	1185	1.58	54%	993	0.77	57%	116	2799
Eistein (Bed Material) (1950)	2.44	24%	521	1.51	55%	1223	1.49	61%	1152	0.50	54%	388	3284
Engelund & Hansen (1967)	1.55	74%	521	1.39	84%	1223	1.09	88%	1152	0.88	82%	388	3284
Kalinske (1947)	4.72	7%	204	2.28	28%	1079	1.71	36%	1060	1.24	41%	388	2731
Laursen (1958)	1.86	71%	178	1.34	80%	1052	1.20	84%	1058	1.34	81%	388	2676
Meyer-Peter & Müller (1948)	0.66	73%	77	0.59	64%	109	0.53	57%	112	0.57	61%	7	305
Rottner (1959)	4.25	12%	204	2.19	35%	1079	1.82	46%	1060	0.68	67%	388	2731
Schoklitsch (1934)	1.29	81%	96	1.11	85%	662	0.84	83%	878	0.66	58%	114	1750
Toffaleti (1968)	1.49	49%	505	0.66	42%	1185	0.42	37%	993	0.32	28%	116	2799
Yang-Sand (1973)	1.28	85%	204	1.09	89%	1079	1.06	93%	1060	1.02	95%	388	2731
Yang-Sand (1979)	1..30	83%	204	1.05	92%	1079	1.01	96%	1060	0.99	97%	388	2731
Yang-Gravel (1984)	0.78	76%	203	0.91	83%	181	1.03	87%	137	0.91	86%	7	528

Note: R_D = Discrepancy ratio; $\bar{R}$ = Average discrepancy ratio; N = Number of data sets; N_T = Total number of data.

Table 9 Comparison of equations of Yang (19973) and Yang (1979) for sand transport

Author of formula	C=10.0-40.0ppm			C=40.0-70.0ppm			C=70.0-100.0ppm		
	Discrepancy ratio		Number of data sets	Discrepancy ratio		Number of data sets	Discrepancy ratio		Number of data sets
	Mean	0.5-2.0		Mean	0.5-2.0		Mean	0.5-2.0	
Yang (1973)	1.46	80%	37	1.30	84%	58	1.21	87%	109
Yang (1979)	1.52	73%	37	1.33	80%	58	1.21	88%	109
	C=100-1000ppm			C=1000-10000			C=10000-200000		
Yang (1973)	1.09	89%	1079	1.06	93%	1060	1.02	95%	388
Yang (1979)	1.09	92%	1079	1.01	96%	1060	0.99	97%	388

Table 10 Summary of comparison of accuracy of formulas in their applicable ranges

Author of Formula	Discrepancy ratio		Number of Data sets
	Mean	Percent of data in range between 0.5 and 2.0	
For coarse silt to very coarse sand, d_{50} = 0.0625 mm – 2 mm			
Yang (1979)	1.04	94	2731
Yang (1973)	1.08	91	2731
Ackers & Whte (1973)	1.11	90	2696
Engelund & Hansen 91967)	1.17	93	2731
Laursen (1958)	1.32	81	2676
Einstein Bed Material (1950)	1.34	58	2731
Rottner (1959)	1.99	42	2731
Kalinske (1947)	2.09	31	2731
For medium sand to coarse gravel, d_{50} =0.25 mm – 32 mm			
Schoklitsch (1934)	0.85	82	1750
Toffaleti (1968)	0.72	41	2779
Einstein Bed Load (1950)	1.67	47	2779
For very coarse sand to coarse gravel, d_{50} = 2 mm – 32 mm			
Yang (1984)	0.89	81	528
Meyer-Peter & Müller (1948)	0.58	63	308
For coarse silt to coarse gravel, d_{50} = 0.0625 mm – 32 mm			
Yang (1979) & Yang (1984)	1.02	91	3259
Yang (1973) & Yang (1984)	1.05	89	3259
Ackers & White (1973)	1.13	88	3231
England & Hansen (1967)	1.25	84	3284
Einstein Bed Material (1950)	1.53	52	3284

Appendix II

SEDIMENT TRANSPORT FORMULAS USED IN THE PAPER

1 SCHOKLITSCH BEDLOAD FORMULA

Schloklitsch (1934) developed a bedload formula based mainly on Gilbert's (1914) flume data with median sediment sizes ranging from 0.3 to 5 mm. The Schoklitsch formula for unigranular material is:

$$G_s = \frac{86.7}{\sqrt{D}} S^{3/2} (Q - Wq_o) \quad (1)$$

in which

$$q_o = \frac{0.00532D}{S^{4/3}} \quad (2)$$

where G_s = the bedload discharge, in pounds per second (lb/s); D = the mean grain diameter, in inches (in.); S = the energy gradient, in feet (ft) per ft; Q = the water discharge in cubic feet per second (ft^3/s); W = the width, in ft; and q_o = the critical discharge, in ft^3/s per ft of width.

The formula is applied to mixtures by summing the computed bedload discharges for all size fractions; the discharge for each size fraction is computed using the mean diameter and the fraction of the sediment in the size fraction. Converting the equation for use with mixtures and changing the grain diameter from in. to ft and the bedload discharge from lb/s to lb/s per ft of width gives:

$$g_s = \sum_{i=1}^{n} i_b \frac{25}{\sqrt{D_{si}}} S^{3/2} (q - q_o) \quad (3)$$

in which

$$q_o = \frac{0.0638 D_{si}}{S^{4/3}} \quad (4)$$

where g_s = the bedload discharge, in lb/s per ft of width; i_b = the fraction, by weight, of bed material in a given size fraction; D_{si} = the mean grain diameter, in ft, of sediment in size fraction, i; q = the water discharge, in ft^3/s per ft of width; q_o = the critical discharge, in ft^3/s per ft of width, for sediment of diameter D_{si}; and n = the number of size fractions in the bed-material mixture.

2 KALINSKI BEDLOAD FORMULA

The formula developed by Kalinski (1947) for computing bedload discharge of unigranular material is based on the continuity equation which states that the bedload discharge is equal to the product of the average velocity of the particles in motion, the weight of each particle, and the number of particles. The average particle velocity is related to the ratio of the critical shear (critical tractive force) to the total shear.

The formula is:

$$g_s = \sum_{i=1}^{n} V_* \gamma_s D_{si} P_i 7.3 \left(\frac{\overline{U} g}{\overline{U}} \right) \quad (5)$$

in which

$$V_* = \frac{\sqrt{\tau_o}}{\rho}, \qquad \frac{\overline{U} g}{\overline{U}} = f\left(\frac{\tau_{ci}}{\tau_o}\right), \qquad \tau_{ci} = 12 D_{si}, \qquad P_i = \frac{0.35}{m}\left(\frac{i_b}{D_{si}}\right) \quad (6), (7), (8), (9)$$

where g_s = the bedload discharge, in lb/s per ft of width; n = the number of size fractions in the bed-material mixture; V_* = the shear velocity, in feet per second (ft/s); g_s = the specific weight of the sediment in pounds per cubic foot (lb/ft^3); D_{si} = the mean grain diameter, in ft, of sediment in size fraction, i; P_i = the proportion of the bed area occupied by the particles in size fraction, i; $\overline{U} g$ = the average velocity, in ft/s, of particles in size fraction, i; $\overline{U}$ = the mean velocity of flow, in ft/s, at the grain level; τ_o = the total shear at the bed, in pounds per square foots (lb/ft^2), which equals $62.4dS$; d = the mean depth, in ft; S = the energy gradient, in ft per ft; ρ = the density of water, in slugs per ft^3; f = denotes function of; τ_{ci} = the critical tractive force, in lb/ft^2; m = the summation of values of i_b/D_{si}

for all size fractions in the bed-material mixture; and i_b = the fraction, by weight, of bed material in a given size fraction.

Using the values of 165.36 for γ_s and 1.94 for ρ, the formula is:

$$g_s = 25.28\sqrt{\tau_o} \sum_{i=1}^{n} \tau_{ci} \frac{\frac{i_b}{D_{si}}}{m} \left(\frac{\overline{U}_g}{\overline{U}} \right) \quad (10)$$

Values of $\overline{U}g / \overline{U}$ are shown in Kalinske's (1947) Figure 2.

3 MEYER-PETER AND MÜLLER FORMULA

Meyer-Peter and Müller (1948) developed an empirical formula for the bedload discharge in natural streams. The original form of the formula in metric units for a rectangular channel is:

$$\gamma \frac{Q_s}{Q} \left(\frac{K_s}{K_r} \right)^{3/2} dS = 0.047\gamma'_s D_m + 0.25 \left(\frac{\gamma}{g} \right)^{1/3} g_s^{2/3} \quad (11)$$

in which

$$D_m = \sum_{i=1}^{n} D_{si} i_b \quad (12)$$

where g = the specific weight of water and equals 1 metric ton per cubic meter (t/m^3); Q_s = that part of the water discharge apportioned to the bed, in liters per second (l/s); Q = the total water discharge, in l/s; K_s = Strickler's (1923) coefficient of bed roughness, and is equal to one divided by Manning's roughness coefficient (n_s); K_r = the coefficient of partile roughness, and is equal to $26/D_{90}^{1/6}$; D_{90} = the particle size, in meters (m), for which 90 percent of the bed mixture is finer; d = the mean depth, in m; S = the energy gradient, in m per m; γ'_s = the specific weight of sediment under water and equals 1.65 t/m^3 for quartz; D_m = the effective diameter of bed-material mixture, in m; g = the acceleration of gravity and equals 9.815 meters per second per second (m/s/s); g_s = the bedload discharge measured under water, in metric tons per second (t/s) per meter (m) of width; n = the number of size fractions in the bed material; D_{si} = the mean grain diameter, in m, of the sediment in size fraction, i; and i_b = the fraction, by weight, of bed material in a given size fraction.

Converting the formula to English units gives:

$$g_s = \left[0.368 \frac{Q_s}{Q} \left(\frac{D_{90}^{1/6}}{n_s} \right)^{3/2} dS - 0.0698 D_m \right]^{3/2} \quad (13)$$

where g_s = the bedload discharge for dry weight, in lb/s per ft of width; Q_s, Q = sediment and water discharges, in ft^3/s, respectively; D_{90}, D_m = sediment particle diameter at which 90 percent of the material, by weight, is finer, and mean particle diameter, respectively; d = water depth in feet; and n_s = Manning's roughness value for the bed of the stream.

The computer program computes the effective diameter of the bed-material mixture, D_m, from the entered sediment size-fraction data. However, the program does not compute the bedload discharge by size fractions.

4 ROTTNER BEDLOAD FORMULA

Rottner (1959) developed an equation to express bedload discharge in terms of the flow parameters based on dimensional considerations and empirical coefficients. Rottner applied a regression analysis to determine the effect of a relative roughness parameter D_{50}/d. Rottner's equation is dimensionally homogenous so that it can be presented directly in English units.

$$g_s = \gamma_s \left[(S_g - 1) g d^3 \right]^{1/2} \left\{ \frac{V}{\sqrt{(S_g - 1) g d}} \left[0.667 \left(\frac{D_{50}}{d} \right)^{2/3} - 0.14 \right] - 0.778 \left(\frac{D_{50}}{d} \right) \right\} \quad (14)$$

where g_s = the bedload discharge, in lb/s per ft of width; g_s = the specific weight of sediment, in lb/ft^3; S_g = the specific gravity of the sediment; g = the acceleration of gravity, in feet per second per second (ft/s/s); d = the mean depth, in ft; V = the mean velocity, in ft/s; and D_{50} = the particle size, in ft, at which 50 percent of the bed material by weight is finer.

In his derivation, wall and bed form effects were excluded, and Rottner stated that the equation may not be applicable when small quantities of bed material are being moved.

5 EINSTEIN BEDLOAD FORMULA

The bedload retention developed by Einstein (1950) is derived from the concept of probabilities of particle motion. A complete description of the complex procedure will not be presented here.

6 LAURSEN BED-MATERIAL LOAD FORMULA

The equation developed by Laursen (1958) to compute the mean concentration of bed-material discharge is based on empirical relations:

$$\bar{C} = \sum_{i=1}^{n} i_b \left(\frac{D_{si}}{d}\right)^{7/6} \left(\frac{\tau_o}{\tau_c} - 1\right) f\left(\frac{V_*}{\omega_i}\right) \tag{15}$$

in which

$$\tau'_o = \frac{\rho V^2}{58}\left(\frac{D_{50}}{d}\right)^{1/3}, \qquad \tau_c = Y_c \rho g (S_g - 1) D_{si} \qquad (16), (17)$$

where $\bar{C}$ = the concentration of bed-material discharge, in percent by weight; n = the number of size fractions in the bed material; i_b = the fraction, by weight, of bed material in a given size fraction; D_{si} = the mean grain diameter, in ft, of the sediment in size fraction, i; d = the mean depth, in ft; τ'_o = Laursen's bed shear stress due to grain resistance; τ_c = critical shear stress for particles of a size fraction; f = denotes function of; V_* = the shear velocity, in ft/s; ω_i = the fall velocity, in ft/s, of sediment particles of diameter D_{si}; ρ = the density of water, in slugs per ft^3; V = the mean velocity, in ft/s; D_{50} = the particle size, in ft, at which 50 percent of the bed material by weight is finer; Y_c = a coefficient relating critical tractive force to sediment size; g = acceleration of gravity, in ft/s/s; and S_g = the specific gravity of sediment.

The density, ρ, has been introduced into the original τ'_o equation presented by Laursen so that the equation is dimensionally homogeneous, and Laursen's coefficient has been changed accordingly.

Substituting for τ'_o and τ_c in equation 15 and converting $\bar{C}$ to C gives:

$$C = 10^4 \sum_{i=1}^{n} i_b \left(\frac{D_{si}}{d}\right)^{7/6} \left[\frac{V^2}{58 Y_c D_{si} (S_g - 1) g d}\left(\frac{D_{50}}{d}\right)^{1/3} - 1\right] f\left(\frac{V_*}{\omega_i}\right) \tag{18}$$

where C = the concentration of bed-material discharge, in parts per million by weight. Values of $f(V_*/\omega_i)$ are shown in Laursen's (1958) Figure 14.

7 ENGELUND AND HANSEN BED-MATERIAL LOAD FORMULA

Engelund and Hansen (1967) applied Bagnold's (1966) stream power concept and the similarity principle to derive the following sediment transport equation:

$$f'\phi = 0.1\theta^{5/2} \tag{19}$$

in which

$$f' = \frac{2gSd}{V^2}, \qquad \phi = \frac{g_s}{\gamma_s (S_g - 1) g D_{50}^3}, \qquad \theta = \frac{dS}{(S_g - 1) D_{50}} \qquad (20), (21), (22)$$

where f' = the friction factor; ϕ = the dimensionless sediment discharge; θ = a dimensionless shear parameter; g = the acceleration of gravity, in ft/s/s; S = the energy gradient, in ft per ft; d = the mean depth, in ft; V = the mean velocity, in ft/s; g_s = the bed-material discharge, in lb/s per ft of width; D_{50} = the particle size, in ft, at which 50 percent of the bed material by weight is finer; S_g = the specific gravity of the sediment; and γ_s = the specific weight of sediment, in lb/ft^3. Substituting for f', ϕ, and θ in equation 19 gives:

$$g_s = \frac{0.05\gamma_s V^2 d^{1/2} S^{3/2}}{D_{50} g (S_g - 1)^2} \quad (23)$$

8 COLBY BED-MATERIAL LOAD FORMULA

Colby (1964) presented a graphical method to determine the discharge of sand size bed material that ranged from 0.1 to 0.8 mm.

The bed-material discharge (g_s), in lb/s per ft of width, at a water temperature of 15.6 degrees Celsius (°C) (Colby's 1964 Figure 6) is

$$g_s = A(V - V_c)^B 0.672 \quad (24)$$

in which

$$V_c = 0.4673 d^{0.1} D_{50}^{0.33} \quad (25)$$

where V = the mean velocity, in ft/s; V_c = the critical velocity, in ft/s; d = the mean depth, in ft; D_{50} = the particle size, in mm, at which 50 percent of the bed material by weight is finer; A = a coefficient; and B = an exponent.

9 ACKERS AND WHITE BED-MATERIAL LOAD FORMULA

Ackers and White (1973) developed a general sediment-discharge function in terms of three dimensionless groups: D_{gr} (size), F_{gr} (mobility), and G_{gr} (discharge). The dimensionless grain diameter, D_{gr}, is expressed as:

$$D_{gr} = D_{50}\left[\frac{g(S_g - 1)}{\nu^2}\right]^{1/3} \quad (26)$$

where D_{50} = the particle size, in ft, at which 50 percent of the bed material by weight is finer; g = the acceleration of gravity, in ft/s/s; S_g = the specific gravity of the sediment; and υ = the kinematic viscosity, in ft²/s.

They defined a dimensionless mobility number, F_{gr}, as:

$$F_{gr} = \frac{V_*^n}{\sqrt{g D_{50}(S_g - 1)}}\left[\frac{V}{\sqrt{32}\log\left(\frac{\alpha d}{D_{50}}\right)}\right]^{1-n} \quad (27)$$

where d = the mean depth, in ft; V_* = the shear velocity, in ft/s; V = the mean velocity, in ft/s; α = the coefficient in the rough turbulent equation with a value of 10; and n = the transition exponent depending on sediment size.

Then they developed the following dimensionless expression for general sediment transport, G_{gr}, based on Bagnold's (1966) stream power concept:

$$G_{gr} = \frac{Xd}{S_g D_{50}}\left(\frac{V_*}{V}\right)^n \quad (28)$$

where X = the sediment-discharge concentration expressed as the mass flux per unit of mass flow rate. Transposing the equation to solve for X, and converting X to C gives:

$$C = 10^6 \frac{G_{gr} S_g D_{50}\left(\frac{V}{V_*}\right)^n}{d} \quad (29)$$

where C = the concentration of bed-material discharge, in parts per million by weight.

Using flume data from other investigators, Ackers and White developed a general transport function, G_{gr}, and evaluated the associated coefficients. The equation is:

$$G_{gr} = C_A\left(\frac{F_{gr}}{A} - 1\right)^m \quad (30)$$

where A = the value of the Froude number at nominal initial motion; m = the exponent in the sediment transport function; and C_A = the coefficient in the sediment transport function.

10 YANG BED-MATERIAL LOAD FORMULA FOR SAND

Yang (1973) derived an equation to compute concentration of the bed-material discharge, for sand bed streams, based on dimensionless analysis and the concept of unit stream power. He defined unit stream power as the rate of potential energy dissipated per unit weight of water, which is expressed by the velocity and slope product, VS. Yang's 1973 dimensionless unit stream power equation is:

$$\log C = 5.435 - 0.286\log\frac{\omega D_{50}}{v} - 0.457\log\frac{V_*}{\omega} + \left(1.799 - 0.409\log\frac{\omega D_{50}}{v} - 0.314\log\frac{V_*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (31)$$

in which the dimensionless critical velocity at incipient motion can be expressed as:

$$\frac{V_{cr}}{\omega} = \frac{2.5}{\log\frac{V_* D_{50}}{v} - 0.06} + 0.66 \quad for \quad 1.2 < \frac{V_* D_{50}}{v} \leq 70 \quad (32)$$

and

$$\frac{V_{cr}}{\omega} = 2.05 \quad for \quad 70 \leq \frac{V_* D_{50}}{v} \quad (33)$$

where C = the concentration of bed-material discharge, in parts per million by weight; ω = the average fall velocity, in ft/s, of sediment particles of diameter D_{50}; D_{50} = the particle size, in ft, at which 50 percent of the bed material by weight is finer; v = the kinematic viscosity, in ft^2/s; V_* = the shear velocity, in ft/s; V = the average velocity, in ft/s; S = the energy slope, in ft/ft; and V_{cr} = the average flow velocity, in ft/s, at incipient motion.

The total bed-material discharge concentration for the graded material is obtained from:

$$C = \sum_{i=1}^{n} i_b C_i \quad (34)$$

where n = the number of size fractions in the bed material; i_b = the fraction, by weight, of bed material in a given size fraction; and C_i = the computed concentration in the size fraction, i.

Yang's 1979 dimensionless unit stream power formula for sand without the consideration of incipient motion criteria is:

$$\log C = 5.165 - 0.153\log\frac{\omega D_{50}}{v} - 0.297\log\frac{V_*}{\omega} + \left[1.780 - 0.360\log\frac{\omega D_{50}}{v} - 0.480\log\frac{V_*}{\omega}\right]\log\frac{VS}{\omega} \quad (35)$$

Equation 34 is used in conjunction with equation 35 for graded materials.

11 YANG BED-MATERIAL FORMULA FOR GRAVEL

Yang (1984), using the same dimensional analysis and multiple regression methods as was used to derive discharge rates in sand bed streams (Yang, 1973), derived a gravel equation to compute the bed-material discharge concentration, in gravel bed streams. The same definition of unit stream power is used in both the sand and gravel transport equations. Yang's dimensionless unit stream power equation for gravel transport is:

$$\log C = 6.681 - 0.633\log\frac{\omega D_{50}}{v} - 4.816\log\frac{V_*}{\omega} + \left[2.784 - 0.305\log\frac{\omega D_{50}}{v} - 0.282\log\frac{V_*}{\omega}\right]\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \quad (36)$$

in which the dimensionless critical velocity at incipient motion is the same as that for sand transport. The total bed-material discharge concentration, C, for the graded material is based on equation 34.

12 EINSTEIN BED-MATERIAL LOAD FORMULA

Einstein (1950) presented a method to combine his computed bedload discharge with a computed suspended bed-material discharge to yield the total bed-material discharge. A complete description of the complex procedure will not be presented here.

13 TOFFALETI FORMULA

The procedure to determine bed-material discharge developed by Toffaleti (1968) is based on the concepts of Einstein (1950) with three modifications: (1) velocity distribution in the vertical is obtained from an expression different from that used by Einstein; (2) several of Einstein's correction factors are adjusted and combined; and (3) the height of the zone of bedload transport is changed from Einstein's two grain diameters. Toffaleti defines his bed-material discharge as total river sand discharge even though he defines the range of bed-size material from 0.062 to 16 mm. The complex procedures used in the Toffaleti formula will not be presented here.