User's Manual for

GSTARS4

(Generalized Sediment Transport model for Alluvial River Simulation version 4.0)

by

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CHAPTER 1

INTRODUCTION

GSTARS4 (Generalized Sediment Transport model for Alluvial River Simulation version 4.0) 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 Hydroscience and Training Center of Colorado State University. It is an enhanced version of the GSTARS3 model (Yang and Simões, 2002). 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 GSTARS4 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 capacity 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 have the capability of computing both steady and truly unsteady flow;
• 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 4.0 is based on GSTARS version 3.0 (Yang and Simões, 2002) and SRH-1D (Sediment and River Hydraulics –One dimension) (Huang and Greimann, 2007). GSTARS4 adopted unsteady flow computational scheme and method from SRH-1D with some revisions. For other capabilities, such as steady/quasi-steady flow computation sediment calculation, and channel geomorphic changes, GSTARS4 uses almost the same method that used for GSTARS3 with some modifications.

GSTARS4 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, GSTARS4 can handle irregular cross sections regardless of whether single channel or multiple channels separated by small islands or sand bars. The major update was made for hydraulic calculation. Previous GSTARS models, GSTARSRS 1.0, 2.0, 2.1, and 3.0, have the capability of steady or quasi-steady hydraulic computation whereas GSTARS4 can simulate both steady and truly unsteady flow. The numerical scheme used for unsteady computation was adopted from GSTAR-1D 1.0 (Yang, et al 2004) and SRH-1D (Hung and Greimann, 2007) unsteady flow modules. SRH-1D is an improved and enhanced model of GSTAR-1D 1.0 supported by the U.S. Bureau of Reclamation. Unsteady flow computations in GSTARS4 are based on SRH-1D.

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 GSTARS4 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 Muller'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.

GSTARS4 uses the same numerical scheme as that in GSTARS3 for sediment routing part with some minor revisions.

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 GSTARS4. 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. For the use of theory of minimum energy dissipation rate, GSTARS4 is the same as the previous GSTARS3 model.

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. GSTARS3 and GSTARS4 use identical procedure for the calculation of bank side stability.

Some of the potential applications and/or features of GSTARS4 are:

- GSTARS4 can be used for water surface profile computations with or without sediment transport by using steady and unsteady scheme.

• GSTARS4 can compute water surface profiles through subcritical and supercritical flow conditions, including hydraulic jumps, without interruption.
• GSTARS4 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.
• GSTARS4 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 GSTARS4

GSTARS4 is based on GSTARS3 with the following modifications and improvements:

• Unsteady flow simulation was added.
• More options for non-equilibrium sediment transport were added.
• Input option of percentage of washload were expanded in case of high sediment concentration laden flows.
• Spatial variation of bed material density can be applicable.
• More options for gradation of incoming sediment from the upstream boundary.
• Water and sediment exchanges between the main channel and tributaries were added.
• Another output file for water and sediment discharges at the downstream boundary is added for other uses, such as downstream impact routing.
• Expanded user's manual

Although most data files prepared for GSTARS3 are fully compatible with GSTARS4, only a few exceptions exist. Therefore, conversion of data files from GSTARS3 to GSTARS4 is easy and straightforward.

1.2 Limits of Application

GSTARS4 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 GSTARS4 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. GSTARS4 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, GSTARS4 should be adequate for solving many river engineering problems.

2. GSTARS4 is based on the stream tube concept. Secondary currents are empirically accounted for. The phenomena of diffusion, and super elevation are ignored.
3. Many of the methods and concepts used in GSTARS4 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. Most parts of the GSTARS4 User's Manual are identical to those in GSTARS3 because the former is based on the latter except reservoir routing and tributary routing were improved and enhanced..
Chapter 2 describes the hydraulic calculations with additional explanations on unsteady flow scheme, and chapter 3 describes the basis of the sediment routing model, including the use of the stream tube concept with some more explanations of new capability of GSTARS4 model. 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. Chapter 4 and chapter 5 are the same as those of GSTARS3. Finally, the main data requirements for GSTARS4 are discussed in chapter 6 with some additions for the new capability. The appendices provide additional information: appendix A gives a detailed description of the input records used by GSTARS4 and new capability are clear stated; 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 GSTARS4; 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 GSTARS4

The latest information about the GSTARS4 program is placed on the World Wide Web. The deleat the unnecessary space between words GSTARS4 Web page can be found by going to www.engr.colostate.edu/ce/facultystaff/yang and following the links therein.
All questions regarding GSTARS4 should be sent to the first author. Dr. Chih Ted Yang is the Director of Hydroscience and Training Center at Colorado State University, Fort Collins, CO 80523 (ctyang@engr.colostate.edu). Request can also be sent to the first author directly (yangco08@gmail.com).
GSTARS4 is in a stage of continuous evolution and unannounced changes may be made at any time. The user is encouraged to check regularly the GSTARS4 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 by the Hydroscience and Training Center (HTC) at Colorado State University. HTC does not guarantee the performance of the program, nor help external users solve their problems.

HTC assumes no responsibility for the correct use of GSTARS4 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. GSTARS4 is a complex program that requires engineering expertise to be used correctly. Like any computer program, GSTARS4 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. HTC and the GSTARS4 manual authors will not be liable for any special, collateral, incidental, or consequential damages in connection with the use of the software.

CHAPTER

2

THE HYDRAULIC COMPUTATION

The hydraulic computations in GSTARS4 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. GSTARS4 model has capability of both steady and unsteady flow simulations. This section presents the basic governing equations for flow computations.

Steady or quasi steady computation in GSTARS4 model is the same as that of GSTARS3. 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 and GSTARS4 solve 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. Governing equations and numerical schemes for steady or quasi-steady simulations are explained in section 2.1. Section 2.1.4 (b) provides additional explanations of GSTARS4 capacities. The explanations are similar to those shown in the GSTARS3 User's Manual.

For unsteady hydraulic routing, GSTARS4 model uses unsteady computation scheme of SRH-1D with some revisions. Section 2.2 includes explanations on the unsteady flow solutions and most explanations on unsteady flow solution in this section can also be found in SHR-1D (Huang and Greimann,2007).

2.1 Steady Flow Computation
2.1.1 Energy Equation
Using the notation of figure 2.2, the energy equation can be written as

$$z + Y + \alpha_v \frac{V^2}{2g} = H \tag{2.1}$$

where z = bed elevation; Y = water depth; V = flow velocity; α_v = velocity distribution coefficient; H = elevation of the energy line above the datum; and g = gravitational acceleration. Eq. (2.1) 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.

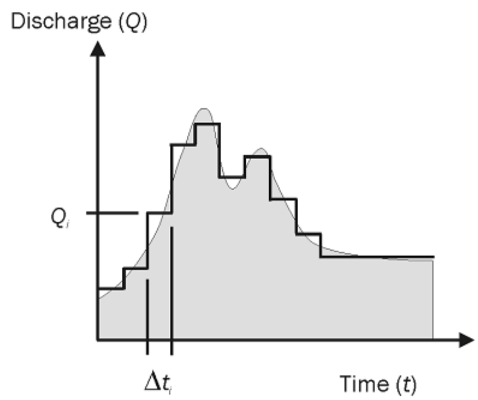

Figure 2.1 Representation of a hydrograph by a series of steps with constant discharge (Q_i) and finite duration (Δt_i).

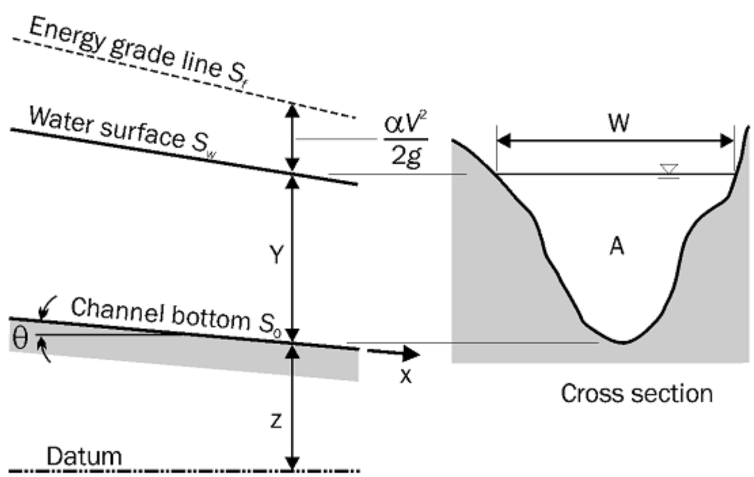

Figure 2.2 Definition of variables

All the figures and tables should be in black and white.

Eq. (2.1) 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

$$Z = \tilde{Z} - \frac{H - \tilde{H}}{1 - \tilde{F}_r (1 \mp 0.5 C_L) \mp \frac{3\tilde{h}_f}{2\tilde{R}}} \tag{2.2}$$

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 $\left|H - \tilde{H}\right|$ is very small (say, $\left|H - \tilde{H}\right| < 0.01$ ft). Note that $\tilde{H}$ is computed using Eq. (2.1), 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

$$F_r^{\,2} = \frac{\alpha V^2}{g W \cos\theta} \tag{2.3}$$

where W = cross section width.

2.1.2 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, GSTARS4 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 a 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 a hydraulic jump is detected, the momentum equation is used:

$$\frac{Q\gamma}{g}(\beta_2 V_2 - \beta_1 V_1) = p_1 - p_2 + W_g \sin\theta - F_f \tag{2.4}$$

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 $\beta_1 = \beta_2 = 1$, Eq. (2.4) becomes

$$\frac{Q^2}{A_1 g} + A_1 \overline{y_1} = \frac{Q^2}{A_2 g} + A_2 \overline{y_2} \tag{2.5}$$

where $\overline{y}$ = depth measured from water surface to the centroid of the cross section containing flow. Eq. (2.5) is solved by an iterative trial-and-error procedure.

2.1.3 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

$$g(D) = Q - K(Y)\sqrt{S_0} = 0 \tag{2.6}$$

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 and GSTARS4, the critical depth is calculated by satisfying equation

$$F(D) = 1 - \alpha_v(Y)\frac{Q^2 W(Y)}{gA^3(Y)} = 0 \tag{2.7}$$

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

$$SF(Y) = \frac{Q^2}{A_t g} + A_m \overline{y} \tag{2.8}$$

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 and GSTARS4, 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

$$SF(Z_a) - SF(Z_b) = 0 \tag{2.9}$$

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

2.1.4 Model Representation

In GSTARS4, 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.

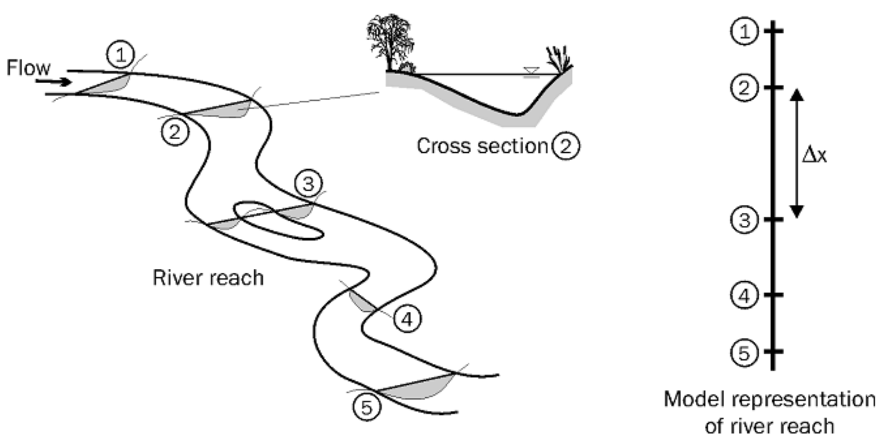

Figure 2.3 Conceptual representation of a river reach by discrete cross sections in GSTARS4

GSTARS4 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 GSTARS4.

(a) Description of Cross Sections

When setting up a GSTARS4 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, topwidth, 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 GSTARS4 will work better if more points are given. This will become clearer later, when the usage of stream tubes in GSTARS4 is presented.

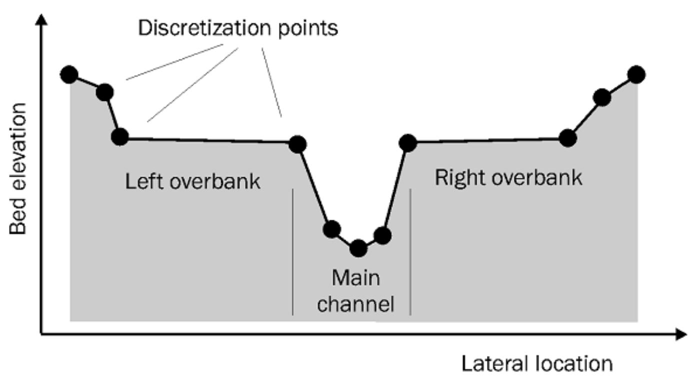

Figure 2.4 Representation of a cross section by a discrete set of points

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.

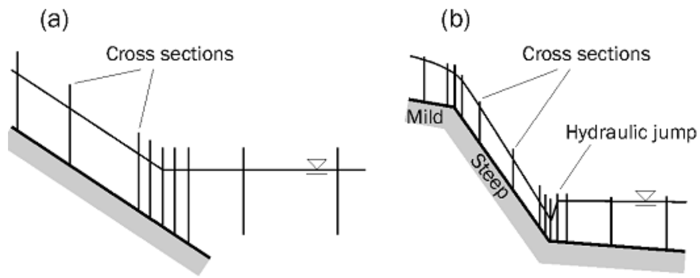

Figure 2.5 Examples of reduction of x at points where the gradients are high: (a) backwater pool, and (b) change in bottom slope and flow regime transition

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).

(b) Flow Resistance

One of the fundamental assumptions in GSTARS4 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:

$$S_f = \left(\frac{Q}{K}\right)^2 \tag{2.10}$$

In GSTARS4, any of the following formulae can be used to compute K:

Manning's formula:

$$Q = KS_f^{1/2} = \left(\frac{1.49}{n} AR^{2/3}\right) S_f^{1/2} \qquad (2.11)$$

Chézy's formula

$$Q = KS_f^{1/2} = \left(CAR^{1/2}\right) S_f^{1/2} \qquad (2.12)$$

or Darcy-Weisbach's formula

$$Q = KS_f^{1/2} = \left[\left(\frac{8gR}{f}\right)^{1/2} A\right] S_f^{1/2} \qquad (2.13)$$

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

$$n = n_0 + n_1 + n_2 + n_3 + n_4 + n_5 \qquad (2.14)$$

Table 2.1 provides 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:

$$h_f = \frac{1}{2}\left(S_{f1} + S_{f2}\right)\Delta x \tag{2.15}$$

From the geometric mean:

$$h_f = \Delta x\sqrt{S_{f1}S_{f2}} \tag{2.16}$$

From the average conveyance:

$$h_f = \left(\frac{2Q}{K_1 + K_2} \right)^2 L\Delta x \tag{2.17}$$

From the harmonic mean:

$$h_f = \left(\frac{2S_{f1}S_{f2}}{S_{f1} + S_{f2}} \right) \Delta x \tag{2.18}$$

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. (2.15) 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

$$h_E = C_E \left| \frac{V_1^2}{2g} - \frac{V_2^2}{2g} \right| \tag{2.19}$$

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

$$h_B = C_B \frac{V_2^{\ 2}}{2g} \tag{2.20}$$

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.

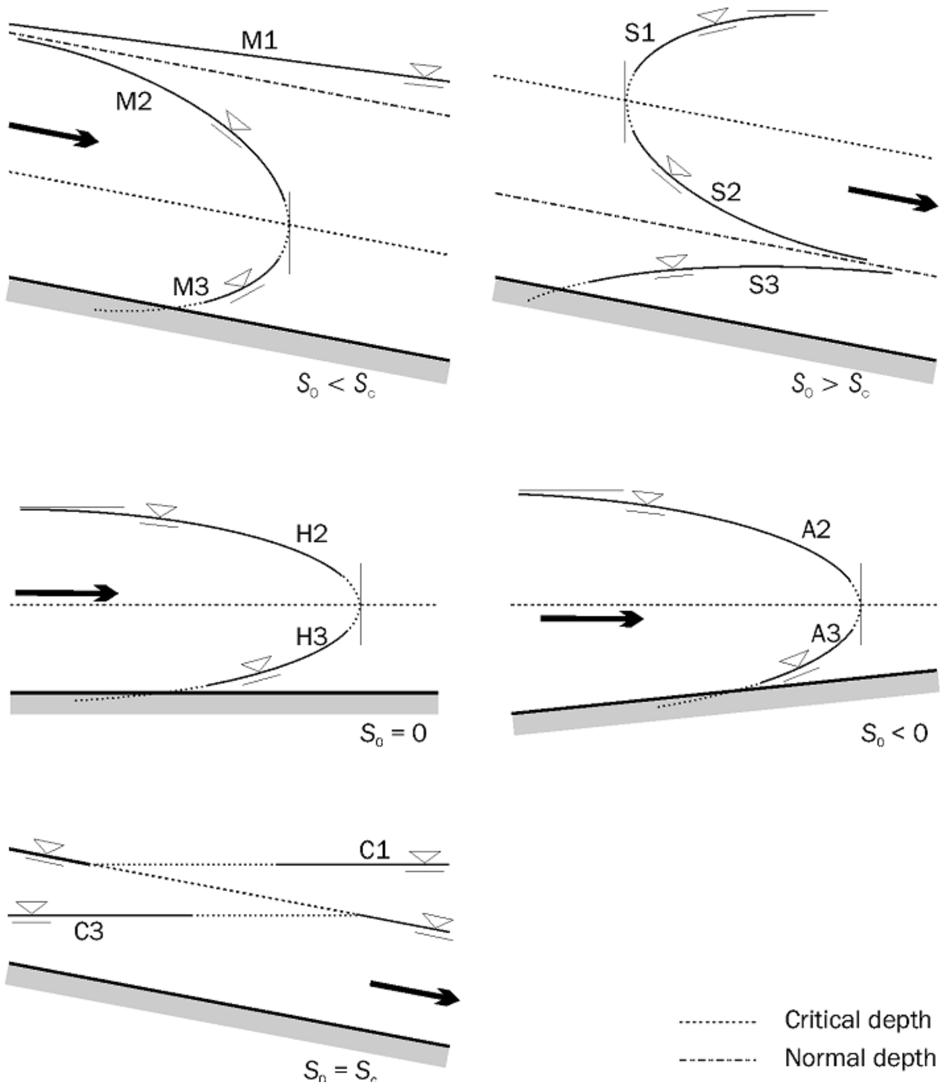

Figure 2.6 Water surface profile types in gradually varied flow

2.1.5 Tributary Influence

2.1.5.1 Table Form of Inflow from Tributaries

Although GSTARS4 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

$$Q_C = Q_A + Q_B \tag{2.21}$$

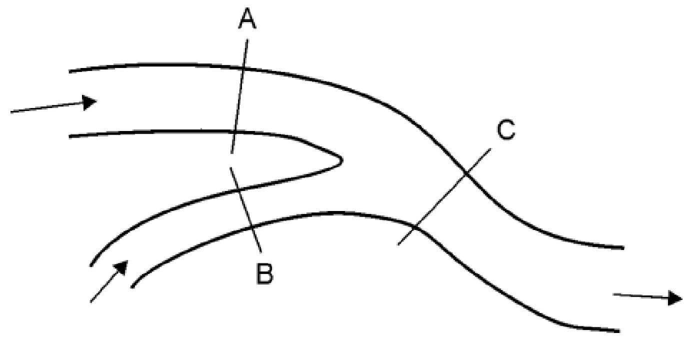

Figure 2.7 Channel junction

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.,

$$\left(z + Y + \alpha_v \frac{V^2}{2g} \right)_A = \left(z + Y + \alpha_v \frac{V^2}{2g} \right)_c + h_f \tag{2.22}$$

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 textbooks, for example, Cunge et al. (1980).

2.1.5.2 Interchanges between a Tributary and the Main Stream

GSTARS4 can simulate water and sediment inflow from tributaries. Not only water and sediment inflow from tributaries but also the volume of a tributary should be considered. If the volume of tributaries are not negligible compared to the total volume of the main stream, volume of tributaries should be included in the simulation. If the inflow of water and sediment of tributaries are very small, compared with those in the main stream, the inflow may be ignored for the routing. The “level pool” concept as shown in figure 2.8 is used to determine the reservoir volume and discharge of tributaries.

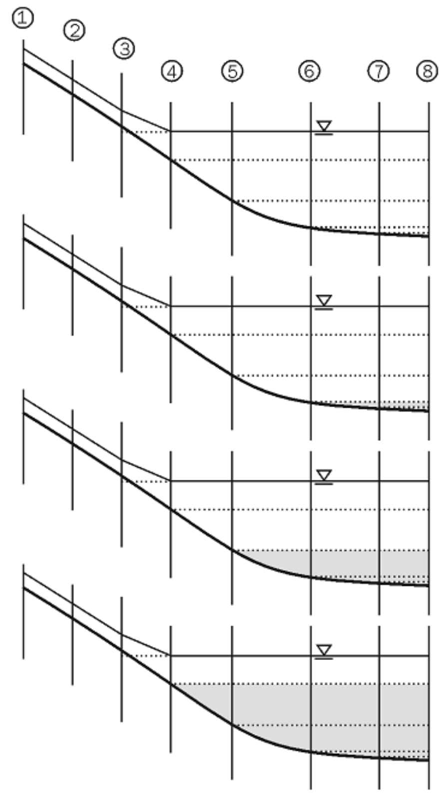

Figure 2.8 Delineation of volumes to build the capacity table for tributaries

During water surface rising stage at the main channel, water flows to tributaries. In other words, direction of lateral flow is from the main stream to tributaries. On the other hand, when water surface draws down, discharge in the reservoir increases because volume of water in tributaries decreases.

GSTARS4 can simulate water and sediment inflow from tributaries and outflow into them. It is required that the amount of water and sediment inflow and outflow with respect to time are provided. In other words, water and sediment discharge table with respect to time, such as hydrograph, should be provided for a given duration. The important aspect is to consider the volume of water and sediment in tributaries. Therefore, tributary impact should be considered with respect to water stage change.

The following simplified assumptions are used for the routing to simulate the interchange of water and sediment between the main stream and a tributary:

1. The tributary mouth bed elevation is the same as that of the main channel at the mouth of the tributary.
2. The sediment concentration and size distribution of a tributary is the same as that in the main stream at the mouth of the tributary.
3. During water surface elevation falling stage in the main channel, tributary water and sediment will be discharged into the main stream.
4. During the sedimentation or silting stage when the main channel water surface elevation is rising, water and sediment will flow into tributaries.
5. The main channel and tributary water surface is horizontal and the discharge of water and sediment into the main river from a tributary is

$$\Delta Q = -\Delta Vol / \Delta t \tag{2.23}$$

where ΔQ = water discharge from a tributary to the main river; ΔVol = change of tributary volume due to the change of the main channel elevation in time Δt as illustrated in figure 2.8. The volume of a tributary depends on water stage and bed elevation at the mouth. Therefore the volume can be computed as follows.

$$Vol = a(h - h_b)^b \tag{2.24}$$

where Vol = volume of water in a tributary; h = water surface; h_b = bed elevation at a tributary mouth; and a and b = coefficients of a tributary.

The value of ΔQ is positive when the water of a tributary is discharged into the main channel during the flushing or water surface elevation falling period. The value of ΔQ is negative when water is discharged from the main stream to a tributary during the sedimentation or filling period when the main channel water elevation is rising. Sediment load to and from a tributary is

$$\Delta Q_s = \Delta Q C_s \tag{2.25}$$

where ΔQ_s = sediment load from or into a tributary; and C_s = sediment concentration at the mouth of a tributary.

To compute ΔQ, water surface elevation should be determined first. The main river routing should be carried out first to determine water surface elevation and sediment concentration at the mouth of each tributary without considering tributaries. Using water surface elevations at the mouth of each tributary, ΔQ and ΔQ_s of each one are calculated. After these processes, main channel routing must be redone to calculate sediment transport and update bed elevation in the main channel using ΔQ and ΔQ_s. This procedure of tributary inflow and outflow computation, which is not included in the previous GSTARS3, is added to GSTARS4.

2.2 Unsteady Computation

GSTARS4 has the capability to simulated unsteady state flows. Unsteady scheme is adopted from SRH-1D with minor revisions. The theoretical back ground used for development of GSTARS4 are based on that of SRH-1D and most of the expressions for this section are directly referring User's Manual of SRH-1D (Huang and Greimann, 2007).

2.2.1 Governing Equations

The continuity equation of one-dimensional flow is

$$\frac{\partial(A + A_d)}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{2.26}$$

The momentum equation is

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2 / A)}{\partial x} + gA\frac{\partial Z}{\partial x} = -gAS_f \tag{2.27}$$

where A_d = ineffective cross section area; q_{lat} = lateral inflow per unit length of channel; t = time; and x = length along the flow direction.

2.2.2 Numerical Scheme

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

$$A_i^n + A_{di}^n - A_i^{n-1} - A_{di}^{n-1} = -\frac{\Delta t}{\Delta x_i}\left(\overline{Q}_{i+1} - \overline{Q}_i\right) \tag{2.28}$$

where the overbars signify a time weighted averaged value with a weighting factor $\theta\,(0 < \theta < 1)$ in the time domain. The time weighted discharges, $\overline{Q}_i$, can be written as

$$\overline{Q}_i = \theta Q_i^n + (1-\theta)Q_i^{n-1} \tag{2.29}$$

and Eq. (2.28) can be written in an iteration form, with *m* signifying the iteration number

$$\Delta A_i^m = \varphi_i \Delta Q_i^m + \delta_i \Delta Q_{i+1}^m + \gamma_i \tag{2.30}$$

where the coefficients are

$$\varphi_i = \frac{\theta \Delta t}{\Delta x_i} \tag{2.30a}$$

$$\delta_i = -\frac{\theta \Delta t}{\Delta x_i} \tag{2.30b}$$

$$\gamma_i = -A_i^n - A_{di}^n + A_i^{n-1} + A_{di}^{n-1} + \left(\overline{Q}_i - \overline{Q}_{i+1}\right)\frac{\Delta t}{\Delta x_i} \tag{2.30c}$$

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

$$Q_i^n - Q_i^{n-1} + \frac{\Delta t}{\Delta s_i}\left(\overline{F}_e - \overline{F}_w\right) = \Delta t g \frac{\overline{A}_i + \overline{A}_{i-1}}{2}\left(\frac{\overline{Z}_i + \overline{Z}_{i-1}}{\Delta s_i} - \overline{S}_{fi}\right) \tag{2.31}$$

where

$$\overline{F}_e = \beta \frac{\left(\overline{Q}_i + \overline{Q}_{i+1}\right)^2}{4\overline{A}_i} \tag{2.31a}$$

$$\overline{F}_w = \beta \frac{\left(\overline{Q}_i + \overline{Q}_{i-1}\right)^2}{4\overline{A}_{i-1}} \tag{2.31b}$$

$$S_{fi} = \frac{4\overline{Q}_i\left|\overline{Q}_i\right|}{\left(\overline{K}_i + \overline{K}_{i-1}\right)^2} \tag{2.31c}$$

SRH-1D provides various options for the treatment of the convective terms and GSTARS4 also has the same options.

Using a weighting factor θ in the time domain, Eq. (2.32) can be written in iteration form

$$\Delta Q_i^m + \theta \frac{\Delta t}{\Delta x_i}\left(\begin{array}{c} \frac{\partial \overline{F}_e}{\partial Q_i^n}\Delta Q_i^m + \frac{\partial \overline{F}_e}{\partial Q_{i+1}^n}\Delta Q_{i+1}^m + \frac{\partial \overline{F}_e}{\partial A_i^n}\Delta A_i^m \\ -\frac{\partial \overline{F}_w}{\partial Q_i^n}\Delta Q_i^m - \frac{\partial \overline{F}_w}{\partial Q_{i-1}^n}\Delta Q_{i-1}^m - \frac{\partial \overline{F}_e}{\partial A_{i-1}^n}\Delta A_{i-1}^m \end{array}\right)$$

$$-\theta \Delta t g \frac{\Delta A_i^m + \Delta A_{i-1}^m}{2}\left(\frac{Z_{i-1}^{n+1} - Z_i^{n+1}}{\Delta s_i} - S_{fi}^{n+1}\right)$$

$$-\theta \Delta t g \frac{\overline{A}_i + \overline{A}_{i-1}}{2}\left(\begin{array}{c} \frac{\Delta A_{i-1}^m}{T_{i-1}^{n+1}\Delta s_i} - \frac{\Delta A_i^m}{T_i^{n+1}\Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n}\Delta A_i^m \\ -\frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n}\Delta A_{i-1}^m - \frac{\partial \overline{S}_{fi}}{\partial Q_i^n}\Delta Q_i^m \end{array}\right) \tag{2.32}$$

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

Substituting Eq. (2.30) into Eq. (2.32), results in

$$a_i \Delta Q_{i-1}^m + b_i \Delta Q_i^m + c_i \Delta Q_{i+1}^m = d_i \tag{2.33}$$

where the coefficients are

$$a_i = \theta \frac{\Delta t}{\Delta s_i}\left(-\frac{\partial \overline{F}_w}{\partial Q_{i-1}^n} - \frac{\partial \overline{F}_w}{\partial A_{i-1}^n}\varphi_{i-1}\right)$$

$$-\frac{\theta \varphi_{i-1}\Delta t g}{2}\left[\frac{Z_{i-1}^{n+1} - Z_i^{n+1}}{\Delta s_i} - S_{fi} + \left(\frac{\overline{A}_i + \overline{A}_{i-1}}{2}\right)\left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n}\right)\right] \tag{2.33a}$$

$$b_i = 1 + \theta \frac{\Delta t}{\Delta s_i}\left(\frac{\partial \overline{F}_e}{\partial Q_i^n} + \frac{\partial \overline{F}_e}{\partial A_i^n}\varphi_i - \frac{\partial \overline{F}_w}{\partial Q_i^n} - \frac{\partial \overline{F}_w}{\partial A_{i-1}^n}\delta_{i-1}\right)$$

$$-\theta \frac{\Delta t g}{2}\left(\varphi_i + \delta_{i-1}\right)\left(\frac{Z_{i-1}^n - Z_i^n}{\Delta s_i} - S_{fi}\right) \tag{2.33b}$$

$$-\theta \frac{\Delta t g}{2}\left(\overline{A}_i + \overline{A}_{i-1}\right)\left[\begin{array}{c} \delta_{i-1}\left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n}\right) \\ +\varphi_i\left(\frac{-1}{T_i^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n}\right) - \frac{\partial \overline{S}_{fi}}{\partial Q_i^n} \end{array}\right]$$

$$c_i = \theta \frac{\Delta t}{\Delta s_i}\left(\frac{\partial \overline{F}_e}{\partial Q_{i+1}^n} + \frac{\partial \overline{F}_e}{\partial A_i^n}\delta\right)$$

$$-\theta \frac{\delta_i \Delta t g}{2}\left[\left(\frac{Z_{i-1}^n - Z_i^n}{\Delta s_i} - S_{fi}\right) + \frac{\overline{A}_i + \overline{A}_{i-1}}{2}\left(\frac{-1}{T_i \Delta s_i} - \frac{\partial S_{fi}}{\partial A_i^n}\right)\right] \tag{2.33c}$$

$$
\begin{aligned}
d_i &= Q_i^{n-1} - Q_i^n \\
&+ \frac{\Delta t}{\Delta s_i}\left(\overline{F}_w - \overline{F}_e - \theta\gamma_i \frac{\partial \overline{F}_e}{\partial A_i^n} + \theta\gamma_{i-1}\frac{\partial \overline{F}_w}{\partial A_{i-1}^n}\right) \\
&+ \frac{\Delta t g}{2}\left(\overline{A}_i + \overline{A}_{i-1} + \theta\gamma_i + \theta\gamma_{i-1}\right)\left(\frac{\overline{Z}_{i-1}^n - \overline{Z}_i^n}{\Delta s_i} - \overline{S}_{fi}\right) \\
&+ \theta\frac{\Delta t g}{2}\left(\overline{A}_i + \overline{A}_{i-1}\right)\left[\gamma_{i-1}\left(\frac{1}{T_{i-1}^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_{i-1}^n}\right) + \gamma_1\left(\frac{1}{T_i^n \Delta s_i} - \frac{\partial \overline{S}_{fi}}{\partial A_i^n}\right)\right]
\end{aligned}
\tag{2.33d}
$$

where T is the flow top width. For a single channel with $N+1$ cross sections, there are $N+2$ unknowns and N equations from Eqs. (2.33) – (2.33d). One upstream and one downstream boundary condition are therefore required.

GSTARS4 offers two options, adopted from SRH-1D, for the simulation of supercritical flow. The options use the Local Partial Inertia (LPI, from Fread and Lewis, 1998) technique to compute the flow. The LPI technique consists of multiplying the convective terms by a parameter, σ, as follows,

$$\sigma\left[\frac{\partial Q}{\partial t} + \frac{\partial\left(\beta Q^2 / A\right)}{\partial x}\right] + gA\frac{\partial Z}{\partial x} = -gAS_f \tag{2.34}$$

$$\sigma = f\left(F_r\right) \tag{2.35}$$

GSTARS4 has two methods to compute the function $f\left(F_r\right)$,

$$\sigma = \max\left(0, 1 - F_r^{-5}\right) \tag{2.36}$$

or

$$\sigma = \min\left(1, F_r^{-2}\right) \tag{2.37}$$

Eq. (2.36) is taken from FLDWAV (Fread and Lewis, 1998) and Eq. (2.37) is taken from MIKE 11 (DHI software, 2002). The function from FLDWAV provides damping of the convective terms for $F_r < 1$, while the function from MIKE 11 does not damp the convective term until $F_r > 1$. The function from FLDWAV will be generally more stable, but the function from MIKE 11 will be generally more accuate. Neither method will accurately simulate the propagation of rapid changing hydrographs that occurs during dam break. In addition, neither method will calculate the location of hydraulic jumps accurately. Regardless of the method of solutions, GSTARS4 and SRH-1D assumes that subcritical flow occurs at the boundaries of a river.

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 GSTARS4 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 GSTARS4 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 GSTARS4 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 GSTARS4 is the conservation of sediment mass. In one-dimensional unsteady flow, the sediment continuity equation can be written as

$$\frac{\partial Q_s}{\partial x} + \eta \frac{\partial A_d}{\partial t} + \frac{\partial A_s}{\partial t} - q_{lat} = 0 \tag{3.1}$$

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.:

$$\frac{\partial A_s}{\partial t} << \eta \frac{A_d}{\partial t} \tag{3.2}$$

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

$$\frac{\partial Q_s}{\partial t} = 0 \text{ or } \frac{\partial Q_s}{\partial x} = \frac{dQ_s}{dx} \tag{3.3}$$

With these assumptions, Eq. (3.1) becomes

$$\eta \frac{\partial A_d}{\partial t} + \frac{\partial Q_s}{\partial x} = q_{lat} \tag{3.4}$$

which is the governing equation used in GSTARS4 for routing sediments in rivers and streams.

3.2 Streamlines and Stream Tubes

GSTARS4 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 GSTARS4.

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

$$\frac{p}{\gamma} + \frac{V^2}{2g} + h = H_t = \text{Constant} \tag{3.5}$$

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 GSTARS4, however, H_t is reduced along the direction of the flow due to friction and other local losses, as described earlier in section 2.1.1.

In GSTARS4, 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.

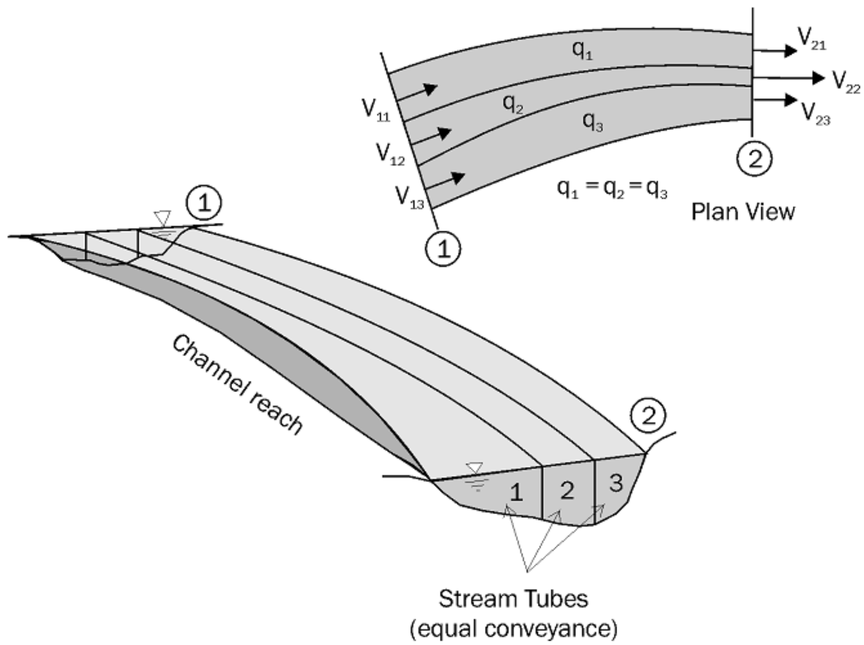

Figure 3.1 Schematic representation illustrating the use of stream tubes by GSTARS4

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 GSTARS4, 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 GSTARS4 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.

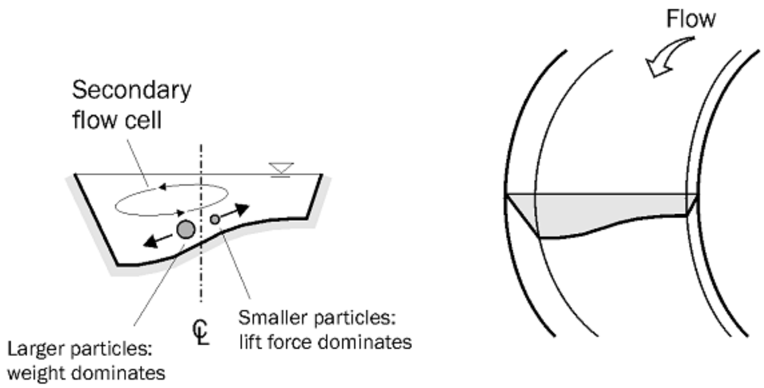

Figure 3.2 Bed sorting in bends due to transverse bed slope and secondary currents

GSTARS4 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

$$\beta = \frac{vh}{u^* A_r R}\left(-4.167 + 2.640\frac{u^*}{\kappa v}\right) \tag{3.6}$$

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 Karman 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

$$\frac{q_r}{q_s} = \tan\sigma = \tan\beta + \frac{1+\alpha\mu}{\lambda\mu}\sqrt{\frac{\tau_0^*}{\tau^*}}\tan\delta \tag{3.7}$$

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. (3.7). The components of the sediment tranport direction vector are given by

$$q_s = q_t \cos\sigma \tag{3.8}$$

$$q_r = q_t \sin\sigma \tag{3.9}$$

where q_t = sediment transport rate per unit width computed by any of the sediment transport equations discussed in section 3.5. Eq. (3.4) 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. GSTARS4 uses van Rijn's (1984) method to determine if a particle of a given size is in suspension or moves as bed load:

$$u^*_{cr,s} = \begin{cases} \dfrac{4\omega_s}{D^*} & \text{if } 1 < D^* \le 10 \\ 0.4\omega_s & \text{if } D^* > 10 \end{cases} \tag{3.10}$$

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

$$D^* = d\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \tag{3.11}$$

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 GSTARS4 program). GSTARS4 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. (3.4) numerically. Note that Eq. (3.4) 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 GSTARS4 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

$$\Delta A_d = \left(aT_{i-1} + bT_i + cT_{i+1}\right)\Delta Z_i \tag{3.12}$$

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

$$a + b + c = 1 \tag{3.13}$$

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:

$$a = 0;\ \ b = 1 - \theta;\ \text{and}\ c = \theta \tag{3.14}$$

where θ is a weighting parameter ($\theta > 0.5$). In GSTARS4, the standard values are $a = c = 0.25$ and $b = 0.5$, but the user can change those to any combination that satisfies Eq. (3.13). Using Eq. (3.12), the partial derivative terms are approximated as follows:

$$\frac{\partial A_d}{\partial t} \approx \frac{\left(aT_{i-1} + bT_i + cT_{i+1}\right)\Delta Z_i}{\Delta t} \tag{3.15}$$

$$\frac{dQ_s}{dx} \approx \frac{Q_{s,i} - Q_{s,i-1}}{1/2\left(\Delta x_i + \Delta x_{i-1}\right)} \tag{3.16}$$

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. (3.4), 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 Eqs. (3.15) and (3.16) into Eq. (3.4) we obtain

$$\Delta Z_{i,k} = \frac{\Delta t}{\eta_i} \cdot \frac{q_{lat}(\Delta x_i + \Delta x_{i-1}) + 2(Q_{s,i-1,k} - Q_{s,i,k})}{(aT_{i-1} + bT_i + cT_{i+1})(\Delta x_i + \Delta x_{i-1})} \tag{3.17}$$

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

$$\Delta Z_i = \sum_{k=1}^{N} \Delta Z_{i,k} \tag{3.18}$$

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.

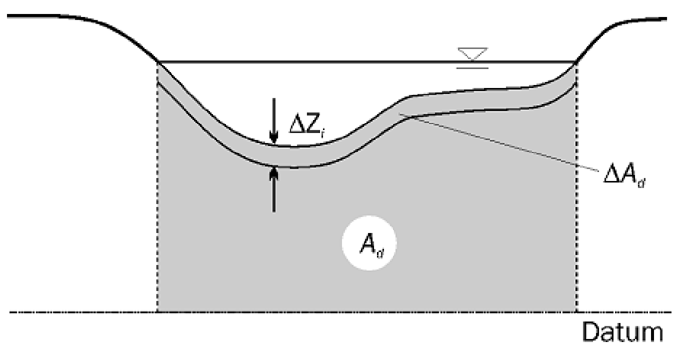

Figure 3.3 Definition of variables for a cross section.

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.

GSTARS4 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 GSTARS4.

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

$$C_r = \frac{\text{celerity of propagation in the analytical solution}}{\text{celerity of propagation in the numerical solution}} \tag{3.19}$$

so that the CFL condition becomes $C_r \leq 1$ 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. GSTARS4 uses an explicit method to solve the sediment routing equation. In this case, the CFL stability criterion is given by

$$\Delta t \leq \frac{\Delta x}{c_s} \tag{3.20}$$

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 GSTARS4 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. (3.3), 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

$$\Delta Z_i << h_i \tag{3.21}$$

for all the computational cross sections and for all time steps. In Eq. (3.21), 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 GSTARS4.

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:

$$\frac{T}{\left(L/V\right)} \geq 100 \tag{3.22}$$

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

$$V = \sqrt{gh} \tag{3.23}$$

where g = acceleration due to gravity, and h = hydraulic depth. Note, however, that the steady flow part of GSTARS4 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 GSTARS4, it is unlikely that the limitations associated with uncoupling hydraulics and sediment transport are significant.

3.4 Bed Sorting and Armoring

GSTARS4 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. GSTARS4 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. (3.4). 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, GSTARS4 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.

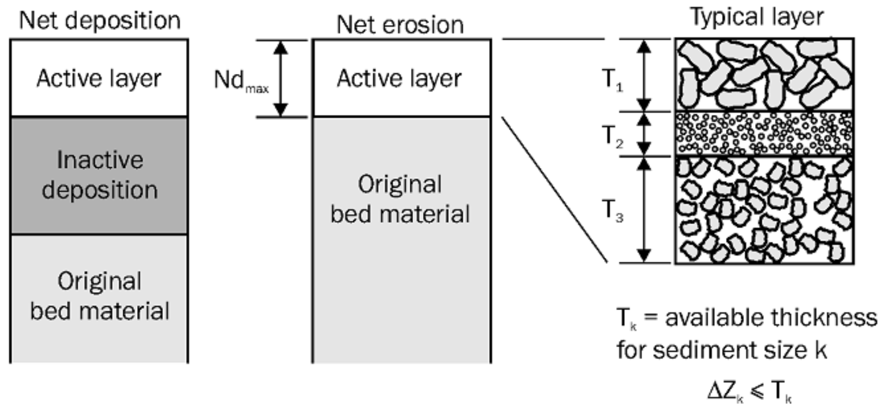

Figure 3.4 Bed composition accounting procedures. ΔZ_k represents the amount of material in size class k eroded during a time step, and T_k is the amount of material of size k present in the active layer, i.e., available for erosion.

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 GSTARS4. 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

$$P_{i,k} = \frac{1}{X} \sum_{m=1}^{NPTS} P_{i,k,m} \cdot \Delta X_i \tag{3.24}$$

$$TAL_{i,k} = \frac{1}{X} \sum_{m=1}^{NPTS} TAL_{i,k,m} \cdot \Delta X_i \tag{3.25}$$

and

$$TIL_{i,k} = \frac{1}{X} \sum_{m=1}^{N} TIL_{i,k,m} \cdot \Delta X_i \tag{3.26}$$

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.

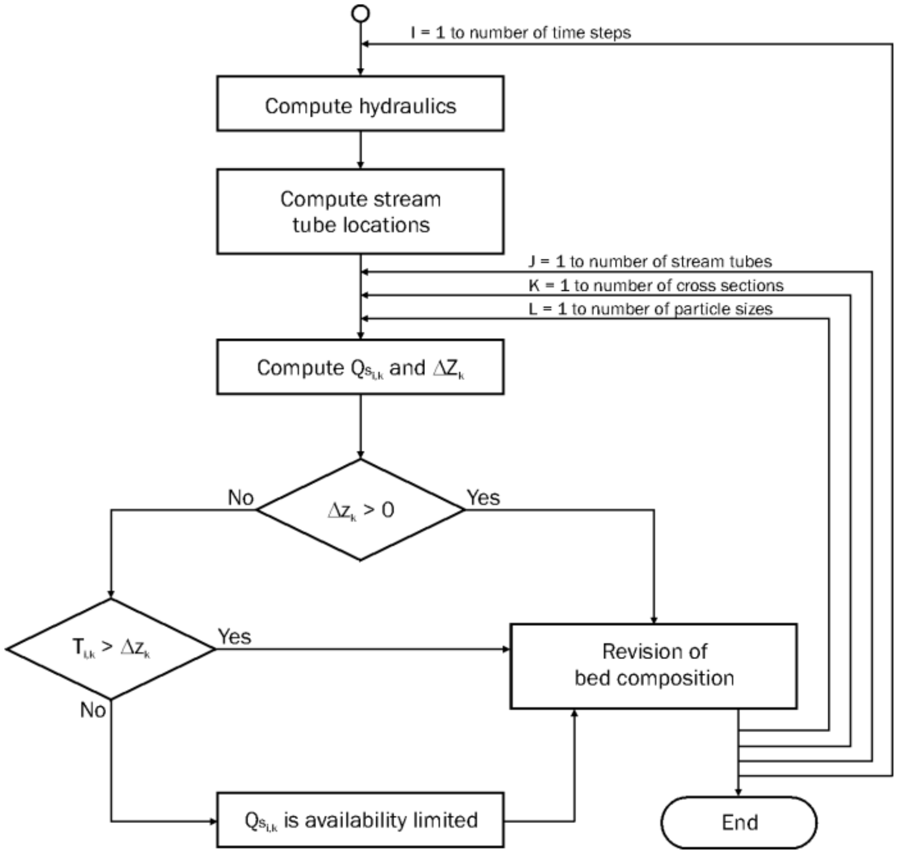

Figure 3.5 Simplified diagram for the bed sorting and armoring processes. Adopted from Bennett and Nordin (1977), with modifications.

Note that GSTARS4 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.

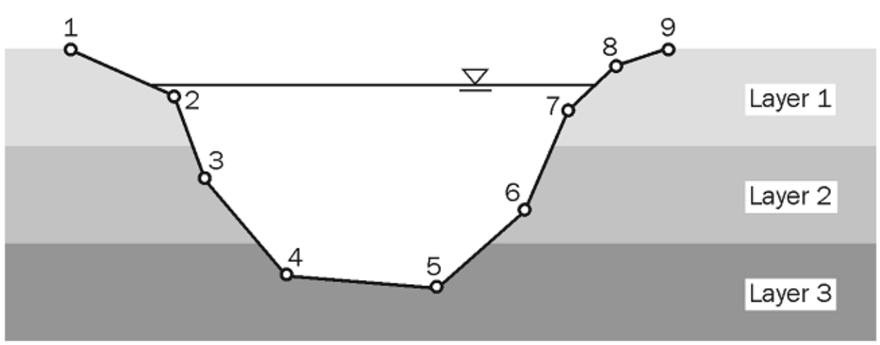

Figure 3.6 Cross section showing how individual discretization points may have different sediment particle distributions.

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 $\Delta Z \leq \delta$.

Alternatively, an estimate of Δt_s can be obtained from a simplified form of Eq. (3.17):

$$\frac{Q_{s,i-1} - Q_{si}}{\eta \Delta x_i P_i} = \frac{\Delta Z}{\Delta t_s} \tag{3.27}$$

where ΔZ is prescribed to satisfy the above criterion (i.e., $\Delta Z \leq \delta$). 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. GSTARS4 has 15 transport functions for cohesionless material, presented in table 3.1. More detailed descriptions of these functions were published by Yang (1996, 2003), 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 GSTARS4 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 GSTARS4, 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:

$$C_t = \sum_{i=1}^{N} \left[r p_i + ((1-r) p_i^* \right] C_i \qquad (3.28)$$

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 ($0 \leq r \leq 1$); 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 = 1) 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:

$$A_{Ri} = aA_{i-1} + bA_i + cA_{i+1} \tag{3.29}$$

$$D_{Ri} = aD_{i-1} + bD_i + cD_{i+1} \tag{3.30}$$

$$V_{Ri} = aV_{i-1} + bV_i + cV_{i+1} \tag{3.31}$$

$$S_{Ri} = aS_{i-1} + bS_i + cS_{i+1} \tag{3.32}$$

The weighting parameters *a*, *b*, and *c* can be chosen in any combination that satisfies Eq. (3.13). By default, GSTARS4 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, GSTARS4 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. GSTARS4 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. (3.12), 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:

$$q_b = K\tau(\tau - \tau_c) \tag{3.33}$$

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:

$$K = \frac{0.173}{d^{3/4}} \tag{3.34}$$

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:

$$\gamma RS\left(\frac{K_s}{K_r}\right)^{3/2} = 0.047(\gamma_s - \gamma)d + 0.25\rho^{1/3}{q_b}^{2/3} \tag{3.35}$$

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); 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. (3.35) can also be expressed in dimensionless form as

$${q_b}^{2/3}\left(\frac{\gamma}{g}\right)^{1/3}\frac{0.25}{(\gamma_s - \gamma)} = \frac{(K_s / K_r)^{3/2}\gamma RS}{(\gamma_s - \gamma)d} - 0.047 \tag{3.36}$$

where

$$\left(\frac{K_s}{K_r}\right)^{3/2} = \frac{S_r}{S} \tag{3.37}$$

and

$$K_r = \frac{26}{d_{90}^{1/6}} \tag{3.38}$$

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

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{D}\right)^{7/6} \left(\frac{\tau^{'}}{\tau_{ci}} - 1\right) f\left(\frac{U^*}{\omega_i}\right) \tag{3.39}$$

where C_t = sediment concentration by weight per unit volume; $U^* = \sqrt{gDS}$; p_i = percentage of materials available in size fraction i; 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, $\tau^{'}$, caused by grain resistance resulting from the use of the Manning equation is

$$\tau^{'} = \frac{\rho V^2}{58}\left(\frac{d_{50}}{D}\right)^{1/3} \tag{3.40}$$

In Eq. (3.39), 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 $f\left(U^*/\omega_i\right)$ 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. GSTARS4 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

$$Q_{ti} = B(q_{bi} + q_{sui} + q_{smi} + q_{sli}) \tag{3.41}$$

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:

$$f^{'}\phi = 0.1\theta^{5/2} \tag{3.42}$$

$$f' = \frac{2gSD}{V^2} \tag{3.43}$$

$$\phi = \frac{q_t}{\gamma_s}\left[\left(\frac{\gamma_s - \gamma}{\gamma}\right)gd^3\right]^{-1/2} \tag{3.44}$$

$$\theta = \frac{\tau}{(\gamma_s - \gamma)d} \tag{3.45}$$

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

$$F_{gr} = U^{*n}\left[gd\left(\frac{\gamma_s}{\gamma} - 1\right)\right]^{-1/2}\left[\frac{V}{\sqrt{32}\log(\alpha D/d)}\right]^{1-n} \tag{3.46}$$

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

$$d_{gr} = d\left[\frac{g}{\nu^2}\left(\frac{\gamma_s}{\gamma} - 1\right)\right]^{1/3} \tag{3.47}$$

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

$$G_{gr} = f(F_{gr}, d_{gr}) \tag{3.48}$$

with

$$G_{gr} = \frac{XD}{(d\gamma_s)/\gamma}\left(\frac{U^*}{V}\right)^n \tag{3.49}$$

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

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^m \tag{3.50}$$

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 GSTARS4. 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

$$\begin{aligned} \log C_{ts} &= 5.435 - 0.286 \log \frac{\omega d}{\nu} - 0.457 \log \frac{U^*}{\omega} \\ &+ \left(1.799 - 0.409 \log \frac{\omega d}{\nu} - 0.314 \log \frac{U^*}{\omega}\right) \log\left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega}\right) \end{aligned} \tag{3.51}$$

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. (3.51) were determined from 463 sets of laboratory flume data. Eq. (3.51) 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

$$\frac{V_{cr}}{\omega} = \begin{cases} \dfrac{2.5}{\log\left(U^* d / \nu\right) - 0.06} + 0.66 & \text{if } 1.2 \le \dfrac{U^* d}{\nu} \le 70 \\ 2.05 & \text{if } 70 \le \dfrac{U^* d}{\nu} \end{cases} \tag{3.52}$$

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

$$\begin{aligned} \log C_{tg} &= 6.681 - 0.633 \log \frac{\omega d}{\nu} - 4.816 \log \frac{U^*}{\omega} \\ &\quad + \left(2.784 - 0.305 \log \frac{\omega d}{\nu} - 0.282 \log \frac{U^*}{\omega} \right) \log \left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega} \right) \end{aligned} \tag{3.53}$$

where C_{tg} = total gravel concentration in parts per million by weight. The coefficients in Eq. (3.53) were determined from 167 sets of laboratory flume data.

The incipient motion criteria given in Eq. (3.52) should be used for Eqs. (3.51) and (3.53). Because of the range of data used for the determination of the coefficients in Eq. (3.53), the equation should be applied to gravel with median particle size between 2 and 10 mm. However, published literature suggests that Eq. (3.53) may be applicable to materials coarser than 10 mm. GSTARS4 uses Eq. (3.53) for sizes up to 100 mm. Eqs. (3.51) and (3.53) were originally derived for uniform materials. When they are applied to nonuniform materials, the total sediment concentration should be computed by using Eq. (3.28).

For natural rivers, the bed-material size may vary from sand to gravel. In this case, the use of both Eqs. (3.51) and (3.53) should be considered. GSTARS4 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

$$
\log C_{ts} = 5.165 - 0.153 \log \frac{\omega d}{\nu} - 0.297 \log \frac{U^*}{\omega} + \left(1.780 - 0.360 \log \frac{\omega d}{\nu} - 0.480 \log \frac{U^*}{\omega}\right) \log \frac{VS}{\omega} \tag{3.54}
$$

The coefficients in Eq. (3.54) were determined from 452 sets of laboratory flume data. Eqs. (3.51) and (3.54) 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. (3.51) and (3.53) or (3.54) and (3.53) for the computation of bed material concentration in a river, depending on sediment size in that river. If bed materials are not uniform, Eq. (3.28) is also applied in GSTARS4.

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

$$
W_i^* = \left(\frac{\gamma_s}{\gamma} - 1\right) \frac{q_{bi}}{p_i DS \sqrt{gDS}} \tag{3.55}
$$

$$
\phi_i = \frac{DS}{d_i \tau_{ri}^*} \left(\frac{\gamma_s}{\gamma} - 1\right)^{-1} \tag{3.56}
$$

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

$$
\tau_{ri}^* = 0.875 \frac{d_{50}}{d_i} \tag{3.57}
$$

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.,

$$
W^* = \begin{cases} 0.0025\phi_{50}^{14.2} & \text{if } \phi_{50} < 1.0 \\ 0.0025\exp\left\{14.2(\phi_{50} - 1) - 9.28(\phi_{50} - 1)^2\right\} & \text{if } 1.0 \le \phi_{50} \le 1.59 \\ 13.685\left(1 - \dfrac{0.853}{\phi_{50}}\right)^{4.5} & \text{if } \phi_{50} > 1.59 \end{cases} \tag{3.58}
$$

In Eq. (3.58), 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:

$$\begin{aligned}\log C_{ts} &= 5.165 - 0.153\log\frac{\omega_m d}{\nu_m} - 0.297\log\frac{U^*}{\omega_m} \\ &+ \left(1.780 - 0.360\log\frac{\omega_m d}{\nu_m} - 0.480\log\frac{U^*}{\omega_m}\right)\log\left[\left(\frac{\gamma_m}{\gamma_s - \gamma_m}\right)\frac{VS}{\omega_m}\right]\end{aligned} \tag{3.59}$$

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. (3.59) are identical to those in Eq. (3.54). 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. (3.51), (3.53), and (3.54), Eq. (3.59) is used in conjunction with Eq. (3.28) 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:

$$Q_s = \Omega\frac{Q^{1.6}S^{1.2}}{W^{0.6}} \tag{3.60}$$

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

Table 3.3 Values of the factor 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 GSTARS4, Eq. (3.60) was adapted for fractional sediment transport. Note, however, that Eq. (3.60) 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 trasport equation is selected for GSTARS4 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 GSTARS4).

3.5.12 Ashida and Michiue Method (1972)

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

$$\frac{q_{bi}}{p_i u_e^* d_i} = 17\tau_{ei}^*\left(1-\frac{\tau_{ci}^*}{\tau_i^*}\right)\left(1-\sqrt{\frac{\tau_{ci}^*}{\tau_i^*}}\right) \tag{3.61}$$

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;

$$\tau_i^* = \frac{u^{*2}}{Ggd_i} \tag{3.62}$$

$$\tau_{ci}^{*} = \frac{u_{ci}^{*\,2}}{Ggd_i} \qquad (3.63)$$

$$\tau_{ei}^{*} = \frac{u_{e}^{*2}}{Ggd_i} \qquad (3.64)$$

Where 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

$$\frac{v}{u_e^*} = 5.75\log\left(\frac{R_h / d_{50}}{1+2\tau^*}\right) + 6.0 \qquad (3.65)$$

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

$$\frac{u_{ci}^2}{u_{c50}^{*2}} = \begin{cases} 0.85 & \text{if } \dfrac{d_i}{d_{50}} < 0.4 \\ \left(\dfrac{\log 19}{\log\left(\dfrac{19d_i}{d_{50}}\right)}\right)^2 & \text{if } \dfrac{d_i}{d_{50}} \geq 0.4 \end{cases} \qquad (3.66)$$

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

$$u_{c50}^* = \sqrt{\tau_{c50}^* Ggd_{50}} \qquad (3.67)$$

τ_{c50}^* is taken equal to 0.05.

Although the original expression due to Ashida and Michiue (1972) is for bed load only, in GSTARS4 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):

$$q_{si} = C_{ai}v\left(e^{-c_1 a} - e^{-c_1 h}\right)\frac{e^{c_1 a}}{c_1} \qquad (3.68)$$

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

$$C_{ai} = p_i K\left[\frac{f(\xi_0)}{\xi_0} - F(\xi_0)\right] \tag{3.69}$$

with

$$f(\xi_0) = \frac{1}{\sqrt{2\pi}}\exp\left\{-0.5\xi_0^2\right\} \tag{3.70}$$

$$F(\xi_0) = \frac{1}{\sqrt{2\pi}}\int_{\xi_0}^{\infty}\exp\left\{-0.5\xi^2\right\}d\xi \tag{3.71}$$

where K = 0.025, $\xi_0 = \omega_i/\left(0.75u^*\right)$, and ω_i is the fall velocity of sediment particles with diameter d_i. In Eq. (3.68), c_i is computed as

$$c_i = \frac{6\omega_i}{\kappa u^* h} \tag{3.72}$$

where κ is the von Kármán 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. (3.61) and (3.68), 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. (3.28) should be set to 1 when the method is used in GSTARS4 runs.

3.6 Cohesive Sediment Transport

At present, the equations for computing the transport potential of cohesive sediments[†] implemented in GSTARS4 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.

[†] 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.

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 studies 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-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 GSTARS4, the transport of silt and clay is computed separately from the remaining size fractions. GSTARS4 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

$$\frac{dC}{dt} = -\frac{P\omega_s C}{h} \tag{3.73}$$

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

$$P = \begin{cases} 1 - \dfrac{\tau_b}{\tau_{cd}} & \text{when } \tau_b < \tau_{cd} \\ 0 & \text{when } \tau_b \geq \tau_{cd} \end{cases} \tag{3.74}$$

When ω_s does not depend on the concentration of suspended sediments (unhindered settling), Eq. (3.73) can be integrated analytically to yield

$$\frac{C}{C_0} = \exp\left\{ -\frac{\omega_s \Delta t}{h}\left(1 - \frac{\tau_b}{\tau_{cd}}\right)\right\} \tag{3.75}$$

where C_0 and C are the concentration at the beginning and end of time step. The time of residence, Δt, is obtained from 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. (3.73) does not offer a closed form solution. For high concentrations, GSTARS4 integrates Eq. (3.73) numerically to obtain:

$$C = C_0 - \frac{\omega_s C_0 \Delta t}{h}\left(1 - \frac{\tau_b}{\tau_{cd}}\right) \tag{3.76}$$

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. (3.75) and (3.76) are both included in GSTARS4. The concentration obtained from their solution is converted into volume and deposited on the bed.

It was mentioned that the adoption of Eq. (3.75) 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 GSTARS4 to these problems should be done carefully and with ample support from field data.

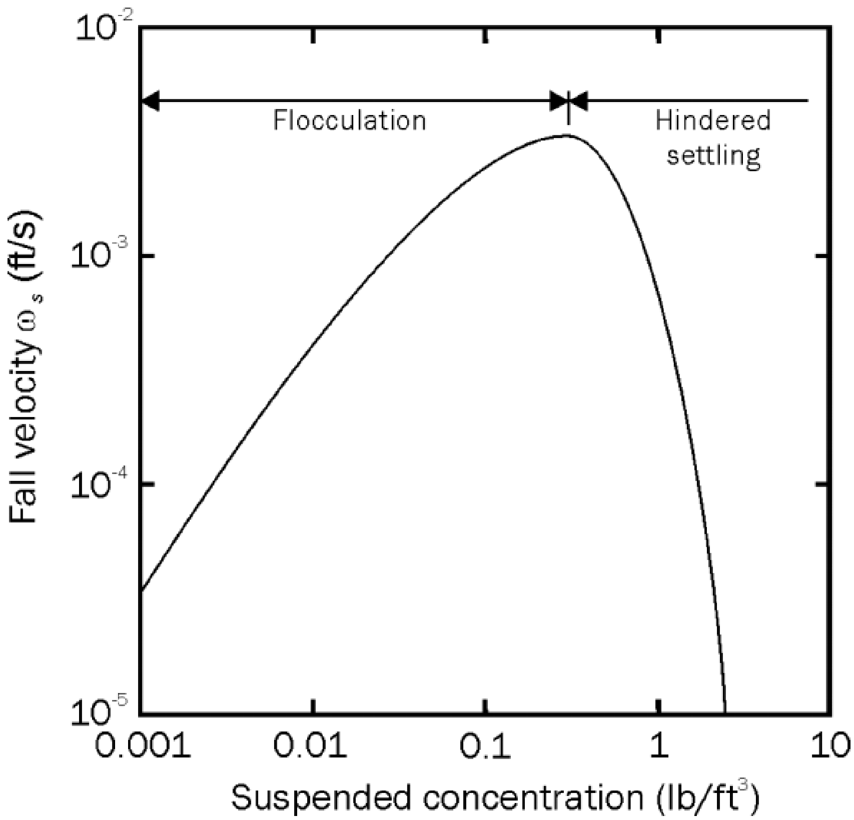

Figure 3.7 Fall velocity of cohesive sediment aggregates in high concentration transport, showing the effects of flocculation and hindered settling

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}. GSTARS4 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[‡], as a linear function of the excess of the bed shear stress with respect to a critical shear stress for erosion:

$$E = M_i \left(\frac{\tau_b - \tau_{ci}}{\tau_{ci}} \right) \tag{3.77}$$

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 noncohesive 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. (3.77) 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):

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

$$E_1 = \frac{1}{A}\frac{dm}{dt} = M_1 \left(\frac{\tau_b}{\tau_{cs}} - 1 \right) \tag{3.78}$$

$\tau_b > \tau_{cm}$:

$$E_2 = \frac{1}{A}\frac{dm}{dt} = M_2 \left(\frac{T_e}{\Delta t} \right) \tag{3.79}$$

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, GSTARS4 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

[‡] Unit of mass of eroded sediment per unit of bed area and per unit of time.

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 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, GSTARS4 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

$$C_i = C_{t,i} + \left(C_{i-1} - C_{t,i-1}\right)\exp\left\{-\frac{\alpha\omega_s\Delta x}{q}\right\} + \left(C_{t,i-1} - C_{t,i}\right)\left(\frac{q}{\alpha\omega_s\Delta x}\right)\left[1-\exp\left\{-\frac{\alpha\omega_s\Delta x}{q}\right\}\right] \quad (3.80)$$

where C = sediment concentration; C_t = sediment carrying capacity, computed from Eq. (3.28); 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. (3.80) 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. Field investigations suggest that α is not a constant.

Although Eq. (3.80) was derived for suspended load, its application to bed-material load is reasonable. The asymptotic behavior of Eq. (3.80) for the larger particles (higher values of ω_s) is correct in the sense that $C_i \rightarrow C_{t,i}$ 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. (3.80) 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 aggradations). The non-equilibrium capacity becomes almost identical for gravel and larger particle sizes.

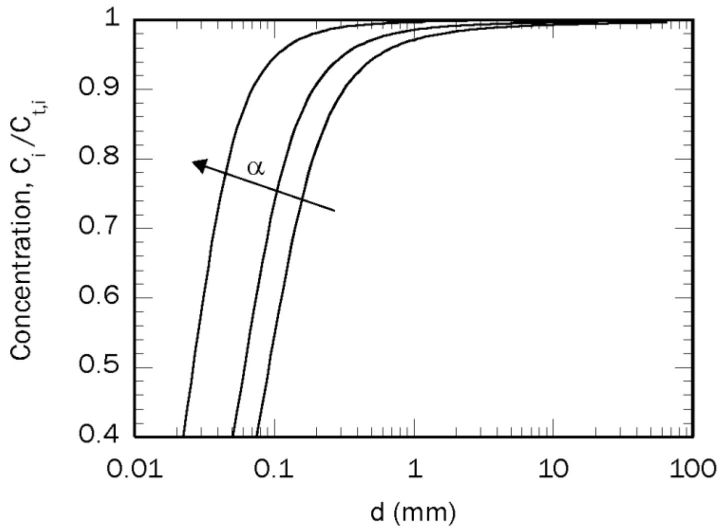

Figure 3.8 Ratio between non-equilibrium concentration and carrying capacity as a function of sediment particle size.

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 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.

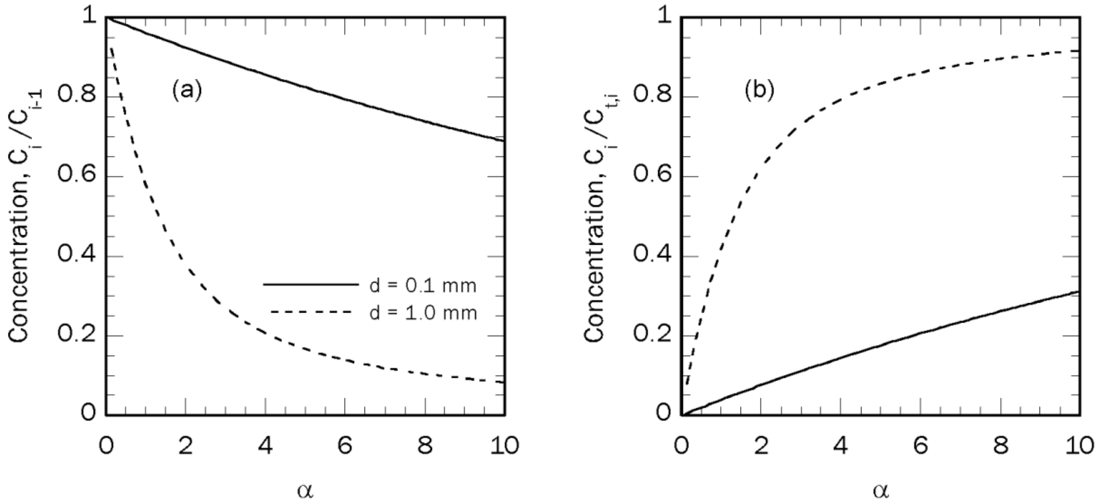

Figure 3.9 Effect of the recovery parameter on the computation of non-equilibrium sediment concentrations for two sediment particle sizes. (a) deposition and (b) erosion

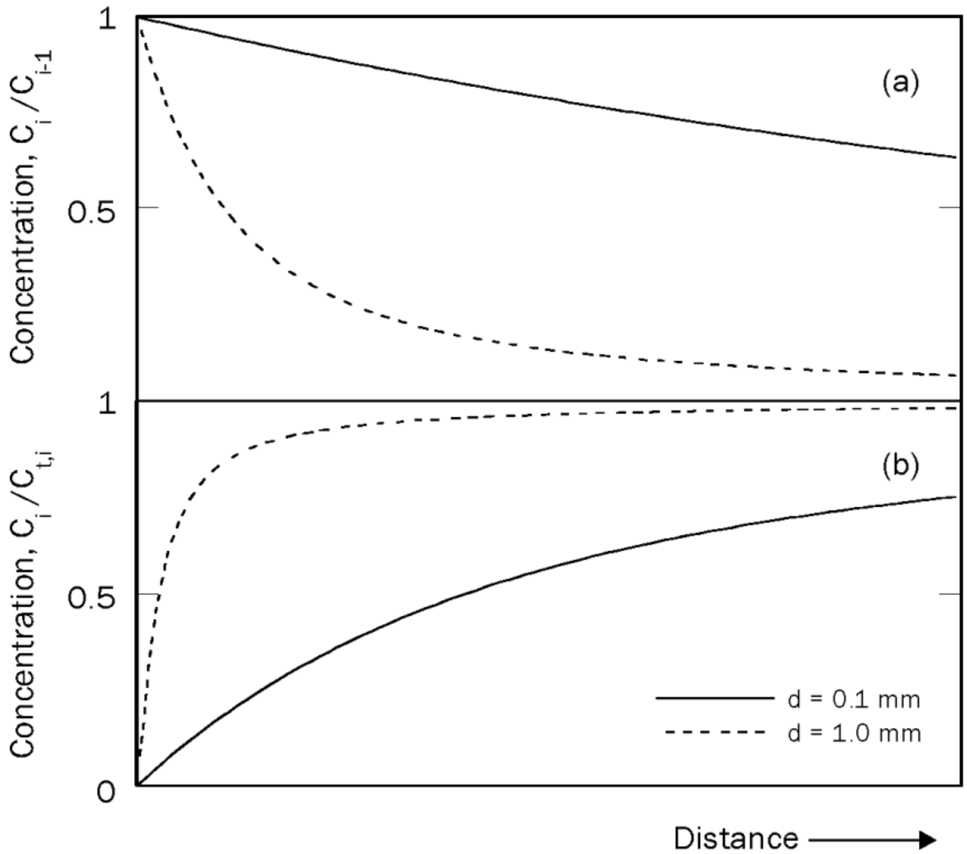

Figure 3.10 Variation of non-equilibrium effects as a function of distance between cross sections for aggradation (a) and for erosion (b)

Note that the non-equilibrium sediment transport phenomenon described by Eq. (3.80) is fundamentally different from the considerations behind the application of Eq. (3.28) in section 3.5. Eq. (3.28) 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. (3.80), 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 GSTARS4 and the user should apply them carefully, with proper engineering judgment.

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:

$$\omega_s = F\sqrt{dg(G-1)} \tag{3.81}$$

where

$$F = \left[\frac{2}{3} + \frac{36\nu^2}{gd^3(G-1)}\right]^{1/2} - \left[\frac{36\nu^2}{gd^3(G-1)}\right]^{1/2} \tag{3.82}$$

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 GSTARS4, 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:

$$\nu = \frac{1.792\times10^{-6}}{1.0 + 0.0337T + 0.000221T^2} \tag{3.83}$$

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). GSTARS4 uses a value for the Corey shape factor of SF = 0.7, where

$$SF = \frac{c}{\sqrt{ab}} \tag{3.84}$$

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:

$$\omega_s = 1.1\sqrt{(G-1)gd} \tag{3.85}$$

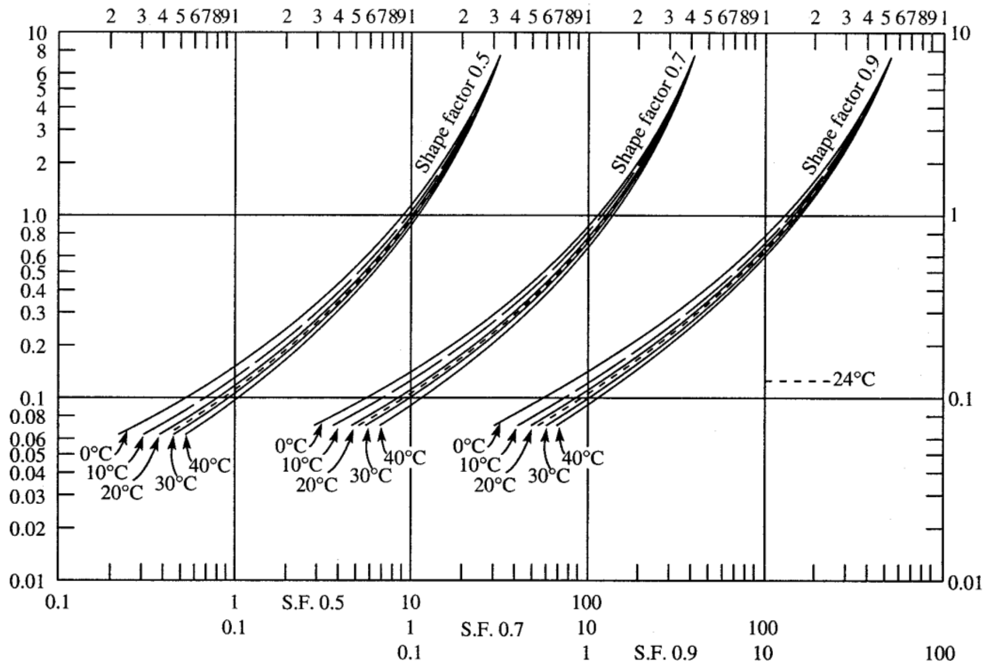

Figure 3.11 Relation between particle sieve diameter and its fall velocity according to the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957)

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:

$$\omega_s = \frac{(G-1)gd^2}{18\nu} \qquad \text{for } C < C_1 \tag{3.86}$$

flocculation range:

$$\omega_s = MC^N \qquad \text{for } C_1 \le C \le C_2 \tag{3.87}$$

hindered settling:

$$\omega_s = \omega_0(1-kC)^l \qquad \text{for } C > C_2 \tag{3.88}$$

where ω_0 is found by equating eqs.(3.87) and (3.88) at $C = C_2$, i.e.,

$$\omega_0 = \frac{MC_2^N}{(1 - kC_2)^l} \tag{3.89}$$

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).

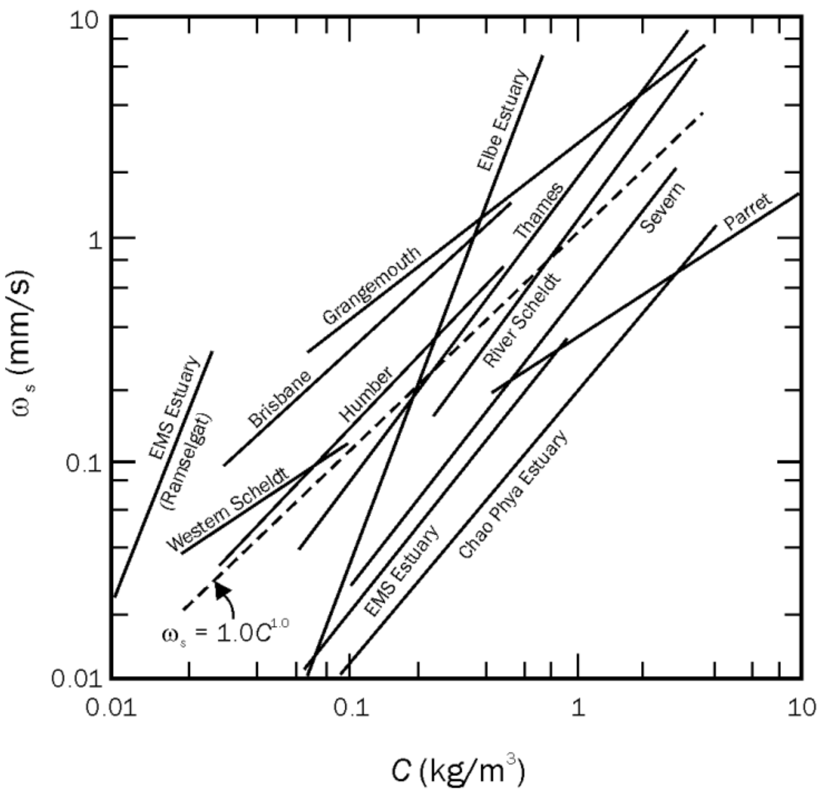

Figure 3.12 Variability of the parameters M and N of eq. (3.87) for several well known rivers and estuaries

CHAPTER

4

COMPUTATION OF WIDTH CHANGES

GSTARS4 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,

$$Q = BDV \tag{4.1}$$

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

$$V = C\left[\frac{BD}{P}S\right]^{1/2} \tag{4.2}$$

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

$$Q_s = f(D, B, V, S, d, ...) \quad (4.3)$$

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 GSTARS4, 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:

$$\Phi = \Phi_W + \Phi_S = \text{a minimum} \quad (4.4)$$

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., $\Phi_W >> \Phi_S$, 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 following equations, 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:

$$\Phi_T = \int \gamma QS dx \quad (4.5)$$

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

$$\Phi_T = \sum_{i=1}^{N} \frac{1}{2} \gamma \left(Q_i S_i + Q_{i+1} S_{i+1} \right) \Delta x_i \tag{4.6}$$

where N = number of stations along the reach; Δx = 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. (4.6) 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 GSTARS4 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. (3.17) 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. (3.17). 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, GSTARS4 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 GSTARS4.

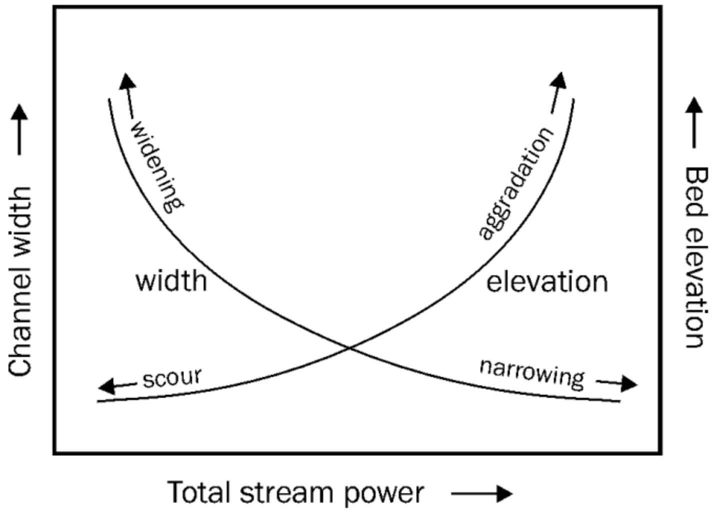

Figure 4.1 Total stream power variation as a function of changes in channel width and bed elevation, with constant discharge and downstream stage

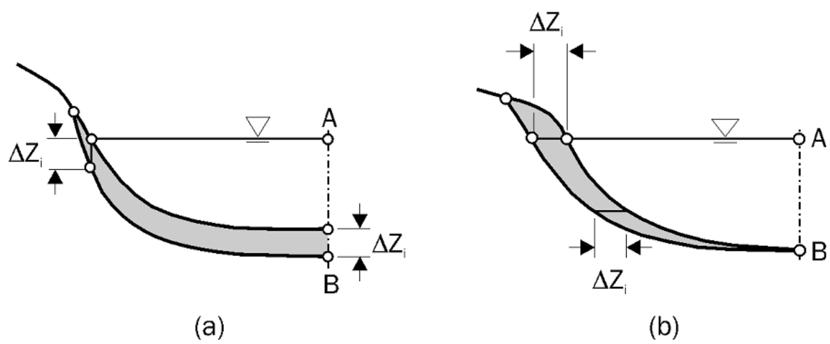

Figure 4.2 Schematic representation of channel changes on exterior stream tubes: (a) bed elevation change due to scour or deposition; (b) width change due to scour or deposition. Line AB denotes the stream tube boundary

4.3 Channel Side Slope Adjustments

GSTARS4 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. (3.25) 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.

GSTARS4 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. GSTARS4 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:

$$A_1 + A_2 = A_3 + A_4 \tag{4.7}$$

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'*.

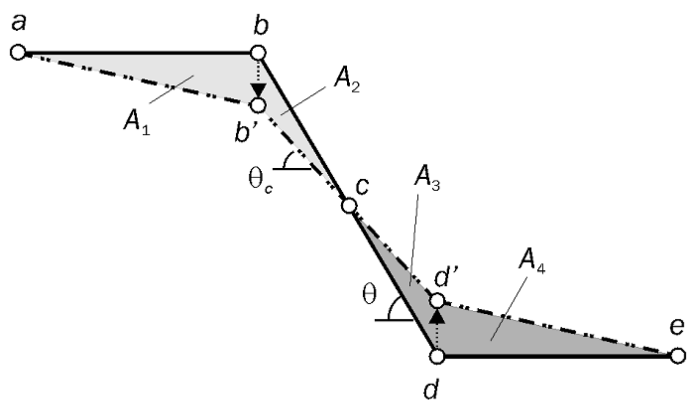

Figure 4.3 Example of angle of repose adjustment

CHAPTER

5

RESERVOIR ROUTING

In GSTARS4, 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. GSTARS3 is applicable for steady or quasi-steady flow simulation. GSTARS4 is applicable to steady and unsteady flows.

There are many different types of water impoundments, and no model exists that can successfully and indiscriminately be used for all. GSTARS4 is a semi-two-dimensional model, therefore it may not be applicable to situations where fully two- or three-dimensional models are required. GSTARS4 is best for 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 sophisticated, 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

$$Q_4 = Q_{in} - a_4 (Q_{in} - Q_{out}) \tag{5.1}$$

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

$$Q_j = Q_{in} - (Q_{in} - Q_{out}) \sum_{k=i}^{j} a_k \tag{5.2}$$

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,

$$\sum_{k=i}^{N} a_k = 1 \tag{5.3}$$

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

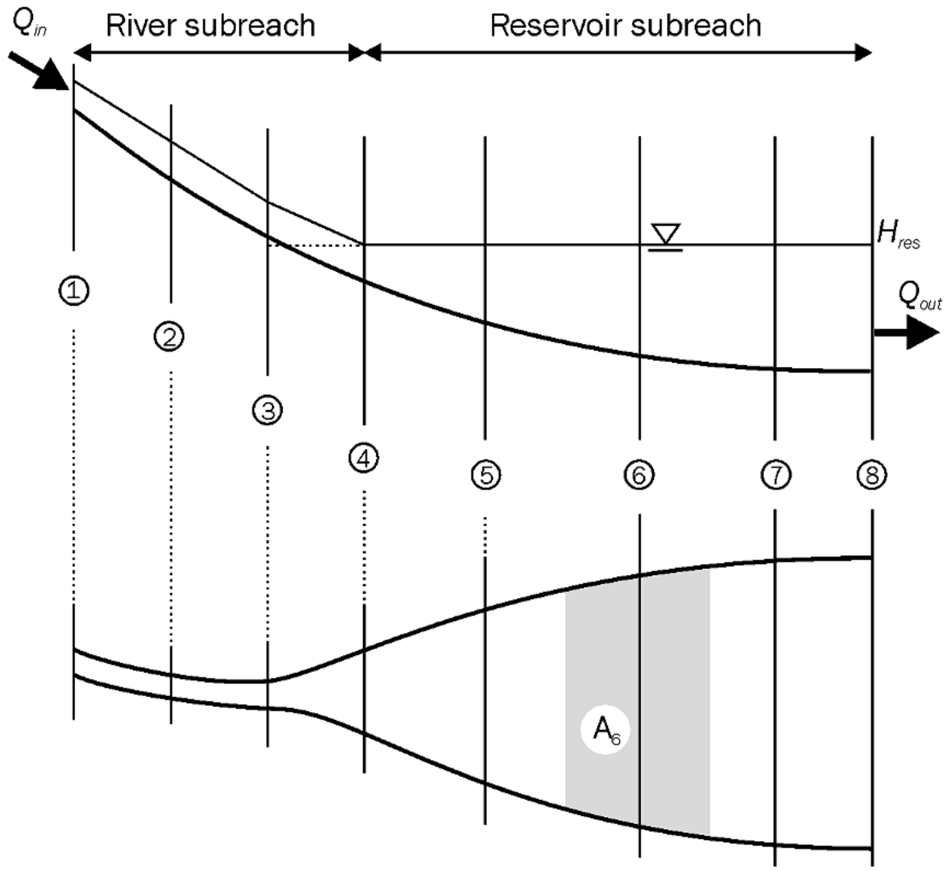

Figure 5.1 Subdivision of a GSTARS4 reach into river and reservoir subreaches for reservoir routing. Top: side view; bottom: top view of the same reservoir. The shaded region depicts the surface area of the reservoir represented by cross section #6

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

$$Q_{in} - Q_{out} = \frac{\Delta V}{\Delta t} \tag{5.4}$$

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).

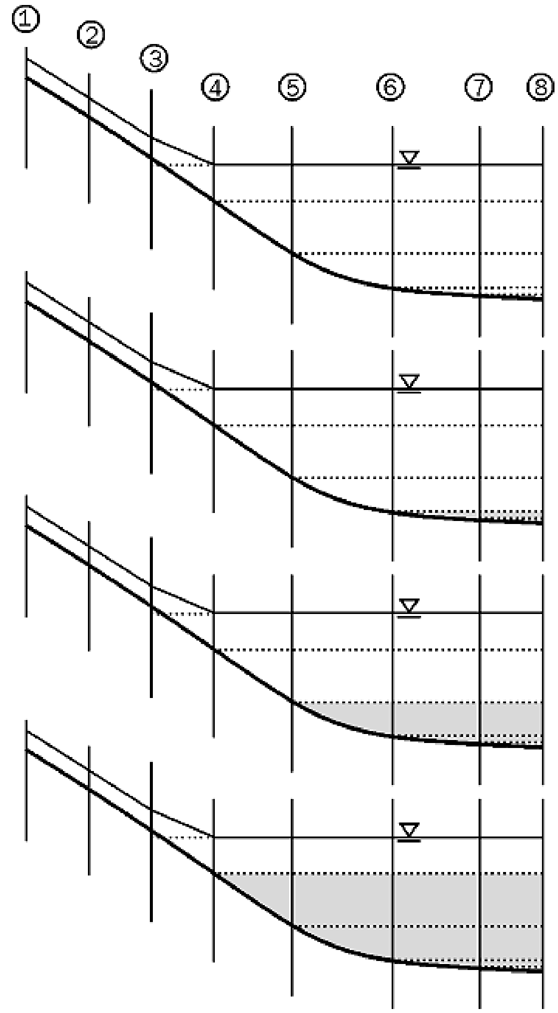

Figure 5.2 Delineation of volumes to build the capacity table used to determine H_{res}

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 $V_{7\rightarrow 8}$ (see top of figure 5.2) and is given by the volume of the frustum[§] of the cone:

$$V_{7\rightarrow 8} = \frac{1}{3}\Delta x\left(A_7 + A_8 + \sqrt{A_7 A_8}\right) \tag{5.5}$$

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 $A_{7\rightarrow 8} + A_{6\rightarrow 7} + A_{5\rightarrow 6} + A_{4\rightarrow 5}$. Each volume is calculated from

[§]The frustum 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.

$$V_{i \to j} = \frac{1}{3} \Delta x_{ij} \left(A_i + A_j + \sqrt{A_i A_j} \right) \quad (5.6)$$

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 GSTARS4, 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).

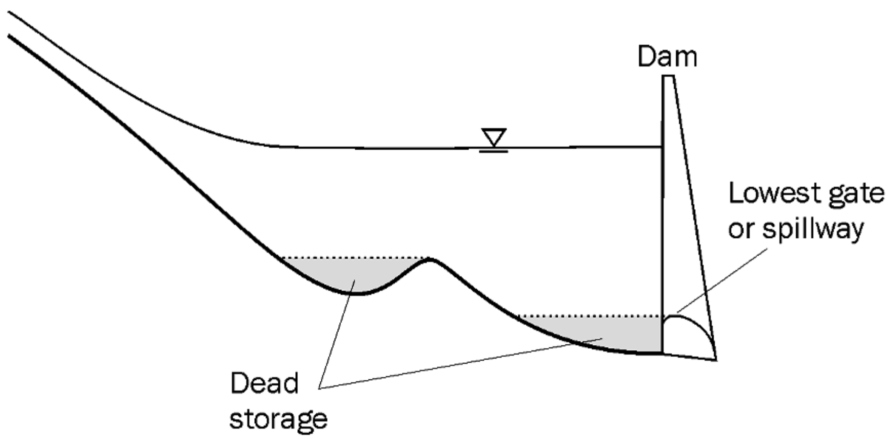

Figure 5.3 Definition of dead storage regions. GSTARS4 does not include these regions in the capacity table used in level-pool computations.

5.2 Sediment Transport

Two reservoir sediment transport equations have been implemented in GSTARS4: 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, and1984) 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 GSTARS4 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. (3.18) using

$$\Delta A_d = W\Delta Z \tag{5.7}$$

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.

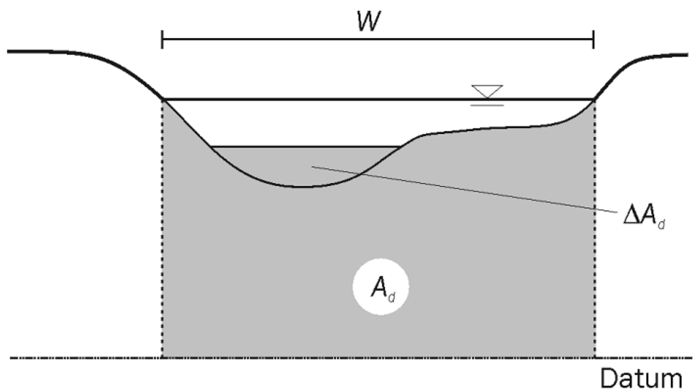

Figure 5.4 Reservoir deposition for a cross section. Compare to figure 3.3

CHAPTER

6

DATA REQUIREMENTS

Application of the GSTARS4 computer model requires the use of appropriate data. From a conceptual point of view, GSTARS4 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 GSTARS4 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 GSTARS4 computer program.

6.1 Input Data Format

In GSTARS4 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 GSTARS4. Field 1 is 6 characters long; fields 2 to 10 are 8 characters long.

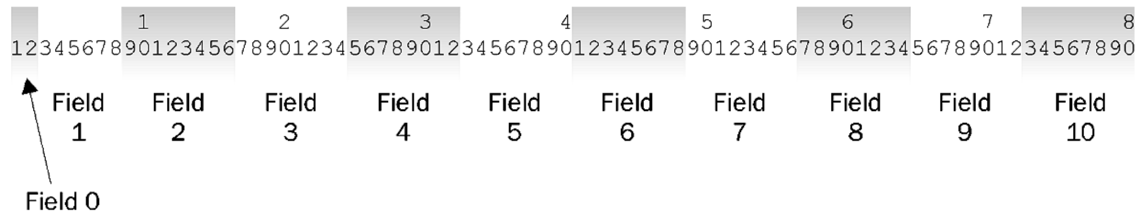

Figure 6.1 Organization of a data record into different fields.

Each record name is unique and is used to input specific data to the program. A comprehensive list of all the records used by GSTARS4 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 GSTARS4 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 GSTARS4.

6.2 Hydraulic Data

As described in the preceding chapters, GSTARS4 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 GSTARS4 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. Either quasi-steady or truly unsteady simulation can be used in GSTARS4 model with a choice of the user. Section 6.2.2 explains data requirements for quasi-steady simulation and data for unsteady flow routing can be found in section 6.2.3. Therefore, section 6.2.2 and 6.2.3 are mutually exclusive.

6.2.1 Channel Geometry, Roughness, and Loss Coefficient Data

The first step to model a river system using GSTARS4 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.

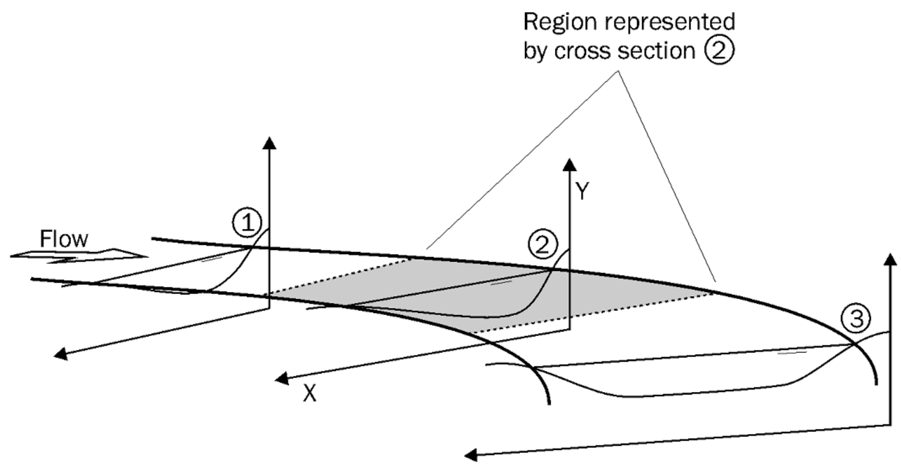

Figure 6.2 Schematic representation of the discretization of a reach by three cross sections.

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 GSTARS4 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 GSTARS4, 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. However, distance between adjacent cross section should be determined carefully for the numerical stability of the routing, because too small spacing may cause instability of the numerical solution, especially for high sediment concentration or transport capacity. 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 GSTARS4 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 GSTARS4 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.

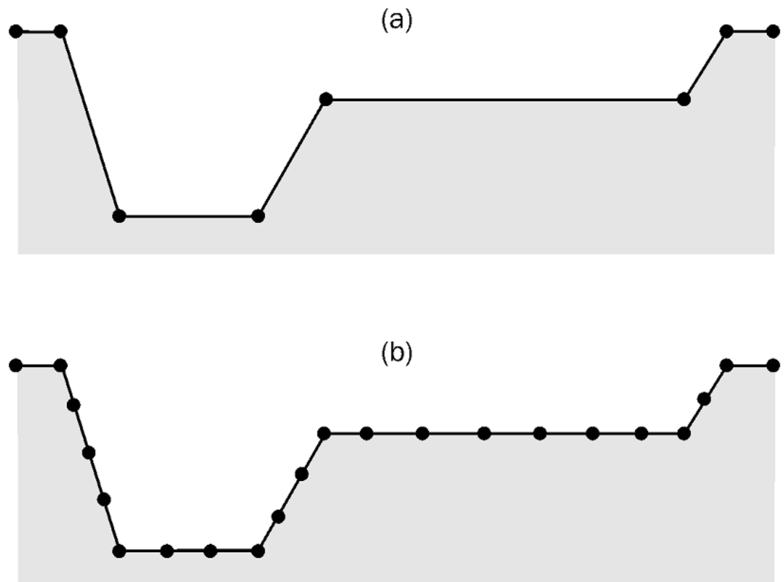

Figure 6.3 Example of a cross section. (a) minimum shape-preserving discretization for the cross section; (b) same cross section discretized with additional points.

The GSTARS4 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 GSTARS4 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 GSTARS4 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 GSTARS4, up to nine channel divisions may be defined, therefore up to nine different roughness coefficient values may be entered for each cross section. Manning, Chezy, 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

$$K_T = \sum_{j=1}^{N} \frac{1.49 A_j R_j^{2/3}}{n_j} = \sum_{j=1}^{N} K_j \tag{6.1}$$

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.

```
         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
```

Figure 6.4 Organization of cross section data in records.

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, GSTARS4 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.

GSTARS4 can use the Manning, Darcy-Weisbach, or Chezy 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 for Quasi-steady Flow Simulation

The hydraulic data necessary for a numerical simulation are water stages and corresponding surface elevation at certain points (boundary conditions). In GSTARS4, 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 GSTARS4, 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 GSTARS4, 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 $\Delta t = 1$ 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.

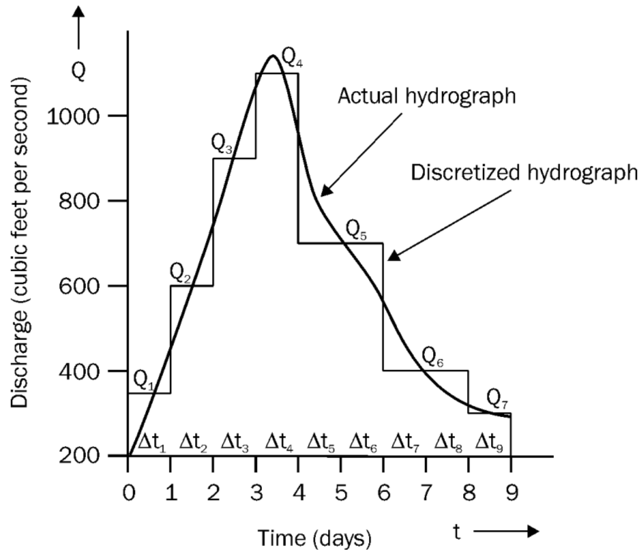

Figure 6.5 Discretization of input discharge hydrograph. Note that $\Delta t_1 = \Delta t_2 = \cdots = \Delta t_9 = \Delta t = 1$ day in this example.

Usually, the discretization process involves a consideration of accuracy, computational burden, and numerical stability, depending 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 GSTARS4, the relationship between stage and discharge is assumed to be in the form

$$\text{Stage (ft)} = C_1 \times Q^{C_2} + C_3 \tag{6.2}$$

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

$$\text{Stage (ft)} = 0.41 \times Q^{0.25} + 1000 \tag{6.3}$$

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 GSTARS4 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

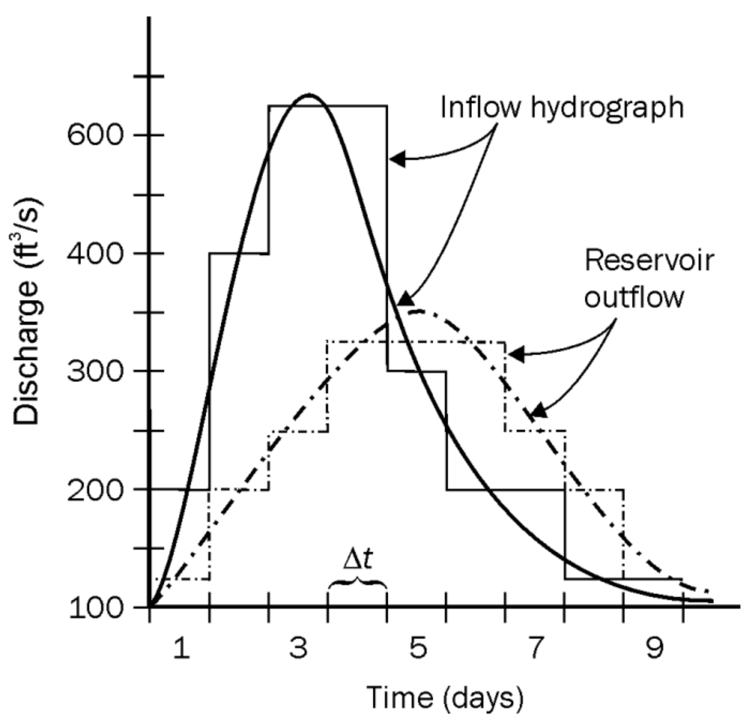

Figure 6.6 Idealized inflow and outflow hydrographs for reservoir routing calculations, with the corresponding discretized stepped hydrographs.

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 different 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.

6.2.3 Discharge and Stage Data for Truly Unsteady Flow Simulation

Unsteady flow simulation requires both upstream and downstream boundary conditions. Upstream boundary condition should be given by discharge. For downstream boundary conditions, some options, such as table of stages, rating curve, and table of discharge.

6.2.3.1 Upstream Flow Boundary Condition

GSTARS4 requires table of discharges for the upstream boundary condition. The discharge should be defined for each computational time step. Two records, UT and UB, records are required to define upstream flow boundary condition. UB record is required to define the table of discharges. Record UB consists of pair of time and corresponding discharge and UT record consists of number of data set.

For example, if an daily discharge is used for the upstream boundary condition for 9 days of simulation, as shown in figure 6.7, record UT should define 10 data set and UB should be given for 10 pairs of time and corresponding discharges, 9 days for each day another for the initial discharge i.e., discharge at $t = 0$. Linear interpolation between given discharges are used for GSTARS4 model. For example, if discharges are given for every 24 hours, then the discharge at 12 hour is mean value of those at 0 and 24 hours.

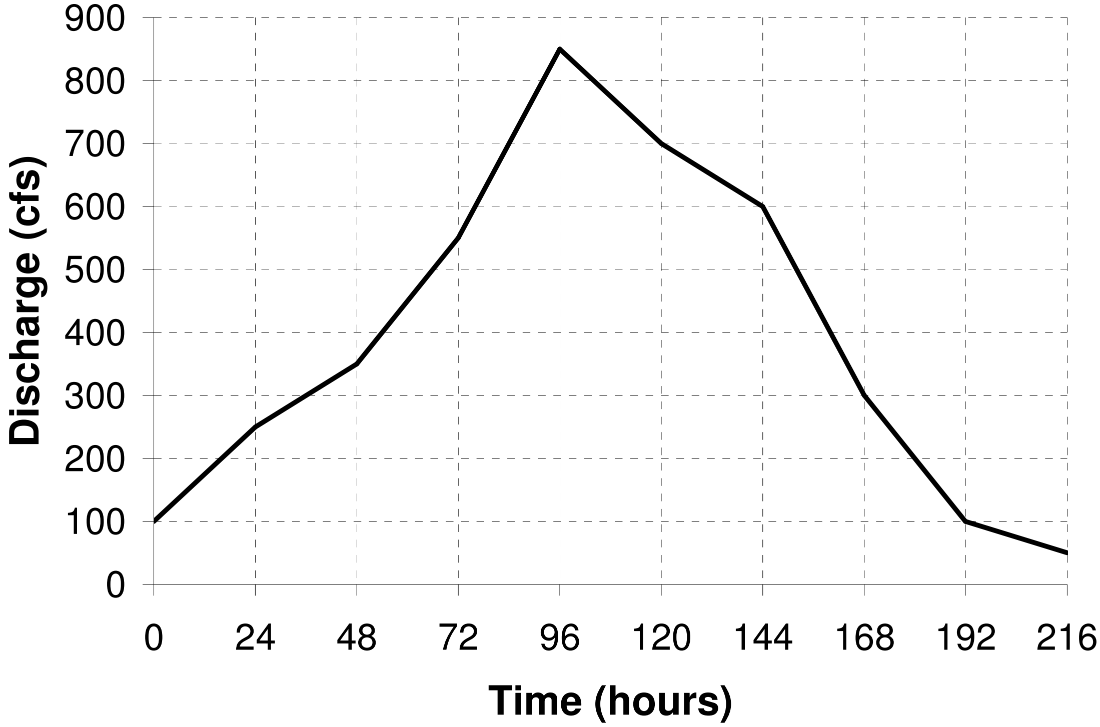

Figure 6.7 Hydrograph for the upstream boundary condition with computation time step for 24 hour, Δt = 24 hour.

Then, record UT should define 10 set would be used and 10 lines of UB records have to be given, the input data records for the upstream flow boundary would be:

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
U	T						2							1	0								
U	B														0						1	0	0
U	B													2	4						2	5	0
U	B													4	8						3	5	0
U	B													7	2						5	5	0
U	B													9	6						8	5	0
U	B												1	2	0						7	0	0
U	B												1	4	4						6	0	0
U	B												1	6	8						3	0	0
U	B												1	9	2						1	0	0
U	B												2	1	6							5	0

Time for record UB should be hour only. Field 1 of record UT should be 2 for GSTARS4 version.

6.2.3.2 Downstream Flow Boundary Condition

A data set for the downstream boundary condition is required for an unsteady flow simulation.

GSTARS4 has capability using three options for the downstream boundary condition, table of stage, table of discharge, and rating curve. One among these three options should

be selected by the user. For downstream boundary condition, DT and DB records should be in the input data regardless of options. DT record selects one among the three options and number of lines for DB records. DB records are defines detailed information of the downstream boundary condition.
Unsteady flow simulation needs initial condition of flow condition for entire reach and GSTARS4 model calculates the initial condition by conducting steady flow simulation with given upstream discharge and water surface elevation at the downstream boundary condition at t = 0. In case of using table of discharge or rating curve, D0 record is required to define, initial water surface elevation at the downstream boundary while table of stage provides initial stage in DB option.

(1) Table of stage
In case of using table stage, DT record should assign the option and number of lines used for DB records, similar to UT record.
Water surface elevation at the downstream boundary should be given by a table in DB records which consists of time, always in hour, and corresponding water stage. If the stage is given for 9 days with computational 24 hour of time step, as shown in figure 6.8, 10 should be defined by DT record and 10 pair of time and stage should be given by 10 lines of DB records. Similar to UT and UB record, one additional pair for DB is required for the initial water stage at t = 0. GSTARS4 assumes water stage varies linearly between two given values, similar to the upstream boundary condition.

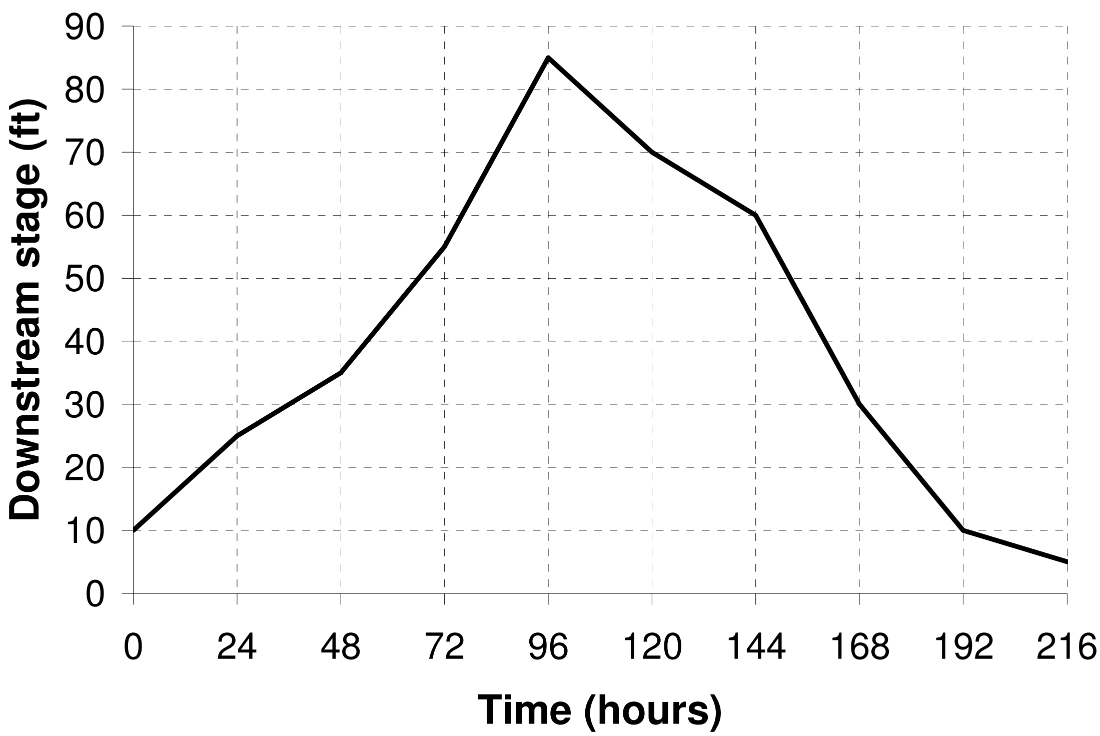

Figure 6.8 Water surface change at the downstream boundary with Δt = 24 hours.

The input file for this downstream boundary condition would be :

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
D	T						1							1	0								
D	B														0							1	0
D	B													2	4							2	5
D	B													4	8							3	5
D	B													7	2							5	5
D	B													9	6							8	5
D	B												1	2	0							7	0
D	B												1	4	4							6	0
D	B												1	6	8							3	0
D	B												1	9	2							1	0
D	B												2	1	6								5

“1” at the first field of DT record is option for table of stage.

(2) Table of Discharge

Option of table of discharge is almost the same as that of table of stage. DT record includes selection of the option and number of data pairs of DB. DB records consist of time and corresponding water discharge. Linear interpretation is also used for downstream discharge table also by GSTARS4.

For the initial flow condition along the reach, an additional D0 record, including the stage at t = 0. For example, the downstream discharge is given by figure 6.9 with initial water stage of 15 ft.

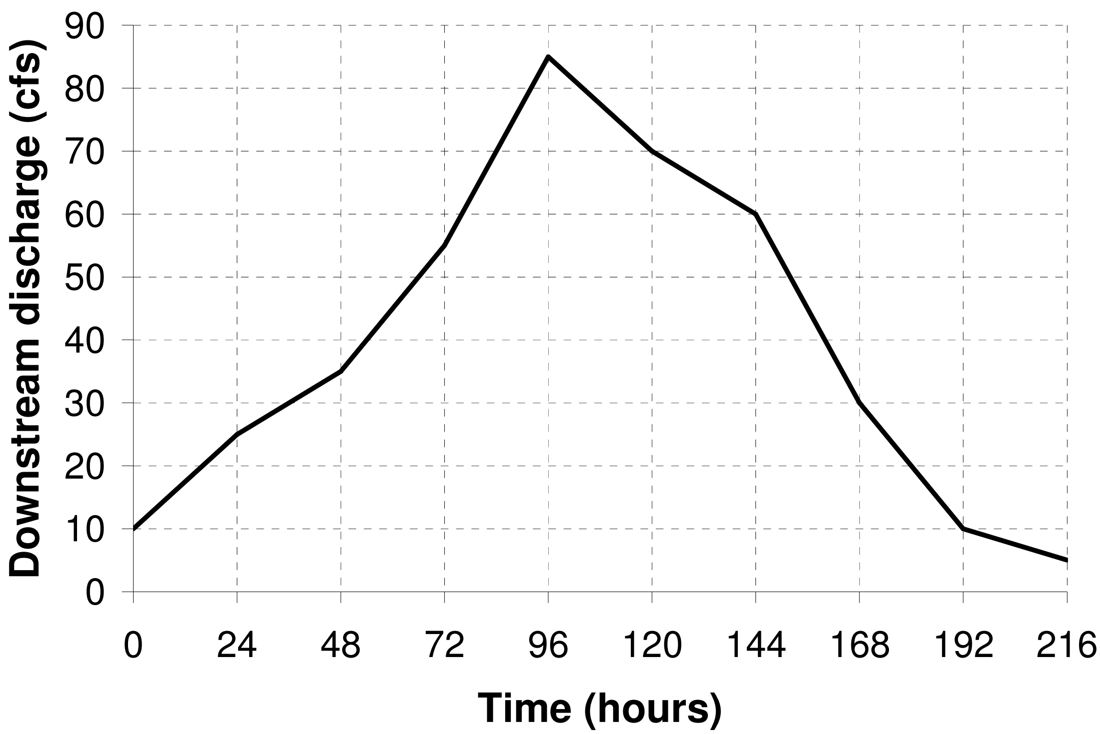

Figure 6.9 Hydrograph for the downstream boundary condition with Δt = 24 hour.

Then the input file for the downstream boundary condition would be :

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
D	T						2							1	0								
D	0					1	5																
D	B														0						1	0	0
D	B													2	4						2	5	0
D	B													4	8						3	5	0
D	B													7	2						5	5	0
D	B													9	6						8	5	0
D	B												1	2	0						7	0	0
D	B												1	4	4						6	0	0
D	B												1	6	8						3	0	0
D	B												1	9	2						1	0	0
D	B												2	1	6							5	0

"2" at the first field of DT record is option for table of stage.

(3) Rating Curve
Eq. (6.2) can be used as downstream boundary condition for unsteady flow simulation. Similar to table of discharge, D0 record should be given to define and compute the initial flow condition. For example, rating curve of Eq. (6.3) is used for the downstream boundary condition with 15 ft of initial water stage at the downstream boundary. Then the input data would be :

									1										2										3		
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2
D	T						9								1																
D	0					1	5																								
D	B											0	.	4	1					0	.	2	5					1	0	0	0

"9" and "1" at the first and the second field of DT record represents option for rating curve and 1 line for DB record, respectively.

6.3 Sediment Data

The information presented in the last section is enough to have GSTARS4 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 GSTARS4, 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, (Yang, 1984) 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, GSTARS4 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 GSTARS4 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 (HR Wallingford, 1990)
3	Toffaleti (1969)		
4	Engelund and Hansen (1972)	11	DuBuois (1879)
5	Ackers and White (1973)	12	Modified Laursen (Madden, 1993)
6	Yang (1973) + Yang (1984)		
7	Yang (1979) + Yang (1984)	13	Ashida and Michiue (1972)
8	Parker (1990)	14	Tsinghua Univ. (IRTCES, 1985)

In GSTARS4 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 GSTARS4 for each of the sediment transport equations. Sediment particles with sizes falling outside of the specified ranges will be immovable, 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 GSTARS4. 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, 2003) 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.

GSTARS4 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 GSTARS4, 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

$$Q_s = aQ^b \tag{6.4}$$

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

$$Q_s = 0.4Q^{1.2} \tag{6.5}$$

the input QR record would take the following format:

```
        1         2         3         4
12345678901234567890123456789012345678901234 5
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 GSTARS4, 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. Record 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. (6.4). In most practical cases, Eq. (6.4) represents only an approximation, and often a very poor one. Figure 6.10 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, GSTARS4 provides the facility to use Eq. (6.4) for those cases in which its use may be warranted.

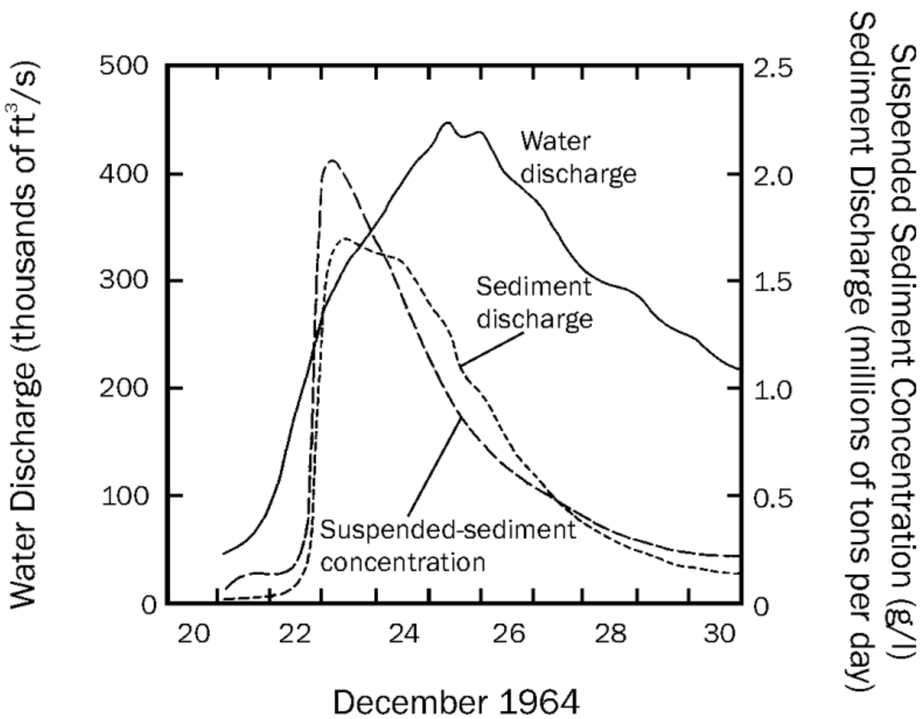

Figure 6.10 Suspended sediment concentration, sediment discharge, and water discharge, Willamette River at Portland, Oregon, December 21-30, 1964. (After Waananen et al., 1971.)

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 I1, IQ, IS records. The gradations must be known as a function of the water discharge or a function of discharge and time, 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
```

If the gradation of incoming sediment is only a function of water discharge during the simulation, IQ and IS records are required as shown above. However, the gradation can be function of time and water discharge, if the upstream inflow is controlled by human operation. For example, if the upstream boundary is a controlled gate of an upstream reservoir, then the gradation may vary with respect to time even with the same discharge. In general, more fine materials discharged from the upstream reservoir in the first stage of gate opening and the sediment size becomes coarser later on. Therefore, the gradation of incoming sediment should be a function of time also. I1, IQ, and IS records are required to define the function. As described above IQ and IS records are used to define the gradation with respect to the water discharge and additional I1 record should be given to define relationship between the gradation and time. For example, the following hypothetical size gradation curves with respect to water discharges for 10 time steps :

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

And another size gradation for the next 15 time steps as follows:

Size fraction no.	Q = 1,000 ft^3/s	Q = 5,000 ft^3/s	Q = 12,000 ft^3/s
1 (fine sand)	35%	40%	40%
2 (medium sand)	45%	35%	30%
3 (coarse sand)	20%	25%	30%

Two I1 records are required, one to define the time 10 time step of the first gradation curve and another for the next 15 time step, then the formation of I1, IQ, and IS records would be:

									1										2										3		
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2
I	1					1	0																								
I	Q						3					1	0	0	0					5	0	0	0				1	2	0	0	0
I	S											0	.	5	0					0	.	6	0					0	.	6	0
I	S											0	.	5	0					0	.	3	0					0	.	2	5
I	S											0	.	0	0					0	.	1	0					0	.	1	5
I	1					1	5																								
I	Q						3					1	0	0	0					5	0	0	0				1	2	0	0	0
I	S											0	.	3	5					0	.	4	0					0	.	4	0
I	S											0	.	4	5					0	.	3	5					0	.	3	0
I	S											0	.	2	0					0	.	2	5					0	.	3	0

The summation of time steps of I1 records should be identical to the total time step defined in IT record. The unit for I1 records is also the same unit that defined in IT records.

GSTARS4 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).

GSTARS4 solves the sediment continuity equation, Eq. (3.4), to route sediments through a channel reach. Eq. (3.4) 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. (3.17). The incoming sediment is used to represent $Q_{s,i-1}$, 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 I1/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, GSTARS4 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 6.11. In GSTARS4, 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 6.11 (see also figure 6.12), 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
```

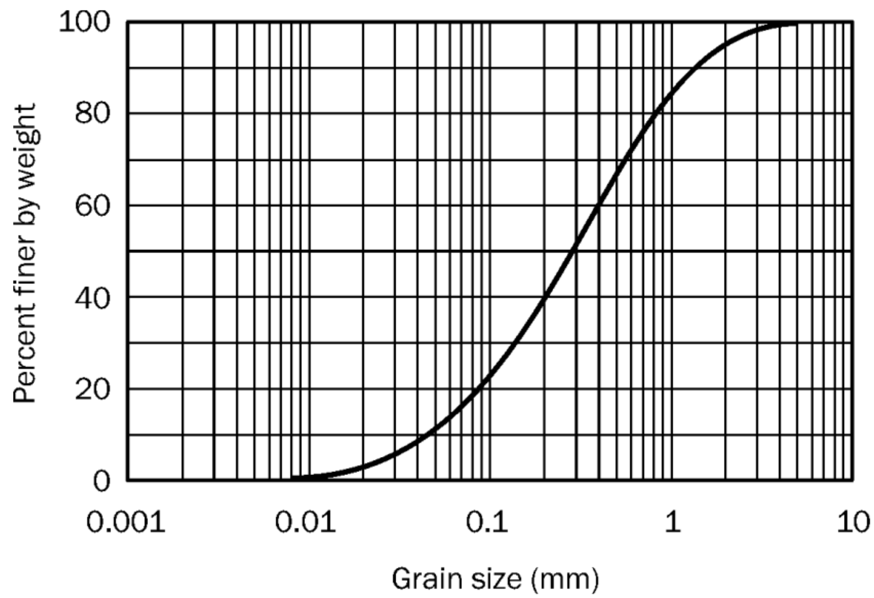

Figure 6.11 Hypothetical size gradation curve.

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:

$$\gamma_m = \gamma G(1 - p_0) \tag{6.6}$$

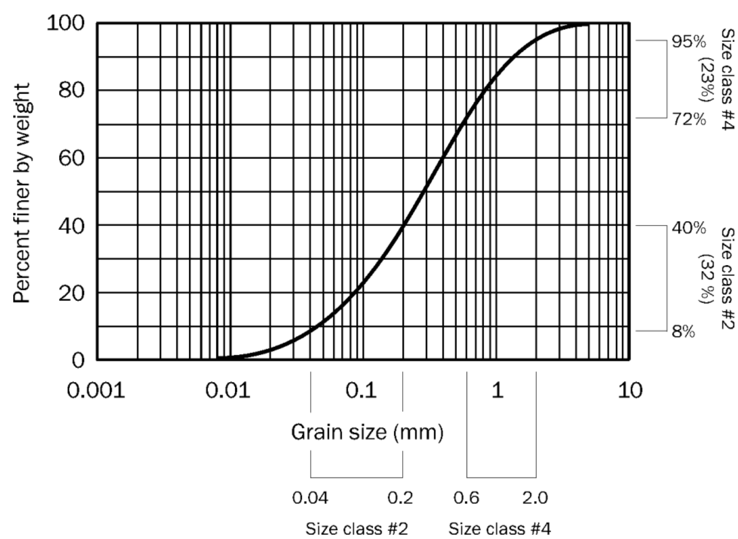

Figure 6.12 Schematic representation on how to extract data from gradation curves for GSTARS4 input. Shown are the second and fourth size classes from a split into five size classes (see text). The gradation curve is the same of figure 6.11.

where γ = specific weight of water at 4ºC; G = specific gravity (G = 2.65 in GSTARS4); and p_o = porosity of the sediment. GSTARS4 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. (6.6) 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):

$$\gamma_m^* = \frac{1}{\sum_{i=1}^{N} \frac{p_i}{\gamma_{mi}}} \tag{6.7}$$

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. (6.6).

The dry specific weight of a size fraction depends on the texture. Especially for very fine sediments, such as clay and silts, their dry specific weight varies whether they are on river or reservoir bed. In general, silt and clay on the reservoir bed are less dense than those on the river bed (Yang, 1996 and 2003). Therefore, the dry specific weight of each sediment size group, especially fine materials, should vary with respect to cross section location, if there is significant change of the flow condition, such as alternation of river and reservoir. The variation of the dry specific weight with respect to location can be defined by SL record in GSTARS4. SL record must be specified for each cross section. If there is 3 sediment size group, each SL record consists of 3 column. In SL records, a SL record defines dry specific weight of sediment at a cross section, $\gamma_{m,i,k}$

$$\gamma_{m,i,k} = n_{i,k} \times \gamma_{mk} \tag{6.8}$$

where $n_{i,k}$ = a user specified positive multiplication factor for defining dry specific weight of size faction k at cross section i. γ_{mk} , dry specific weight of sediments of size fraction k, given by SF and SG records.

For example, if hypothetical sediment group and their dry specific density are given by SF and SG records as follows:

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
S	F						5																
S	G		0	.	0	0	2				0	.	0	0	4							3	0
S	G		0	.	0	0	4				0	.	0	6	2							7	0
S	G		0	.	0	6	2				0	.	0	5	0							9	7

If the first sediment size group has dry specific weight of 60lb/ft^3 = 2×30lb/ft^3 for only cross section 1 and 2, then n_1 = 2 for cross section 1 and 2. And the dry specific weight for other size fraction, $n_2 = n_3 = 1$, and other cross section, then SL records would be :

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
S	L				2	.	0						1	.	0						1	.	0
S	L				2	.	0						1	.	0						1	.	0
									.	.	.	.	.	.									
S	L				1	.	0						1	.	0						1	.	0
S	L				1	.	0						1	.	0						1	.	0
S	L				1	.	0						1	.	0						1	.	0
S	L				1	.	0						1	.	0						1	.	0
S	L				1	.	0						1	.	0						1	.	0
S	L				1	.	0						1	.	0						1	.	0

One SL record is necessary for each cross section, and the data is entered to the upstream-most cross section and proceeding in the downstream direction. Total number of SL records should be the same as the number cross section given by record NS (section 6.2.1).

If there is no significant change of the flow condition or composition of silt or clay is negligible, there is no need to define variation of the dry specific weight with respect to cross section location.

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 6.12. 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 6.11, 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. GSTARS4 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 6.13: 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 6.13 would be

```
         1         2         3         4
123456789012345678901234567890123456789012345

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
...
```

		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	-

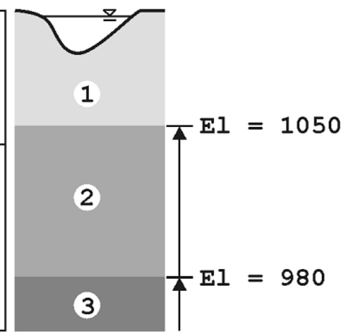

Figure 6.13 Example of layered river bed.

The same information can be entered using NB/BG/EL sets of records. If the bed sample presented in figure 6.13 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 GSTARS4 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 GSTARS4. Of course that the classes defined in table 6.4 can be used in GSTARS4, 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 ($N \leq 10$). Select the lower and upper bound diameters for each interval i in the following way:

$$d_{\min,i} = 2^{a+(i-1)\frac{b-a}{N}}, \; i = 1, \ldots, N \tag{6.9}$$

and

$$d_{\max,i} = 2^{a+i\frac{b-a}{N}}, \; i = 1, \ldots, N \tag{6.10}$$

As an example, consider the grain size distribution presented in figure 6.11. 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

$$d_{mean,i} = \sqrt{d_{\min,i} \times d_{\max,i}} \tag{6.11}$$

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 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

$$\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \tag{6.12}$$

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:

$$f(d) = \frac{1}{\sigma_z d \sqrt{2\pi}} \exp\left\{ -\frac{(\ln d - \mu_z)^2}{\sigma_z^2} \right\} \tag{6.13}$$

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 μ_z = -1.04 and σ_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 6.14. 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.

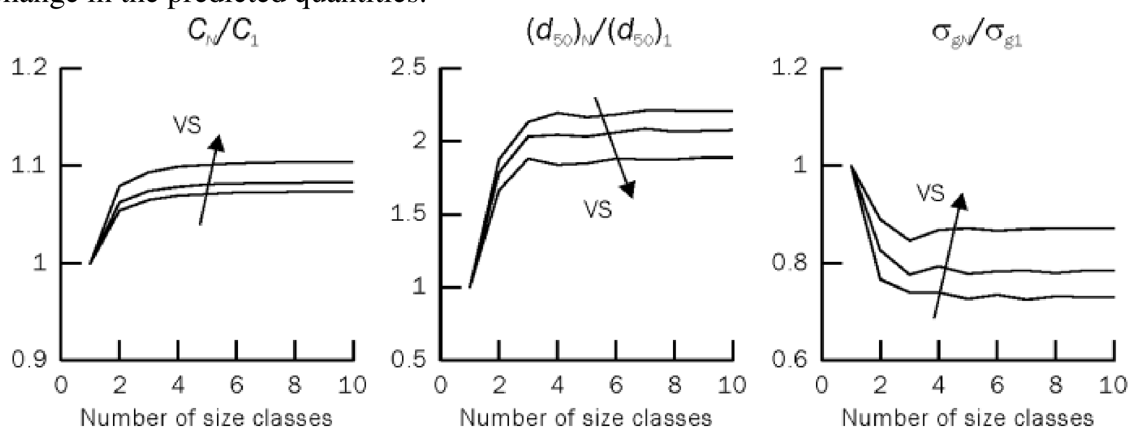

Figure 6.14 Normalized sediment concentration, mean diameter, and standard deviation of the transported sediment mixture using Yang (1973) sand transport equation. The arrows show the direction of increasing values of the unit stream power, *VS*.

This simple study was repeated using a similarly synthesized bed distribution in the range of sand and gravel (1 to 64 mm), with μ_z = 2.08 and σ_z = 0.7. The Meyer-Peter and Müller (1948) equation was used. The results, shown in figure 6.15, 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.

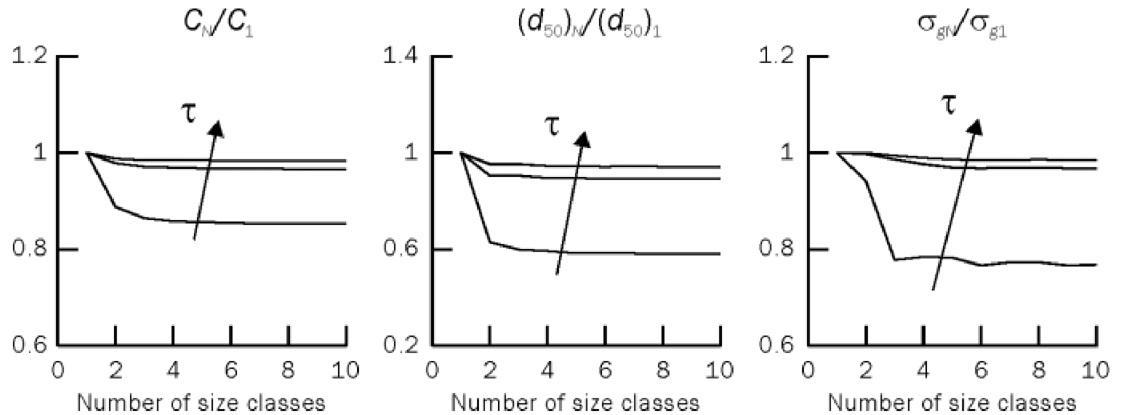

Figure 6.15 Normalized sediment concentration, mean diameter, and standard deviation of the transported sediment mixture using Meyer-Peter and Müller (1948) transport equation. The arrow shows the direction of increasing values of the bed shear stress, τ.

6.3.4 Cohesive Sediment Transport Parameters

The parameters necessary to model cohesive sediment transport are schematically represented in figure 6.16. Because these parameters are highly case dependent, and because they vary within orders of magnitude, GSTARS4 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 6.16, *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% ≤ *ERLIM* ≤ 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 6.17 (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 carrying capacity concept used for the larger particle sizes. The transport capacity is computed using the equation selected in record SE.

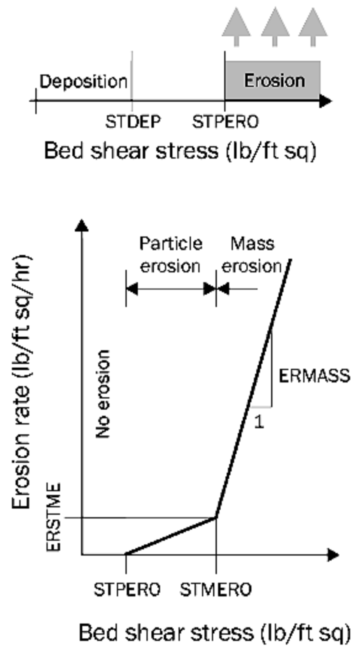

Figure 6.16 Schematic representation of the parameters necessary to model the transport of cohesive sediments.

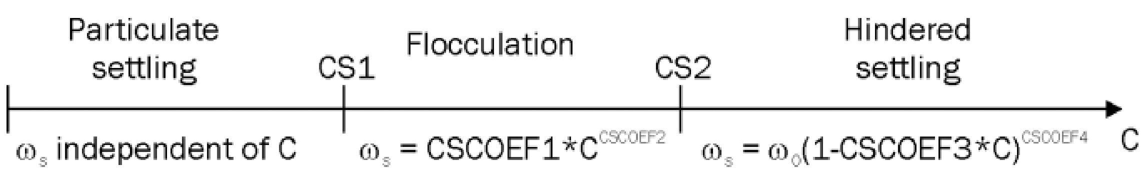

Figure 6.17 Representation of the parameters necessary to describe the fall velocity of cohesive sediments, ω_s, in water.

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 6.18.

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 6.18, 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 records GSTARS4 assumes there is no transfer of sediment across stream tube boundaries.

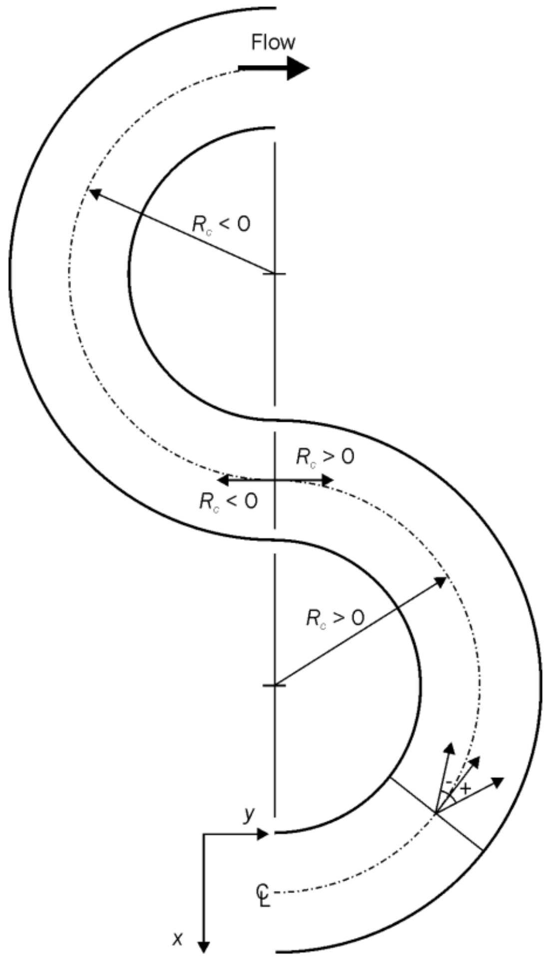

Figure 6.18 Schematic top view of a two-loop meander. Note the reference system used (at inlet of meander) and the convention used to define positive and negative curvature radii.

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 GSTARS4, 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 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 GSTARS4. 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

GSTARS4 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, .DBG., and .QDB. 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 GSTARS4 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 GSTARS4.

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 supersede 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 GSTARS4 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 running 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 GSTARS4 model.

6.6 Tributary Inflow/Outflow Data

Theoretical background of tributary is explained in section 2.1.5. There are two options to define tributary influences. One is table form of water and sediment inflow from a tributary and the other is interchanges of water and sediments depending on the flow condition in the main channel. These two options are compatible in a GSTARS4 simulation.

6.6.1 Table Form of Inflows from Tributaries

This section explains how to define input format for tributary inflow following a theoretical background in section 2.1.5.1.

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 GSTARS4 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     0.20    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, 20% 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 GSTARS4 runs, starting by using uniform mixing across the stream 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).

6.6.2 Interchanges between a Tributary and the Main Stream

This section explains how to define values for a input format of tributary influence following a theoretical background in section 2.1.5.2.

GSTARS4 can simulate interchanges of water and sediments between tributaries and the main channel depending on flow condition in the main channel as described in section 2.1.5.2. TR record and TI record(s) are necessary for this case. TR record arranges computational memory for interchanges. See appendix A for further details. Similar to LI record, a TI record should be located after the RH record corresponding to the cross section located immediately downstream from the tributary. A TI record has to indicate coefficients and bed elevation at a tributary mouth as shown in Eq. (2.24). For example, TI record with a = 4150, b = 2.21, and h_b = 208.1 would be :

									1										2				
1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4
T	I			4	1	5	0					2	.	2	1				2	0	8	.	1

6.7 Using GSTARS4 in Command Line Mode

After preparing the input data file using a plain ASCII text editor (using blank spaces, not tabs), GSTARS4 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:\> GSTARS4.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 GSTARS4 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 GSTARS4 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 GSTARS4 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.

sample.qdb: The .QDB file contains water and sediment passed through the downstream boundary. For the convenience of further uses, gradation of sediment is also included. Information from this file can be used as the upstream boundary condition for a downstream routing.

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 GSTARS4, 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

GSTARS3 data files will run successfully in GSTARS4 without any change. Many of the code and algorithms of GSTARS4 were rewritten in order to upgrade the performance of the model. As a result, a GSTARS4 run using input data files from earlier versions may, in general, produce slightly different but similar results from those of earlier versions.

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