Available online at www.sciencedirect.com
ScienceDirect
International Journal of Sediment Research 23 (2008) 197-211
ELSEVIER
INTERNATIONAL JOURNAL OF SEDIMENT RESEARCH
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GSTARS computer models and their applications, part I: theoretical development

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Abstract

GSTARS is a series of computer models developed by the U.S. Bureau of Reclamation for alluvial river and reservoir sedimentation studies while the authors were employed by that agency. The first version of GSTARS was released in 1986 using Fortran IV for mainframe computers. GSTARS 2.0 was released in 1998 for personal computer application with most of the code in the original GSTARS revised, improved, and expanded using Fortran IV/77. GSTARS 2.1 is an improved and revised GSTARS 2.0 with graphical user interface. The unique features of all GSTARS models are the conjunctive use of the stream tube concept and of the minimum stream power theory. The application of minimum stream power theory allows the determination of optimum channel geometry with variable channel width and cross-sectional shape. The use of the stream tube concept enables the simulation of river hydraulics using one-dimensional numerical solutions to obtain a semi-two-dimensional presentation of the hydraulic conditions along and across an alluvial channel. According to the stream tube concept, no water or sediment particles can cross the walls of stream tubes, which is valid for many natural rivers. At and near sharp bends, however, sediment particles may cross the boundaries of stream tubes. GSTARS3, based on FORTRAN 90/95, addresses this phenomenon and further expands the capabilities of GSTARS 2.1 for cohesive and non-cohesive sediment transport in rivers and reservoirs. This paper presents the concepts, methods, and techniques used to develop the GSTARS series of computer models, especially GSTARS3.

Key Words: Numerical modeling, Sediment transport, Backwater computations, Stream tubes, Stream power minimization

1 Introduction

The study of natural river changes and the interference of man in natural water bodies is a difficult but important activity, as increasing and shifting populations place more demands on the natural sources of fresh water and have increasing impact in riparian ecosystems. Although the basic mechanical principles for these studies are well established, a complete analytical solution is not known but for the most basic cases. The complexity of flow movement and its interaction with its deformable boundaries have precluded the development of closed form solutions to the governing equations that describe the mechanical behavior of fluid and solid-fluid mixtures. As a result, alternative techniques have been developed to provide quantitative predictions of these phenomena as an aid to engineering projects and river restoration efforts. Numerical modeling is one such technique.

To make a mathematical formulation of a computer model, certain assumptions and simplifications may be needed, and the solutions thus obtained are approximations of the prototype. A thorough understanding of the physical phenomena and the theories relevant to their mathematical formulation is

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Note: The original manuscript of this paper was received in July 2007. The revised version was received in May 2008. Discussion open until Sept. 2009.

critical to the success of developing a computer model for solving river and reservoir sedimentation problems. After the solutions are obtained from a computer model, the investigator must have the ability to use his/her knowledge and experience to make correct and appropriate interpretation of the results. Figure 1 illustrates the computer modeling cycle from prototype to modeling results (Simões and Yang, 2006).

The cycle starts with the prototype being studied and ends with the interpretation of model results to withdraw conclusions about it. In the first interpretation step, all the relevant physical processes that were identified in the prototype are translated into governing equations that are compiled into the mathematical model. The mathematical model constitutes the first approximation to the problem and it is at this time that many simplifying approximations are made, such as steady-state versus unsteady, one- versus two- versus three-dimensional formulations; simplifying descriptions of turbulence; etc.

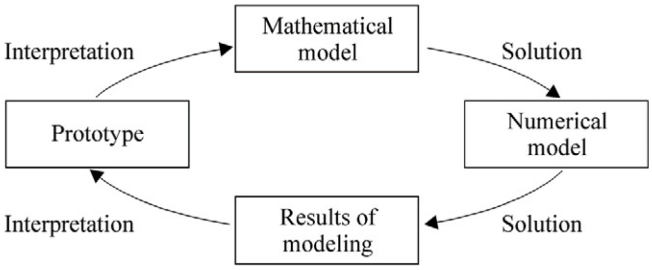

Fig. 1 Computer modeling cycle, from prototype to modeling results

Next, a solution step is required to solve the mathematical model. The numerical model embodies the numerical techniques used to solve the set of governing equations that form the mathematical model. In this step one chooses, for example, finite-difference versus finite-element versus finite-volume discretization techniques; selects the approach to deal with the nonlinear terms; adopts a time-stepping method; etc. This is a further approximating step, because the partial differential equations are transformed into algebraic equations, which are approximate but not equivalent to the former.

Finally, the data produced by the computer model needs to be interpreted and placed in the appropriate prototype context. This last step closes the modeling cycle and ultimately provides the answer to the problem that drives the modeling efforts. A few iterations of this process may be needed, in which the mathematical and numerical models are revised as a result of the analysis of the numerical data and its interpretation in the context of the prototype.

The choice of model for each specific problem should take into account the requirements of the problem, the knowledge about the system, and the data available. The model must take into account all the significant phenomena that are known to occur in the system and that will influence the aspects that are being studied. However, model complexity is limited by the available data. At this time there is no universal best model that can be applied to every problem. The success of a study depends, to a large degree, on the engineer's understanding of fluvial processes, associated theories, and the capabilities and limitations of computer models. In many cases, the selection of a modeler is more important than the selection of the computer model.

A generalized water and sediment routing computer model should have the ability to solve complicated river and reservoir engineering and morphology problems with limited available data. Its complexity should be commensurate with the data at hand, but should also offer the possibility to include more complex phenomena as the necessary data become available. The GSTARS models (GSTARS stands for Generalized Stream Tube model for Alluvial River Simulation), especially GSTARS 2.1 and GSTARS3, have been developed with those requirements in mind (Moninas and Yang, 1986). In GSTARS3, GSTARS stands for Generalized Sediment Transport model for Alluvial River Simulation because sediment particles are allowed to cross the boundaries of stream tubes at or near a sharp bend.

GSTARS are a series of computer models developed by the US Bureau of Reclamation for alluvial river and reservoir sedimentation studies. A series of needs could not be met, all at once, by the generally available models. To address those needs, a unique set of features was specified to guide the model development. Therefore, the GSTARS models were developed with the following characteristics:

(1) GSTARS should be able to compute hydraulic parameters for open channels with fixed as well as with movable boundaries.

(2) It should have the capability of computing water surface profiles in the subcritical, supercritical, and mixed flow regimes, i.e., in combinations of subcritical and supercritical flows without interruption.

(3) It should be able to simulate and predict the hydraulic and sediment variations both in the longitudinal and in the transverse directions.

(4) 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.

(5) It should incorporate site specific conditions such as channel side stability and erosion limits.

(6) It should be able to simulate and predict sediment transport by size fraction so that the formation and destruction of armor layer can be determined for long-term simulation.

(7) It should incorporate field data requirements that are not too extensive or too difficult to obtain.

(8) It must be based on sound theories and the numerical solutions must be stable and accurate.

In the present paper the governing equations and numerical techniques used in GSTARS are presented with some detail. Section 2 presents the main governing equations and section 3 contains the details of how their implementation is achieved in the GSTARS computer programs. This paper constitutes part 1 of a two-paper series. In part 2 of this series laboratory and field applications done by the authors and co-workers are presented, and by others in different institutions, to illustrate the capabilities of GSTARS models for solving river morphology, river engineering, and sedimentation problems.

Among the GSTARS models, only GSTARS2.1 and GSTARS3 are currently available for public use. GSTARS2.1 is an improved version of GSTARS2.0 with user interphase to make the model more users friendly. GSTARS2.1 is mainly intended for alluvial rivers. GSTARS3 is the third and the latest version of GSTARS model without user interphase.

In addition to the capabilities of previous versions, GSTARS3 emphasizes reservoir sedimentation, non-equilibrium sediment transport, and cohesive sediment transport. If a user is interested in non-cohesive sediment transport in rivers only, GSTARS2.1 should be adequate for solving river engineering and sedimentation problems without using the more sophisticated and more comprehensive GSTARS3 model.

2 Theorectical background

Many of the sediment transport models used in river engineering are one-dimensional (1D), especially those used for long-term simulation of a long river reach. 1D models generally require the least amount of field data for calibration and testing. The numerical solutions are more stable and require the least amount of computer time and capacity. Although one-dimensional models are unable to simulate truly two- or three-dimensional local phenomena, they can be very effective to predict bulk, reach-averaged quantities, such as flow velocity, bed friction, sediment concentrations, etc. An essentially one-dimensional approach was adopted in GSTARS, augmented by the use of stream tubes to provide the ability to compute lateral variations in the cross section—a semi-two-dimensional approach that does not require the complexity of traditional two-dimensional (2D) models, as explained later in section 2.2.

2.1 The flow equations

1D models are usually based on the same conservation principles as the 2D and three-dimensional (3D) models, i.e., the conservation of mass and momentum. Conservation of mass (the continuity equation) in a 1D model can be expressed as

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_l \tag{1}$$

where A = cross-sectional area of the flow, Q = water discharge, q_l = lateral inflow per unit length, t = time, and x = distance. Conservation of momentum can be expressed by

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+gA\frac{\partial \eta}{\partial x}+gA\left(S_f-S_0\right)=0 \tag{2}$$

where S_f = friction slope, S_0 = bed slope, β = momentum correction coefficient $(\beta\approx 1)$, and g = gravitational acceleration. Eqs. (1) and (2) are known as the de Saint Venant equations and can be amply found in the literature—see, for example, Cunge et al. (1980). They assume that all the main variables are uniform across the cross section, that the bed slope is small, and that all curvature effects can be neglected. Finally, the friction slope is assumed to be a function of the flow, such that

$$S_f = \frac{Q|Q|}{K^2} \tag{3}$$

where K = conveyance, which can be calculated using a resistance function, such as Manning's or Chézy's.

2.2 The stream tube concept

The basic concept and theory regarding streamlines, stream tubes, and stream functions can be found in textbooks of fluid mechanics (Liggett, 1994). In this section, only some of the basic concepts are given, as they are applicable to all GSTARS computations.

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 cross sectional area. Figure 2 illustrates the application of this concept in GSTARS models. The use of stream tubes enables us to obtain semi-two-dimensional variations of the velocity field along and across a river by solving one-dimensional equations along each stream tube. Because the concept of stream tube is based on potential flow theory, no secondary current or super elevation can be simulated. After the hydraulic conditions in each stream tube are determined, sediment transport formulas can be used for sediment routing for the determination of scour and deposition along each stream tube resulting in uneven distribution of scour and deposition along stream tubes and across a river. Thus semi-three-dimensional variations of bed geometry and profile can be simulated by the use of the stream tube concept.

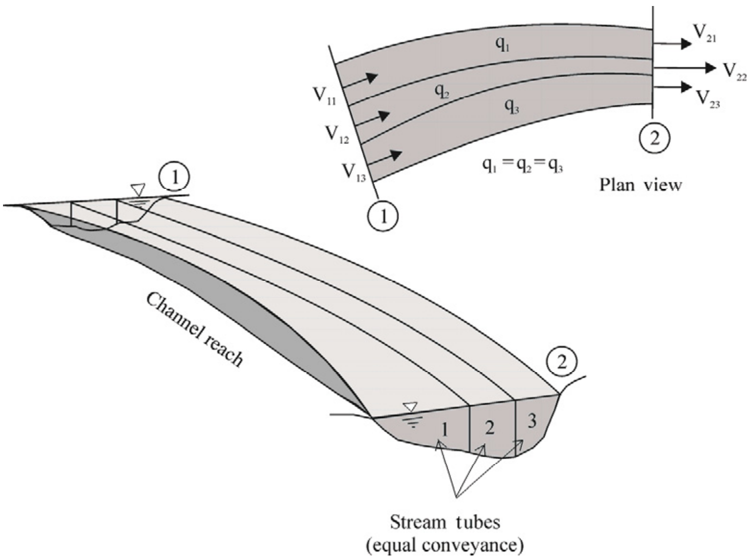

Fig. 2 Schematic representation illustrating the use of stream tubes between two cross sections, numbered 1 (upstream) and 2 (downstream)

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

$$\frac{F_p}{\gamma} + \frac{V^2}{2g} + D = H_t = \text{Constant} \tag{4}$$

where F_p = pressure acting on the cross section, γ = unit weight of water, D = hydraulic head, and V = flow velocity. In GSTARS, Eq. (4) is used along each stream tube, but H_t is reduced along the direction of the flow due to friction and other local losses.

2.3 Sediment transport

The basis for sediment routing computation in 1D models is the equation of sediment conservation:

$$\frac{\partial Q}{\partial x} + \eta \frac{\partial A_d}{\partial t} + \frac{\partial A_s}{\partial t} - q_{lat} = 0 \qquad (5)$$

where Q_s = volumetric sediment discharge, η = volume of sediment in a unit bed layer volume (one minus porosity), A_d, A_s = sediment volume in bed and in suspension, respectively, t = time, and q_{lat} = lateral sediment inflow. If the change of suspended sediment concentration in a cross section is much smaller than the change of river bed and if the parameters in the sediment transport function for a cross-section can be assumed to remain constant during a time step, Eq. (5) simplifies to (Simões and Yang, 2006)

$$\eta \frac{\partial A_d}{\partial t} + \frac{dQ_s}{dx} = q_{lat} \qquad (6)$$

Sediment routing computations in GSTARS models is based on Eq. (6) applied separately for each stream tube.

2.4 Minimum energy dissipation rate and minimum stream power

For alluvial rivers with adjustable boundaries there are more unknowns than independent equations available for solving them. Consequently, conventional fluvial hydraulics with sediment transport is indeterminate without using some site specific empirical relationships or assumptions. Moreover, fluvial models usually assume that the channel width is constant in time and all bed variations are done in the vertical direction. The minimum energy dissipation rate theory (Yang, 1996 and 1992; Yang and Song, 1986 and 1979; Chang, 1979 and 1990) can be derived from thermodynamic analogy between a thermosystem and a river system (Yang, 1971). The theory also can be derived directly from mathematical arguments (Yang, 1992; Yang and Song, 1979 and 1986). The application of this theory can provide us the needed additional independent theoretical equation(s) for solving fluvial hydraulic problems.

The minimum energy dissipation rate theory states that for a closed and dissipative system in a state of dynamic equilibrium condition, the energy dissipation rate must be at its minimum value. The minimum value depends on 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. However, the system will adjust itself in such a manner that the energy dissipation rate can be reduced to a minimum and regain equilibrium. Under equilibrium condition, an open system can be converted to a closed system so the theory is applicable.

Some of the “extremal hypotheses” (ASCE, 1998) have been used for the determination of river width adjustments. Unlike the theory of minimum energy dissipation rate, these hypotheses are based on empirical or field observations without rigorously derived from established theories and mathematics. The theory of minimum unit stream power and the theory of minimum stream power are simplified versions of the general minimum energy dissipation rate theory (Yang and Song, 1986).

Due to the dynamic nature of a natural river, it is difficult and may not be possible for a river to reach its true equilibrium condition. However, a river will adjust its width, depth, channel cross-sectional shape, and longitudinal bed profile to reduce its energy dissipation rate in the process of self adjustment. The GSTARS models utilize the second part of the minimum energy dissipation rate, as stated above, for the determination of optimum channel geometry and profile.

For open channel flows, the minimum energy dissipation rate theory can be reduced to the minimization of stream power γQS, where γ = specific weight of water, Q = water discharge, and S = longitudinal channel or energy slope. Because γ is a constant for water, the total minimum stream power theory can be expressed by

$$\phi_T = \int QSdx = \text{a} \quad \text{minimum} \qquad (7)$$

In the GSTARS models, Eq. (7) is used to determine channel width variation.

3 Implementation details

The theoretical principles described in the previous section are the basis for many numerical models that describe river and reservoir systems (Chang, 1990; Holly et al., 1990; USACE, 1993; Hudson et al., 2005), just to name a few. The major differences are in the choice of numerical techniques to solve the equations and to deal with complex boundary geometry. In this section we present the approaches used in the GSTARS models to solve the governing equations that describe the fluid flow and sediment movement phenomena of interest in river and reservoir systems. Only broad strokes are used here and the interested reader is referred to Yang and Simões (2002) for more detailed information.

3.1 Hydraulic computations

The numerical solutions of GSTARS models are based on the uncoupled finite-difference method, i.e., rout water first and then rout sediment. The standard step method is used in all GSTARS models for water-surface profile computation of subcritical flows. The energy equation for open channel flows is

$$Z + Y + \alpha \frac{V^2}{2g} + H \tag{8}$$

where Z = bed elevation, Y = water depth, V = flow velocity, α = velocity distribution coefficient, H = elevation of the energy line above the datum, and g = gravitational acceleration. For the reaches where an hydraulic jump is detected, the momentum equation is used instead:

$$\frac{Q\gamma}{g}\left(\beta_2 V_2 - \beta_1 V_1\right) = p_1 - p_2 + W_g \sin\theta - F_f \tag{9}$$

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 θ is small and if $\beta_1 = \beta_2$, Eq. (9) can be reduced to

$$\frac{Q^2}{A_1 g} + A_1 y_1 = \frac{Q^2}{A_2 g} + A_2 y_2 \tag{10}$$

Conjunctive use of Eqs. (8) and (10) allows GSTARS to compute water-surface profiles through sub-critical, hydraulic jumps and supercritical flows without interruption. Molinas and Yang (1985) provide detailed step-by-step methods of water-surface profile computations for single and divided channels. Manning's, Chezy's, or Darcy-Weisbach's formulas are available for the computation of energy loss due to friction, contraction, expansion, and other local losses. Average friction slope, geometric mean friction slope, and average conveyance methods also are available user options (Yang and Simões, 2002).

GSTARS models are quasi-steady flow models representing an unsteady hydrograph by a series of steps of constant discharge Q_i with a finite duration Δt_i. Different values of Δt_i can be selected to have a more economic and accurate approximation of the true hydrograph.

3.2 Sediment routing

GSTARS employs an uncoupled approach to sediment routing. This means that the backwater profiles are computed first, followed by the sediment routing and bed changes. In this type of uncoupled method, it is assumed that the computed hydraulic parameters are frozen during sediment routing computations.

The change in the volume of bed sediment due to deposition or scour is calculated as

$$\Delta A_d = (aT_{i-1} + bT_i + cT_{i+1})\Delta Z_i \tag{11}$$

where T = top width, ΔZ = change in bed elevation (positive for aggradation, negative for scour), i = cross section index, and a, b, and c = constants that must satisfy $a + b + c = 1$. There are many possible choices for the values of a, b, and c. $a = c = 0$ and $b = 1$ assumes that the wetted perimeter at station i represents the perimeter for the entire reach. $b = c = 0.5$, and $a = 0$ emphasizes the downstream end of the study reach. The standard values used in GSTARS are $a = c = 0.25$, and $b = 0.5$, but other combinations can be used. The choice of different combinations of these parameters reflect a tradeoff between accuracy and numerical stability.

The derivative terms in Eq. (6) are approximated by

$$\frac{\partial A_d}{\partial t} = \frac{\left(aT_{i-1} + bT_i + cT_{i+1}\right)\Delta Z_i}{\Delta t} \tag{12}$$

$$\frac{\partial Q_s}{dx} = \frac{Q_{s,i} - Q_{s,i-1}}{\left(\Delta x_t + \Delta x_{i-1}\right)/2} \tag{13}$$

where Δx_i distance between cross section i and $i+1$, Δt = time step interval, and $Q_{s,i}$ sediment transport rate at cross section i. The parameters *a*, *b*, and *c* in Eq. (12) play the same role as those in Eq. (11) and are subject to the same constraint ($a + b + c = 1$), but they can be chosen independently. Sediment routing is computed for each stream tube in a 1D manner. The bed elevation change in each sediment size fraction within each stream tube is given by

$$\Delta Z_{i,k} = \frac{\Delta t}{\eta_i} \frac{q_{lat}\left(\Delta x_j + \Delta x_{i-1}\right) + 2\left(Q_{s,i-1} - Q_{s,i,k}\right)}{\left(aT_{i-1} + bT_i + cT_{i+1}\right)\left(\Delta x_i + \Delta x_{i-1}\right)} \tag{14}$$

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 k at cross section i. The total bed elevation change for each stream tube at cross section i is computed taking into account the contributions of all the size fractions:

$$\Delta Z_i = \sum_{k=1}^{N} \Delta Z_{i,k} \tag{15}$$

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. The particle size is assumed fully mixed across a given stream tube, but can vary among different stream tubes.

At the time of writing of this paper, GSTARS included 15 methods to compute the sediment transport capacity Q_s in Eq. (6), which included bed load formulas, bed-material formulas, and methods for cohesive sediment transport. A complete list is given in Yang and Simões (2002). In GSTARS, these methods, which were developed mainly for fairly uniform sediments of a certain representative particle size, were extended for graded sediments and the following equation is used to compute sediment transport capacity

$$Q_{s,i,k} = \sum \left[rp_i + (1-r)\tilde{p}_i\right] Q^*_{s,i,k} \tag{16}$$

where p_i = percentage of material of size fraction *i* available in the bed, $\tilde{p}_i$ = percentage of material of size fraction *i* incoming into the computational reach, $Q^*_{s,i,k}$ = transport capacity for each size fraction computed by one of the sediment transport methods for a single particle size d_i, r = a factor between 0 and 1, and N = number of size fractions. Factor *r* is a weighting factor that allows the inclusion of the incoming sediment distribution into the carrying capacity of the flow. Most models use a value $r = 1$, however, in this case any material entering a reach that is not already present in the bed (i.e., with $p_i = 0$) will deposit instantaneously due to sudden loss in capacity. In other words, if material with a certain size fraction enters a reach ($\tilde{p}_i \neq 0$) with $p_i = 0$, then $r = 0$ implies that $Q_{s,i,k} = 0$, which 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 $r = 1$ was found to work well.

Further modifications to the sediment transport capacity per size fraction, C_i, include the adoption of the method developed by Han (1980) to account for non-equilibrium sediment transport. Using this technique, the non-equilibrium sediment transport rate is computed from

$$C_i = C_{t,i} + \left(C_{i-1} - C_{t,i-1}\right)\exp\left[-\frac{\alpha\omega_s\Delta x}{q}\right] + \left(C_{t,i-1} - C_{t,i}\right)\left[\frac{q}{\alpha\omega_s\Delta x}\right]\left[1 - \exp\left(\frac{-\alpha\omega_s\Delta x}{q}\right)\right] \tag{17}$$

where C = sediment concentration, C_t = sediment transport capacity computed from Eq. (16), q = discharge of flow per unit width, Δx = reach length, ω_s = sediment fall velocity, *i* = cross-section index (increase from upstream to downstream), and α = a dimensionless recovery factor. Eq. (17) is employed for each of the particle size fraction in the cohesionless range, i.e., with particle diameter greater than 62.5 μ m. Han and He (1990) recommended an α value of 0.25 for deposition and 1.0 for entrainment.

Although Eq. (17) was derived for suspended load, its application to bed-material load is reasonable. The asymptotic behavior of Eq. (17) for the larger particles with higher values of ω_s is correct in the sense that $C_i \rightarrow C_{t,t}$ as ω_s or particle diameter d becomes larger, as shown in Fig. 3.

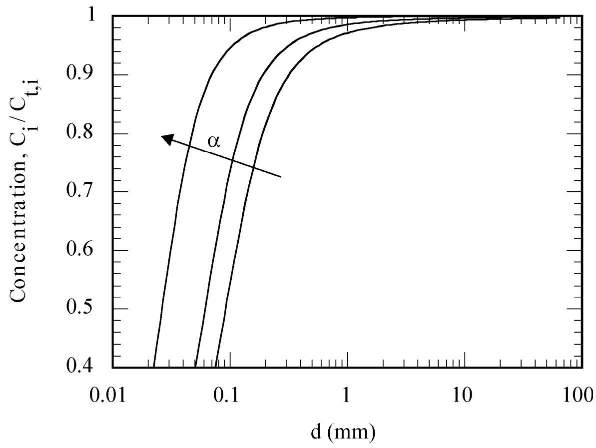

Fig. 3 Ratio between non-equilibrium concentration and sediment transport capacity as a function of sediment particle size

The influence of the recovery factor α is illustrated in Fig. 4 (Fig. 3). The depositional case represents a situation in which there is a sudden loss of carrying capacity $(C_{t,i} = 0)$ from an upstream equilibrium condition $(C_{i-1} = C_{t,i-1})$. The plot shows the actual normalized concentration for two sizes of the sediment particles. It is clear that the non-equilibrium effect is stronger on the finer particles, and that it diminishes as α increases. The erosional case represents a sudden gain of transport 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.

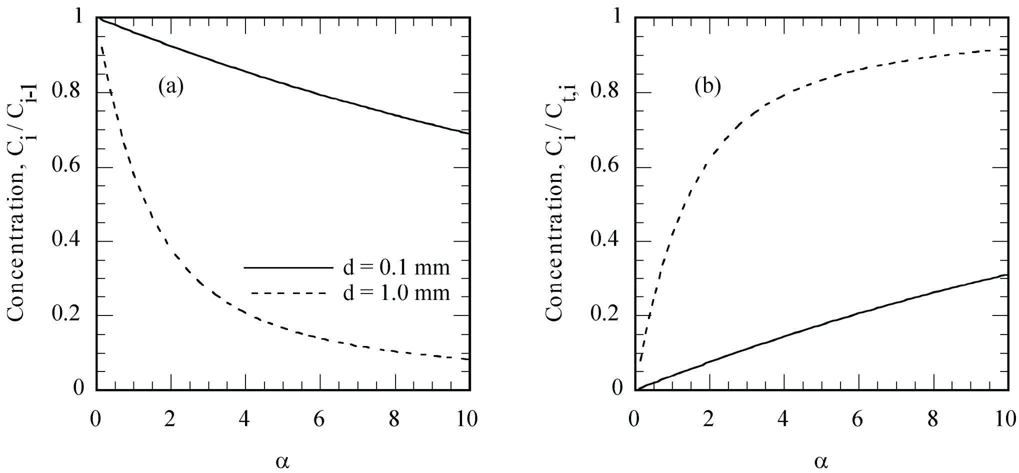

Fig. 4 Effect of the recovery parameter α on the computation of non-equilibrium sediment concentrations for two sediment particle sizes. (a) deposition and (b) erosion

Another important factor in non-equilibrium calculations is distance between computational cross sections, Δx . Fig. 5 shows how the non-equilibrium effects vary with distance for the same situations and particle sizes in Fig. 4. In practice, the values of α can vary widely. For example, a value of α = 0.001 has been used for depositional rivers with high concentrations of fine materials 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.

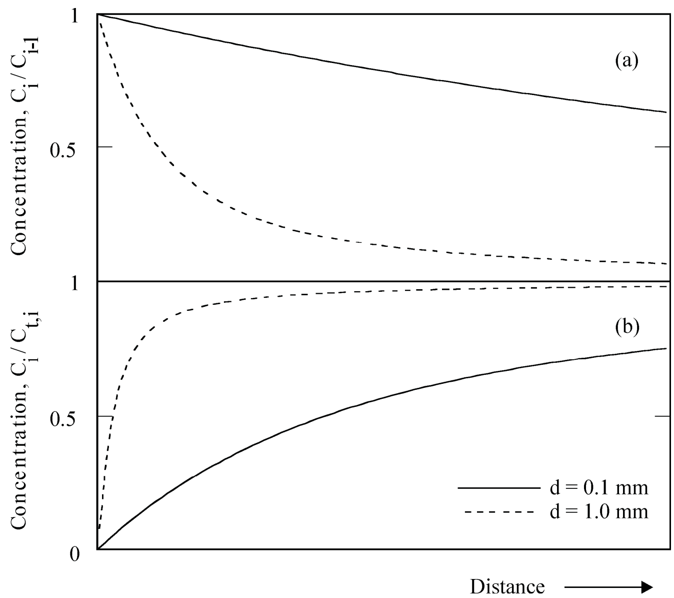

Fig. 5 Variation of non-equilibrium effects as a function of distance between cross sections for aggradation (a) and for erosion (b)

3.3 Cohesive sediment transport

In spite of the progress of recent years in modeling cohesive sediment transport, reliable predictive techniques are still not available. The main difficulty in describing the behavior of mud or fine particles stems from the fact that cohesive sediments are not characterized by their particle properties alone. 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. These highly variable and site dependent parameters are too complex and poorly understood to be used directly in a model. In the GSTARS models, the transport of silt and clay is computed separately from the cohesionless size fractions.

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 a critical bed shear stress for deposition, τ_{cd}. τ_{cd} is the critical value of the bed shear stress above which no deposition occurs. Deposition is governed by integrating

$$\frac{dC}{dt} = -\frac{P\omega_s C}{h} \tag{18}$$

where C = depth averaged concentration of sediments, h = water depth, ω_s = settling velocity of the sediment, and P is a parameter representing the probability for deposition. The effects of high concentration of suspended sediments are included through ω_s using methods that account for unhindered settling, flocculation, and hindered settling. A detailed overview of these techniques, which would take too much space to describe here, can be found in Yang and Simões (2002). Erosion is computed using the method of Partheniades (1965) for particle erosion and Ariathurai and Krone (1976) for mass erosion.

It is necessary to make additional modifications to the above methods to deal with sediment mixtures. For example, the presence of clay in the active layer of the bed (section 3.4) 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 for the cohesionless fractions. Another peculiarity of these methods lies in the fact that the equations used for erosion of cohesive sediments do not constrain the concentration of clay and silt being transported, which can grow to unrealistically high values. These and other effects are further described in Yang and Simões (2002), and the reader is directed there for a more comprehensive treatment of this subject.

3.4 Bed sorting and armoring

As described in the previous sections, sediment transport is computed by size fraction and 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. The carrying capacity for each size fraction presented in the bed is calculated with a selected sediment transport formula or method, but the actual amount of materials moved is computed by the sediment routing, Eq. (6). The concepts of bed sorting and armor layer are used in the computations.

The 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 transport capacity, causing the armor layer to break and restart the erosion processes in the reach. Bed sorting requires that bed composition be tracked for the percentage of each particle size class. These effects are accounted by the procedure proposed by Bennett and Nordin (1977). This method uses two layers for scour and three layers for deposition. The process is schematically illustrated in Fig. 6. The top layer contains the bed material available for transport and is called the active layer. Beneath the active layer is the inactive layer used for storage. Beneath these two layers is the undisturbed original bed with the initial bed material composition.

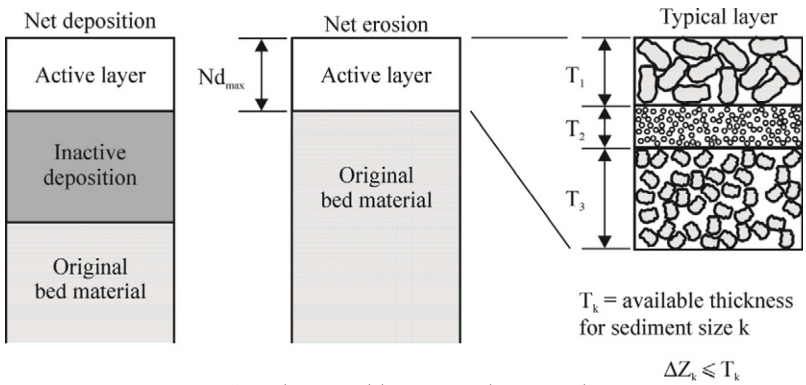

Fig. 6 Bed composition accounting procedures

The thickness of the active layer is proportional to the geometric mean of the largest size class with at least 1 percent of the bed material at that location. Active layer thickness is closely related to the time-step duration. Erosion of a particular size of bed material is limited by the amount of sediments of the size class present in the active layer, and availability limited and capacity limited transport can be successfully simulated by this approach. 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 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.

The above procedures are carried out separately along each stream tube. The locations of stream tube boundaries change with changing flow conditions and channel geometry at each time step of computation. 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 also are 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. Complete details of this process are described in Yang and Simões (2002).

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 shown in Fig.7, the substratum is composed of three different layers, each layer with its own sediment particle distribution. For the case shown with one stream tube, for the sake of brevity, a weighted average is composed from the particle distributions of layer 1 (point 2 and 7), layer 2 (point 3 and 6), and layer 3 (point 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 point.

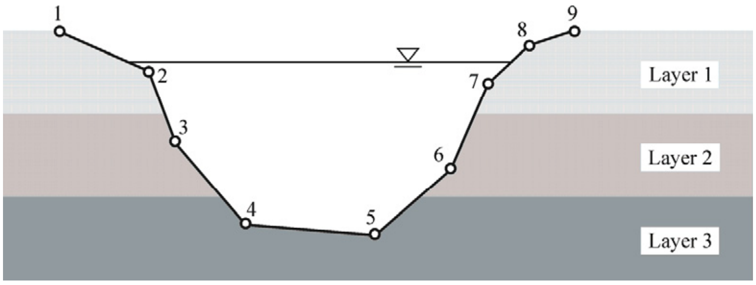

Fig. 7 Cross section showing individual discretization points with different sediment particle distributions

3.5 Transfer of sediment across stream tubes

When the streamline curvature or the transverse bed slope are large, the lateral movement of sediments may become important and some exchange of sediments my take place across stream tube boundaries. Figure 8 illustrates the mechanism of bed sorting in bends due to transverse bed slope and secondary currents. In GSTARS3 (other versions of GSTARS do not include these calculations), the effects due to secondary flows are modeled following Kikkawa et al. (1976). The angle that the bed shear stress vector makes with the downstream direction, φ, is given by

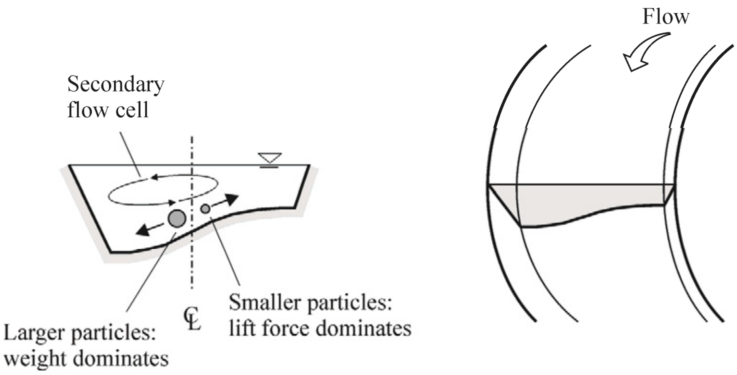

Fig. 8 Bed sorting in bends due to transverse bed slope and secondary currents

$$\varphi = \frac{vh}{u^* A_r R}(-4.167 + 2.640\frac{u^*}{\kappa v}) \tag{19}$$

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 Kármán constant = 0.41.

In a bed with transverse slope, the gravity force causes the direction of the sediment particles to be different from that of 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

$$\frac{q_r}{q_s} = \tan\sigma = \tan\varphi + \frac{1+\alpha\mu}{\lambda\mu}\sqrt{\frac{\tau_0^*}{\tau^*}}\tan\delta \tag{20}$$

where q_s, q_r = unit sediment transport rate in the channel's longitudinal and transverse directions, respectively, σ = the angle between the direction of transport and the channel's downstream direction, τ_0^*, τ^* = non-dimensional critical shear stress and bed shear stress, respectively, δ =transverse bed slope, α = ratio of lift to drag coefficients on sediment particle = 0.85, λ = sheltering coefficient = 0.59, and μ = dynamic Coulomb friction factor = 0.43. The direction of sediment transport is calculated from Eq. (20). The components of the sediment transport direction vector are given by

$$q_s = q_t \cos\sigma \tag{21}$$

$$q_r = q_t \sin\sigma \tag{22}$$

where q_t = sediment transport rate per unit width computed by any of the traditional sediment transport equations implemented in GSTARS. Eq. (6) is then solved using $Q_s = q_s \Delta y$ and $q_{lat} = q_r$, where Δy = stream tube width.

The above methods are applicable only to sediment moving as bed load. Sediment moving as suspended load is not allowed to cross stream tube boundaries. Van Rijn's (1984a,b) method is used to determine if a particle of a given size is in suspension or moving as bed load. The lateral water-surface elevation is assumed to be horizontal in the stream tube method, therefore the extrapolation to two-dimensional distributions has it limitations. For example, the number of stream tubes allowed in GSTARS3 is limited to five. Furthermore, GSTARS3 is not a truly two-dimensional model, consequently it can not simulate phenomena such as recirculation flows or eddies, reverse flows, transverse water-surface variation, or super elevation.

3.6 Channel width adjustments

In the GSTARS models, there are two mechanisms that allow for channel width variation computation: the use of the minimum energy dissipation rate (see section 2.4) and bank collapse due to stability criterion violation. For the first method, stream power minimization is used, in which Eq. (7) is discretized following Chang (1982):

$$\phi_T = \sum_{i=1}^{N} \frac{1}{2}(Q_i S_i + Q_{i+1} S_{i+1})\Delta x_i \tag{23}$$

where N = number of stations along the study reach, Δx_i distance between stations i and i + 1, and Q_i, S_i = discharge and slope at station i, respectively. Eq. (23) is used for the determination of optimum channel geometry. Whether the adjustment should be in the depth or width direction at each time step of computation depends on which one will lead to a lower value of the stream power. Figure 9 illustrates the relations among total stream power and the adjustments in width and bed elevation. Figure 10a is a schematic representation of the exterior stream tube depth change due to scour or deposition and Fig. 10b shows stream tube width change.

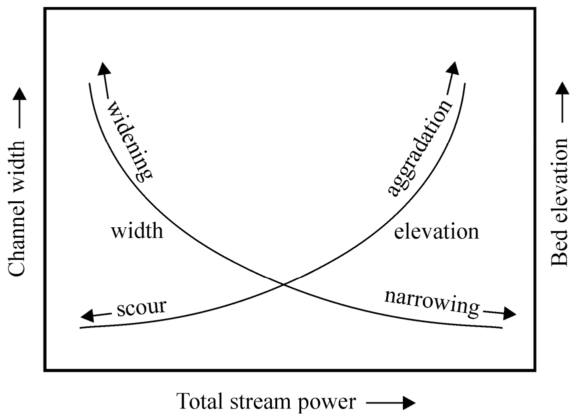

Fig. 9 Total stream power variation as a function of changes in channel width and bed elevation, with constant discharge and downstream stage

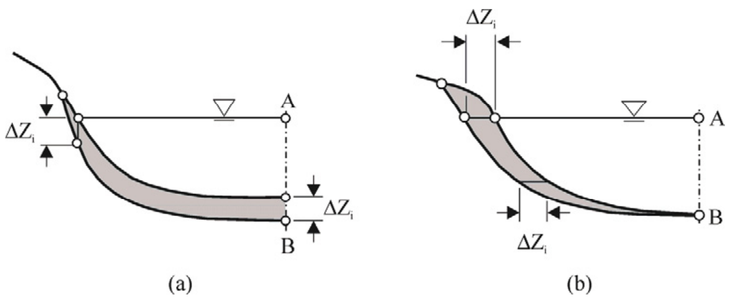

Fig. 10 Schematic representation of channel changes on exterior stream tubes

Channel geometry adjustment can take place in both the 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. (14) is straightforward. For an exterior tube, 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 value may vary from case to case, depending on the type of soil and the existence of natural or artificial protection.

In GSTARS, the angle of repose is checked for violation of a known critical value, which is a user supplied quantity (different values may be used for points above and below the water surface). The cross sections are scanned at the end of each time step of computation to determine if any vertical or horizontal adjustments have caused the banks to become too steep. If violations occur, the two points adjacent to the violating segments are adjusted vertically until the slope equals the critical slope. For the situation shown in Fig.11, the bank is adjusted from *abde* to *ab'd'e* such that the calculated angle, θ, is reduced to the critical angle, θ_c. The adjustments are governed by the conservation of mass equation

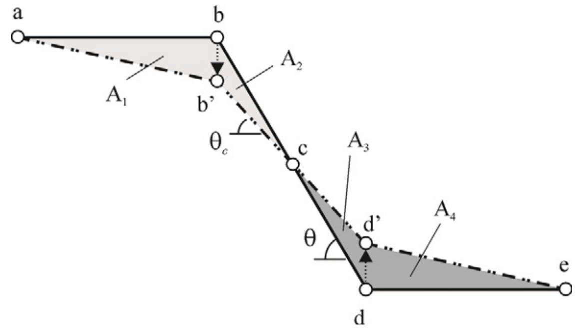

Fig. 11 Example of angle of repose adjustment

$$A_1 + A_2 = A_3 + A_4 \tag{24}$$

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'*.

4 Summary and conclusions

The first part of this two-part paper series provides a review and summary of the basic theories and concepts used in the GSTARS computer models, especially those used in GSTARS3. The GSTARS models are based on sound theories and concepts. The use of these theories and concepts allow the simulation and prediction of river and reservoir morphological processes by solving one-dimensional equations along stream tubes to obtain semi-two-dimensional variations of the hydraulic conditions. Coupled with sediment routing along stream tubes, the GSTARS models are a powerful engineering tool for simulating and predicting channel geometry and profile variation in a semi-three-dimensional manner. Some of the more important aspects discussed include:

(1) The use of stream tubes, which allows for a transverse variation of the parameters while still using the simpler 1D computation techniques and reduced data requirements (when compared with multi-dimensional models). In particular, lateral variation of sediment transport quantities allow for semi-three-dimensional variations in the cross section, i.e., both erosion and deposition can be computed simultaneously for a given cross section and a given time step.

(2) Application of the minimum stream power theory enables the channel's width, depth, and shape to be treated as variables for the estimation and prediction of the optimum channel geometry.

(3) The application of the armor layer concept and bed sorting to rout sediment by size fraction can give realistic long-term simulation of the scour and deposition processes.

(4) The use of non-equilibrium sediment routing can improve the prediction of sediment transport, scour, and deposition processes, especially for the finer size fractions and in reservoir sedimentation.

(5) The GSTARS models have the capability to handle cohesive and non-cohesive sediment transport, including high concentration of suspended sediments, flocculation, and hindered settling. They also account for the effects that the cohesive sediments have on the transport of the cohesionless size fractions.

(6) The stream tube concept is based on the potential flow theory. Consequently, some truly multidimensional effects cannot be simulated, such as secondary currents, recirculation eddies, and super elevation.

The Bureau of Reclamation no longer maintains the GSTARS models. Interested readers can contact the first author of this paper for instructions on how to download the user's manual, executable codes, and examples of GSTARS 2.1 and GSTARS3 free of charge.

DISCLAIMER: any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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