# GENERALIZED SEDIMENT TRANSPORT MODELS FOR ALLUVIAL RIVERS AND RESERVOIRS

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## ABSTRACT

The U.S. Bureau of Reclamation has developed a series of computer models (GSTAR) for the simulation and prediction of sediment transport, scour, and deposition processes in alluvial rivers and reservoirs. GSTARS, GSTARS 2.0/2.1 and GSTARS3 are based on the stream tube concept using one-dimensional approach along stream tubes to obtain a semi-two-dimensional variation of the hydraulic conditions in rivers and reservoirs. The hydraulic conditions coupled with uneven distribution of scour and deposition among stream tubes can give a semi-three-dimensional variation of the bed geometry. The theory of minimum stream power is used to determine the optimum channel width and geometry. GSTARS, GSTARS 2.0/2.1 and GSTARS3 are intended for quasi-steady flows. GSTAR-1D is a one-dimensional steady and unsteady flow and sediment transport model. It can also model cohesive sediment transport, internal boundary conditions, and stream networks. It does not include the same minimization methods of previous GSTARS models

The Generalized Sediment Transport models for Alluvial Rivers (GSTAR) have been used by many organizations and universities around the world for engineering, research, and teaching purposes. Examples of applications will be presented to illustrate the capabilities of using these models for solving engineering problems.

## 1. INTRODUCTION

The U.S. Bureau of Reclamation (Reclamation) Technical Service Center has developed a series of computer models for alluvial rivers and reservoirs. These models are in public domain and have been applied by Reclamation, other government agencies, universities, research institutes, and engineers in the United States and other countries for erosion, sedimentation, river morphology, river engineering, and river restoration studies. These models have also been used by universities for teaching purposes. One of the unique and common features of all the Generalized Sediment Transport models for Alluvial Rivers (GSTAR) is the application of some optimization methods.

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The minimum stream power theory can be used for the determination of optimum channel width and geometry for a given set of hydraulic, geological, sediment, and man-made constraints. Another unique feature of GSTAR models is the application of stream tube concept using one-dimensional computations alone stream tubes to simulate semi-two-dimensional flow conditions and semi-three-dimensional variations of bed geometry. The stream tube computations are used for all GSTAR models except GSTAR-1D (Yang et al. 2004).

This paper provides a brief description of GSTARS (Molinas and Yang 1989), GSTARS 2.0 (Yang et al. 1998), GSTARS 2.1 (Yang and Simões 2000), GSTARS3 (Yang and Simões 2002), and GSTAR-1D (Yang et al. 2004) models. Some computed and predicted results from using these models are used to illustrate the capabilities of using these models for alluvial river and reservoir sedimentation and morphology studies.

## 2. THEORETICAL DEVELOPMENTS

### 2.1 Stream Tube Concept

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. For steady and incompressible fluids, the total head along a stream tube of an ideal fluid is constant. For real fluids in alluvial rivers, water surface profile computation is used to determine the energy loss in a study reach. Figure 1 provides a schematic representation of the stream tube concept.

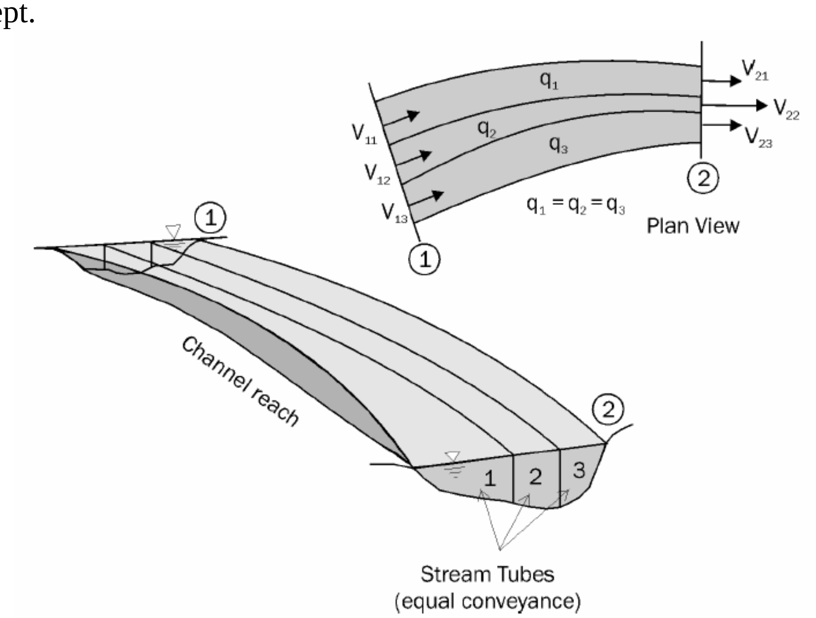


Figure 1. Schematic representation of the use of stream tube concept (Yang and Simões 2002).

### 2.2 Water Surface Profile Computation

For steady or quasi-steady flows, the standard-step method can be used for the water surface profile computation based on the use of Manning, Chezy, or Darcy-Weisbach's formula. The local energy loss due to contraction and expansion can also be computed. Detailed procedures of water surface profile computation for single or divided channels are given by Molinas and Yang (1985). Water surface profile computation in GSTAR models can be applied to sub-critical, super-critical, and a combination of both without interruption.

## 2.3 Optimization Methods

The minimum energy dissipation rate theory was developed by Yang (1976, 1983a, 1983b, 1985) and by Yang and Song (1979, 1986, 1990). The theory states that for a closed and dissipative system in dynamic equilibrium, its energy dissipation rate must be at its minimum value. The minimum value depends on the constraints applied to the system. An open system under equilibrium can be converted to a closed system and the theory is still applicable (Yang and Song 1986). The minimum energy dissipation rate theory can be derived not only from mathematical argument based on the definition of a closed and dissipative system; it can also be derived from the basic law in thermodynamics (Yang, 1971). For open channel hydraulics, the minimum energy dissipation rate theory can be simplified to the minimum unit stream power theory if the velocity $V$ and slope $S$ are fairly uniformly distributed at a given cross section, i.e.

$$VS = \text{a minimum} \tag{1}$$

where $VS$ = unit stream power or the rate of potential energy dissipation per unit weight of water (Yang 1973). If the velocity is not uniformly distributed across a channel, it should be integrated across the channel and the minimum stream power theory should be applied, i.e.

$$QS = \text{a minimum} \tag{2}$$

where $Q$ = water discharge, and $QS$ = stream power.

It is apparent that the minimum unit stream power and minimum stream power theories are special and simplified versions of the more general minimum energy dissipation rate theory. The minimum values in Eqs. (1) and (2) depend on the constraints applied to the system. In addition to geologic and man-made constraints, water discharge and sediment load are two common constraints imposed on an alluvial river system. An alluvial river will adjust its channel geometry and slope to minimize its stream power or unit stream power. Computed results from using Eq. (1) and Eq. (2) may be different. Because $Q$ is more readily available than $V$ from field data, $QS$ is more often used by hydraulic engineers than $VS$ in the minimization computations.

All GSTARS models except GSTAR-1D use Eq. (2) for the determination of optimum channel geometry because the $Q$ values are readily available from most river gauging station records. GSTAR-1D provides four optimization options: maximization of channel conveyance; minimization of total stream power which is the integration of $QS$ along the study reach; minimization of energy slope change; and minimization of bed slope change.

## 2.4 Channel Side Stability

With the exception of GSTAR-1D, all GSTARS models use Eq. (2) for the determination of optimum channel geometry. The minimum $QS$ value depends on local geological constraints, such as the angle of repose of materials on the channel side slope or other geological conditions. Figure 2 illustrates how to balance the materials on the channel side slope based on the angle of repose. The materials in abcb$'$a is balanced by the materials in cd$'$edc. Different values of angle of repose can be assigned at different elevations to reflect the local geological conditions.

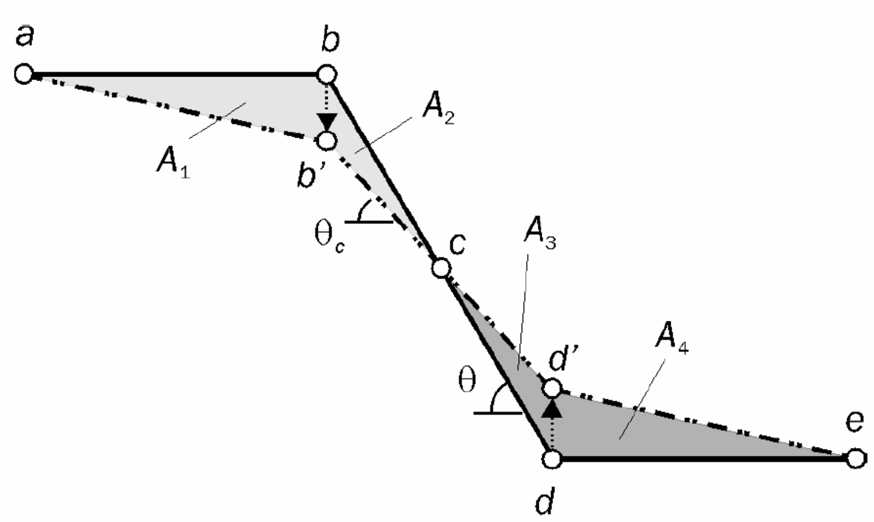


Figure 2. Schematic representation of channel side slope adjustment (Yang and Simões 2000).

## 2.5 Sediment Transport Formulas

More than a dozen of commonly used sediment transport formulas are included in the GSTAR computer models for users to choose for the computation of non-cohesive and cohesive sediment transport rates or concentrations. Yang (1996, 2003) made some recommendations on the selection of sediment transport formulas under different flow and sediment conditions. Sediment transport computations by size fractions, bed sorting and armoring are included in all GSTAR models. In addition to equilibrium sediment transport, the method developed by Han (1980) is included in GSTAR models for non-equilibrium sediment transport computations.

## 2.6 Numerical Solutions

The numerical method used in GSTAR models is a finite difference uncoupled method. Finite difference method is used to discretize the governing differential equations. The uncoupled method computes water surface profile first, and the sediment routing and bed changes are computed afterwards, keeping all the hydraulic parameters frozen during the calculations. Users can choose different weighting factors to best fit with local conditions.

GSTAR-1D is intended for truly unsteady flows and different numerical methods are needed. GSTAR-1D uses a method similar to the “New C” scheme by Kntija and Newett (2002). The local partial inertia technique (Fread and Lewis 1998) is used in GSTAR-1D to ensure stability for supercritical flows.

The boundary conditions can be upstream or downstream using either a rating curve or a known water surface elevation. Some internal boundary conditions such as dams, bridges, weirs, and gates may exit along a natural river and special treatments are required in the numerical model. For each internal cross sectional structure, the water discharge and water surface elevation values are needed to satisfy the continuity equation and some special stage-discharge relationship of the international boundary conditions. Structures currently supported by GSTAR-1D are listed in its user’s manual (Yang et al. 2004). Internal boundary conditions are interpolated using a step function for steady flow simulations and interpolated linearly in time for unsteady flow simulation. Internal structures are assumed to occur between cross sections and are identified by the cross section that occurs immediately upstream.

# 3. APPLICATIONS

## 3.1 GSTARS

The Generalized Stream Tube model for Alluvial River Simulation (GSTARS) was developed by Molinas and Yang (1986) for main frame computer applications. Yang, et al. (1989) applied GSTARS to simulate and predict the scour depth and pattern at the Lock and Dam No. 26 replacement site on the Mississippi River. Figure 3 shows the three-dimensional variations of channel cross section at 4, 36, and 72 days of simulation using three stream tubes. The computed scour depth from GSTARS is within 1 foot from field measurements. Reclamation no longer maintains and uses GSTARS since the release of the PC version of GSTARS 2.0 in 1998.

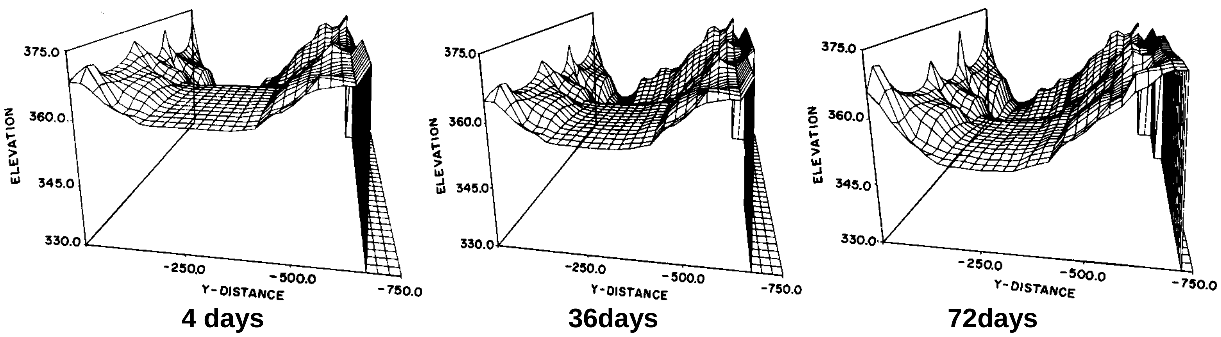


Figure 3. Three-dimensional plot of the variation of computed scour pattern at the Mississippi River Lock and Dam No. 26 replacement site (Yang, et al. 1989).

GSTARS was adopted and modified by Lee et al. (1989) to include the capability of flood routing in a channel network with fluctuating downstream water surface elevation due to tide. The modified GSTARS was successfully applied to the Keelung River flood control project and the Shiemen Reservoir sedimentation studies in Taiwan. The simulated and predicted results are in good agreement with field measurements and analytical solutions.

## 3.2 GSTARS 2.0/2.1

GSTARS 2.0 is the first PC version of the GSTAR model series. GSTARS 2.1 is a revised and enhanced version of GSTARS 2.0. Some of the modifications and improvements made in GSTARS 2.1 over GSTARS 2.0 are : (1). Accepts tributary flows of sediment and water; (2) The codes were rewritten from Fortran IV and Fortran 77 to Fortran 90/95 syntax; and (3). Java-based graphical user interface for data entry and analysis to make the model more user friendly. GSTARS 2.1 has replaced GSTARS 2.0, and Reclamation no longer maintains GSTARS 2.0.

GSTARS 2.0 and GSTARS 2.1 have been used by engineers and researchers not only in the United States but also in other countries. For example Cellino and Essyad (2002) applied GSTARS 2.0 to study engineering alternatives for reduction of sediment deposition in the Dranse River, which is a tributary of the Rhone River in Switzerland. The computed results from GSTARS 2.0 were verified by physical model tests and field measurements. “The comparison is quite encouraging; the width-averaged deposition measured and computed are both approximately 7 cm. The numerical computation was performed by introducing only two stream tubes” (Cellino and Essyad 2002). Othman and Wang (2004) applied GSTARS 2.1 to simulate the degradation and armoring processes of the Tigris River below the Mosul Dam in Iraq. Figure 4 shows the comparison between measured and computed scour depth. Figure 5 shows the comparison between the measured and computed median sediment diameter variation. Results in Figures 4 and 5 indicate that GSTARS 2.1 can accurately simulate and predict the scour depth and variation of sediment particle diameter.

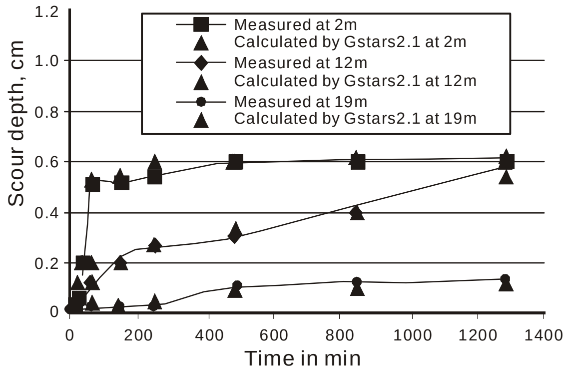


Figure 4. Comparisons between measured and computed scour depth (Othman and Wang 2004).

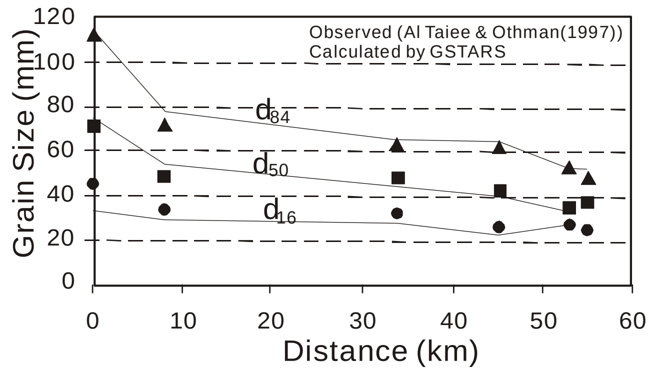


Figure 5. Comparisons between measured and computed median sediment particle diameter ( Othman and Wang 2004).

Figure 6 shows the measured and predicted channel cross session change with and without the use of minimum stream power optimization option in GSTARS 2.1. It is apartment that the use of minimization option can more accurately predict the variation of channel geometry of the unlined spillway below the Lake Mescalero Reservoir in New Mexico.

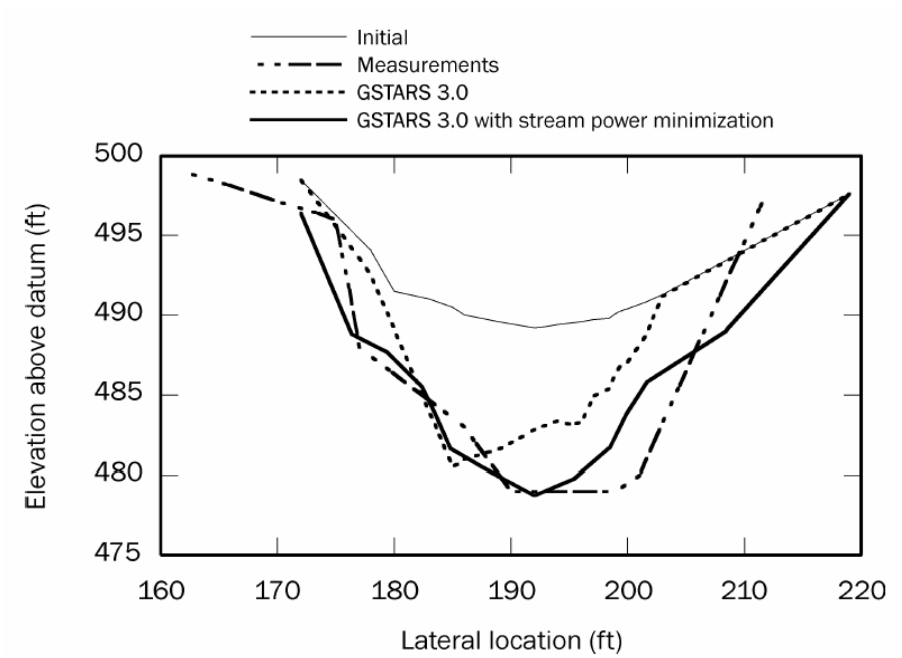


Figure 6. Comparison between measured and predicted channel geometry at station 60 below the Lake Mescalero Reservoir unlined emergency spillway (Yang and Simões 2000).

## 3.3 GSTARS3

GSTARS3 is based on GSTARS 2.1 with the following modifications and improvements: (1). Reservoir routing; (2). The program was re-written using Fortran 90/95 to improve accuracy and speed; (3). Dynamic memory allocation is used instead of static, fixed-size arrays; (4) Additional sediment transport equations are added for specific aspects of reservoir sedimentation; (5) Multiple bed layers of different particle size distribution; (6). Cohesive sediment transport methods are extended for high concentrations of fines, including flocculation and hindered settling; (7). Methods of computing sediment transport across stream tube boundaries; (8). Transmissive cross sections and input sediment rates based on equilibrium principles. Figure 7 shows the simulated results agrees very well with surveyed delta development of the Tarbela Reservoir in Pakistan over a period of 22 years.

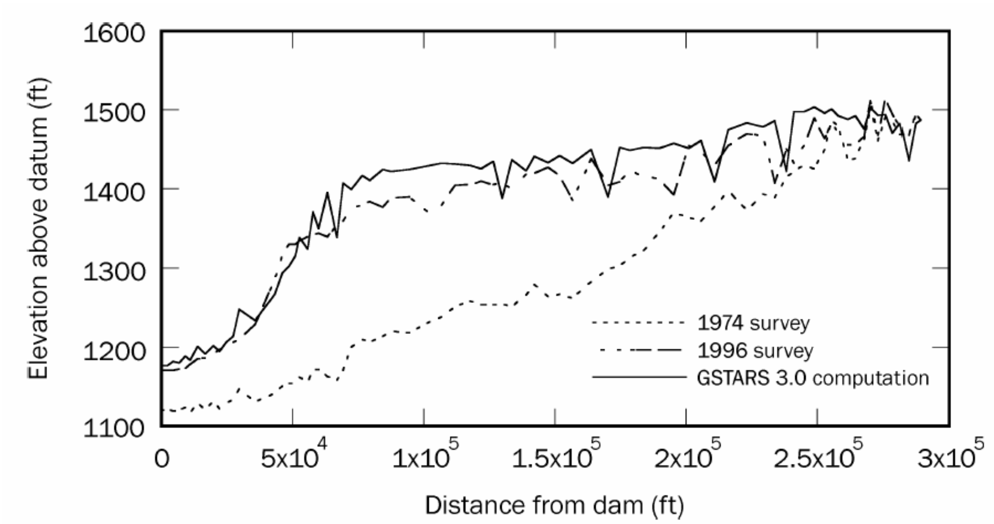


Figure 7. Comparison between surveyed and simulated Tarbela Reservoir delta over 22 years (Yang and Simõs 2002).

### 3.4 GSTAR-1D

GSTAR-1D is a one-dimensional model for steady or unsteady flow in a single channel or a channel network. The codes in GSTAR-1D are new and are not based on modifications of the previous GSTAR models. The emphasis of GSTARS-1D is unsteady cohesive sediment transport. Figure 8 is a sketch of a river network. Figure 9 shows the bed and water surface profiles of the river network.

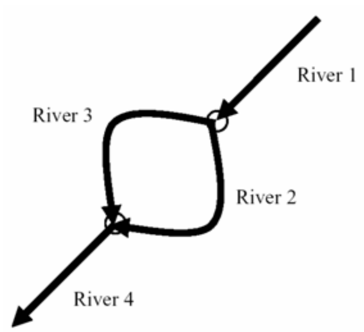


Figure 8. Sketch of a river network (Yang et al. 2004).

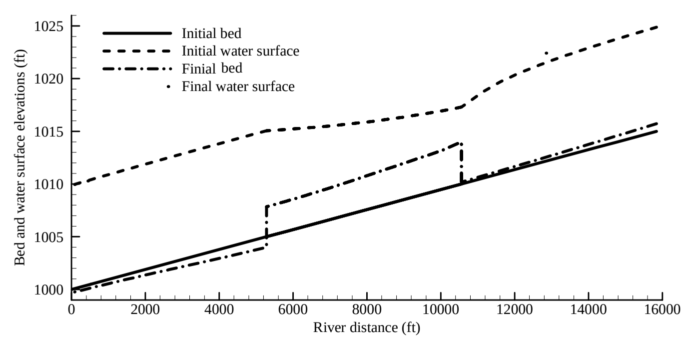


Figure 9. Bed and water surface variations in a river network (Yang et al. 2004).

The middle section is the profile for river 2 and 3, which are identical in the calculation. Due to larger conveyances and lower energy slopes in rivers 2 and 3, the sediment transport capacity is lower and sediment deposition occurs in rivers 2 and 3. The lower section experiences erosions because some of the sediments are deposited in rivers 2 and 3, and there is not enough sediment supply. The deposition in rivers 2 and 3 also raises the water surface elevation in river 1, resulting in sediment deposition in river 1.

GSTAR-1D was applied by Klumpp et al. (2005) to simulate unsteady cohesive sediment transport in unsteady flow in the California Aqueduct near Arroyo Pasajero with several locks in the study reach. The bed materials consist of 2% sand and 98% silt and clay. Figure 10 shows the bed elevations before and after a flood. The sediments allowed into the aqueduct near river mile 136 are deposited just downstream of the inlet and raising the channel bed elevation. The sediments are eroded after the flood, and the bed returns to its initial form after the flood.

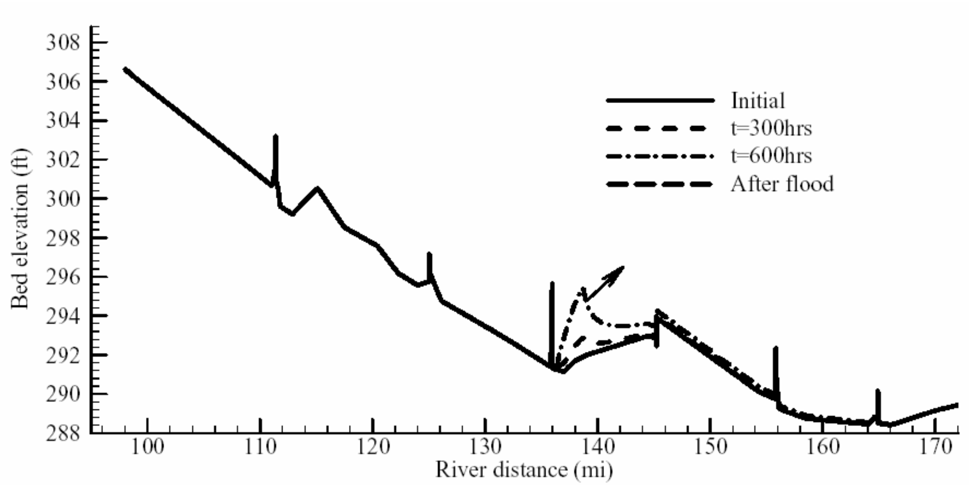


Figure 10. Bed elevation change of the SLC before and after a flood event (Yang et al. 2004, Klumpp et al. 2005).

## 4. SUMMARY AND CONCLUSIONS

This paper provides a brief summary of the GSTAR computer model series developed by the U.S. Bureau of Reclamation for river engineering and river morphology studies. Examples used in this paper illustrate some capabilities of the GSTAR models for solving various river engineering and sedimentation problems. The simulated and predicted results are in good agreement with field measurements. The GSTAR computer programs and their user's manuals are in public domain and can be found by accessing http://www.usbr.gov/pmts/sediment and following the links on the web page.

## REFERENCES

Cellino, M., and Essyad, K. (2002). "Reduction of Sediment Deposition by Introducing an Artificial Stony Bank. A Practical Example in Upper Rhone River, Switzerland", Proceedings of the International Conference on Fluvial Hydraulics, Louvain-La-Neuve, Belgium, pp. 951 – 959.

Fred, D. L., and Lewis, J. M. (1998). NWS FLDWAV Model, Hydrologic Research Laboratory, Office of Hydrology, National Weather Service, NOAA, Silver Springs, MD, 20910.

Han, Q. (1980). "A Study on the Non-Equilibrium Transportation of Suspended Load", Proceedings of the International Symposium on River Sedimentation, Beijing, China, pp. 793 – 802. (in Chinese).

Klumpp, C., Huang, J., and Greimann, B. P. (2005). “Sediment Model of the Arroyo Pasajero and California Aqueduct”, U.S. Bureau of Reclamation repart prepared for the California Department of Water Resources.

Kutija, V., and Newett, C. J. M. (2002). “Modeling of Supercritical Flow Conditions Revisited; New C Scheme”, Journal of Hydraulic Research, Vol. 40, No. 2, pp. 145 – 152.

Lee, H.-Y., Hsieh, H.-M., Yang, J.-C., and Yang, C. T. (1997). “Quasi-Two Dimensional Simulation of Scour and Deposition in Alluvial Channels”, ASCE Journal of Hydraulic Engineering, Vol. 123, No. 7, pp.600 – 609.

Molinas, A., and Yang, C. T. (1985). “Generalized Water Surface Profile Computations”, ASCE Journal of Hydraulic Engineering, Vol. 111, No. 3, pp. 381 – 397.

Molinas, A., and Yang, C. T. (1986). Computer Program User’s Manual for GSTARS, U. S. Bureau of Reclamation Engineering and Research Center, Denver, CO, 80225.

Othman, K. I., and Wang, D. (2004). “Application of GSTARS 2.1 Model for Degradation in Alluvial Channels”, Proceedings of the 9th International Symposium on River Sedimentation, Yichang, China, pp. 1532 – 1537.

Yang, C. T. (1971). “Potential Energy and Stream Morphology”, AGU Water Resources Research, Vol. 7, No. 2, pp. 311 – 322.

Yang, C. T. (1973). “Incipient Motion and Sediment Transport”, ASCE Journal of the Hydraulics Division, Vol. 99, No. HY7, pp. 919 – 934.

Yang, C. T. (1976). “Minimum Stream Power and Fluvial Hydraulics”, ASCE Journal of the Hydraulics Division, Vol. 102, No. HY 7, pp. 919 – 934.

Yang, C. T. (1983a). “Rate of Energy Dissipation and River Engineering”, Proceedings of the 2nd International Symposium on River Sedimentation, Nanjing, China, pp. 575 – 585.

Yang, C. T. (1983b). “Minimum Rate of Energy Dissipation and River Morphology”, Proceedings of D. B. Simons Symposium on Erosion and Sedimentation, R. M. Li and P. L. Lagassee editors, Colorado State University, Fort Collins, CO, 80523, pp. 3.2 – 3.19.

Yang, C. T. (1985). “Theory of Minimum Rate of Energy Dissipation and Its Applications”, Proceedings of the Pakistan Engineering Congress Annual Convention, Lahor, Pakistan, pp. 105 – 129.

Yang, C. T. (1996). Sediment Transport: Theory and Practice, McGraw-Hill Companies, New York (reprint by Krieger Publishing Company, Malabar, FL, 2003).

Yang, C. T., and Simões, F. J. M. (2000). User’s Manual for GSTARS 2.1 (Generalized Stream Tube model for Alluvial River simulation version 2.1), U. S. Bureau of Reclamation Technical Service Center, Denver CO, 80225.

Yang, C. T., and Simões, F. J. M. (2002). User’s Manual for GSTARS3 (Generalized Sediment Transport model for Alluvial River Simulation version 3.0), U. S. Bureau of Reclamation Technical Service Center, Denver, CO, 80225.

Yang, C. T., and Song, C. C. S. (1979). “Theory of Minimum Rate of Energy Dissipation”, ASCE Journal of the Hydraulics Division, Vol. 105, No. Hy7, pp. 769 – 784.

Yang, C. T., and Song, C. C. S. (1986). “Theory of Minimum Energy and Energy Dissipation Rate”, Chapter 11 of Encyclopedia of Fluid Mechanics, Gulf Publishing Company, Houston, Texas, pp. 353 – 399.

Yang, C. T., and Song, C. C. S. (1990). “Optimum Channel Geometry and Minimum Energy Dissipation Rate”, International Journal of Sediment Research, Vol. 5, No. 1, pp. 57 – 65.

Yang, C. T., Huang, J. V., and Greimann, B. P. (2004). User’s Manual for GSTAR-1D 1.0 (Generalized Sediment Transport for Alluvial Rivers – One Dimensional, Version 1.0). U. S. Bureau of Reclamation Technical Service Center, Denver, CO, 80225.

Yang, C. T., Molinas, A., and Song, C. C. S. (1989). “GSTARS – Generalized Stream Tube model for Alluvial River Simulation”, Twelve Selected Computer Stream Sedimentation Models Developed in the United States, U. S. Interagency Subcommittee Report on Sedimentation, edited by S. S. Fan, Federal Energy Regulatory Commission, Washington, D. C. pp. 148 – 178.

Yang, C. T., Treviño, M. A., and Simões, F. J. M. (1998). User's Manual for GSTARS 2.0 (Generalized Stream Tube model for Alluvial River Simulation version 2.0), U. S. Bureau of Reclamation Technical Service Center, Denver, CO, 80225.