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# N

## NUMERICAL MODELS AND SIMULATION OF SEDIMENT TRANSPORT AND DEPOSITION

A numerical model simulating sediment transport and deposition is an equation set describing the spatial and temporal evolution of a fluid flow carrying sediment over, and interacting with, an adjacent mobile particulate bed. Although literally scores of such models exist, each starting from quite different assumptions and incorporating quite different sedimentary processes, the most common and the focus of this entry are process-based models constructed with the mutual goals of prediction and understanding. Given water and sediment mass fluxes delivered to a geomorphic system through time, these numerical models are expected to accurately predict the total mass flux and character of sediment passing each point in the system at time and space scales appropriate for the application. To do so, each model must capture how changes in state variables of the fluid flow, the sediment transport, and the deforming bed influence one another through feedback loops. Each also must embody the physical processes thought to be relevant and consequently each is a conjecture about the dynamical behavior of the geomorphic system. Thus, for example, if the geomorphic system is a river channel reach of a given initial hydraulic geometry and sediment characteristics with a given sediment and water feed at the upstream end, the model in question should predict accurately the temporally-evolving flux of water and sediment along the reach and the amount of bed erosion or deposition through time using conservation and rate laws that describe all the processes and their interactions. This entry describes the character, use, and limitations of this general class of sediment transport model. Channelized flows are emphasized, although much of the discussion also applies to sediment transport models of lakes and coastal oceans. Also, the emphasis here is on non-cohesive sediment transport because most models, if they address cohesive sediment at all, are still quite primitive in its treatment. Table N1 list some popular examples.

### Model components

There are five components or computation modules in a sediment transport model: (1) a hydrodynamic module to compute the flow field; (2) a shear stress module to calculate the stress effective in transporting sediment as the bed roughness evolves and in some models, to calculate the shear stress distribution arising from turbulent fluctuations; (3) a bedload transport module; (4) a suspended load transport module; and (5) a bed module that keeps track of bed erosion, deposition, and the evolving bed texture. The computation modules are organized into a solution algorithm, the structure of which depends upon whether the equation set is to be solved simultaneously or in series. Figure N13 gives a typical organization of the computation modules for a series solution of a 1-D, unsteady, nonuniform application. Because continuous solutions to the equation set are not known, the set is always solved by either finite-difference or finite element techniques at discrete nodes in the model space, $x = 1\Delta x, 2\Delta x, \ldots, n\Delta x$, $y = 1\Delta y \ldots$, $t = 1\Delta t \ldots$, and so on.

Each of the five components is described below. For the purposes of illustration, a right-handed Cartesian coordinate system is assumed in which $x$ defines the primary horizontal flow direction, $y$ the transverse direction, and $z$ is positive upwards.

### Hydrodynamic module

An accurate description of the fluid flow field is a necessary condition for predicting sediment transport and deposition. Without significant loss of generality most geomorphic hydraulic models assume that the fluid is incompressible, the fluid density is everywhere equal, the pressure distribution in the fluid is hydrostatic, and the eddy viscosity approach can be used to describe the role of turbulence in momentum transfer (see Lane, 1998 for a review). Whether further simplifications are justified depends upon the application. In the most demanding applications the flow field is unsteady and nonuniform and significant secondary circulation exists. Consequently, the hydraulic module must compute the instantaneous, turbulence-average flow velocities $u$, $v$, and $w$

**Table N1** Some popular numerical sediment transport models

| Model | Authors | Comments |
|---|---|---|
| HEC-6 4.1 | US Army Corps of Engineers | 1D, movable bed, open channel flow model simulating scour and deposition from steady flows; FEMA[a] approved |
| TABS-SED2D 4.5 | US Army Corps of Engineers | SED2D computes sediment loadings and bed elevation changes when supplied with a flow field from TABS or RMA2; treats clay beds; FEMA approved |
| MIKE 11 | DHI Water and Environment, Inc. | 1D, commercial movable bed open channel flow model simulating cohesive and non-cohesive sediment transport and deposition; FEMA approved |
| CH3D-SED | Gessler *et al.*, 1999 | 3D model of unsteady flows in estuaries and rivers, including vertical mixing and surface heat exchange; suspended sediment transport modeled by 3-D advection–diffusion equation |
| MIDAS | van Niekerk *et al.*, 1992 | freely-available, 1D, open channel, uncoupled unsteady, gradually-varied flow and sediment model |
| FFDC | Tetratech | freely-available, curvilinear orthogonal coordinate, coupled hydrodynamic and sediment model for coastal oceans |
| ECOM-SED | HydroQual, Inc. & Delft Hydraulics | 3D, commerical hydrodynamic and sediment model |

[a] US Federal Emergency Management Agency

at all nodes in the model space, as well as the water surface elevation, h at all surface nodes. Four dependent variables require four equations for their solution. The equations are the $x$- and $y$-directed general laws of motion, the hydrostatic pressure distribution in the vertical, and conservation of mass equation:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial}{\partial y}uv+\frac{\partial}{\partial z}uw=fv-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(A_H\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_V\frac{\partial u}{\partial z}\right) \quad \text{(Eq. 1)}$$

$$\underbrace{\frac{\partial v}{\partial t}}_{(1)}+\underbrace{\frac{\partial}{\partial x}uv+\frac{\partial v^2}{\partial y}+\frac{\partial}{\partial z}vw}_{(2)}=\underbrace{fu}_{(3)}-\underbrace{\frac{1}{\rho}\frac{\partial p}{\partial y}}_{(4)}+\underbrace{\frac{\partial}{\partial x}\left(A_H\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial v}{\partial y}\right)}_{(5)}+\underbrace{\frac{\partial}{\partial z}\left(A_V\frac{\partial v}{\partial z}\right)}_{(6)} \quad \text{(Eq. 2)}$$

$$\frac{\partial p}{\partial z}=-\rho g \quad \text{(Eq. 3)}$$

(minus sign

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \text{(Eq. 4)}$$

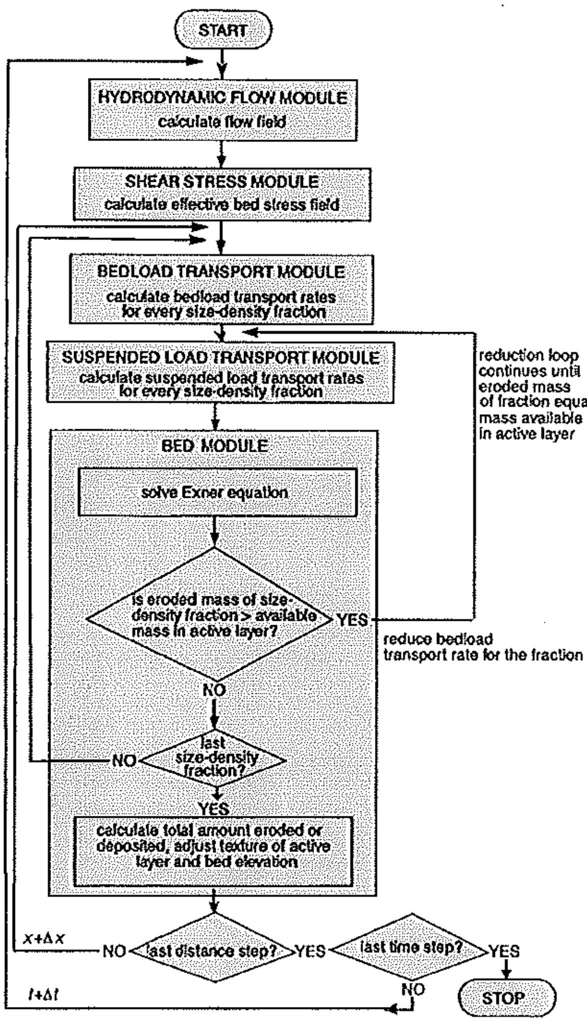


**Figure N13** Flow Chart of a typical sediment transport model.

where $u$, $v$, $w$ = velocity components in the $x$, $y$, $z$-directions; $t$ = time; $f$ = Coriolis parameter; $\rho$ = local fluid density, accounting for temperature, salinity, and sediment concentration; $p$ = pressure; $A_H$ = horizontal turbulent diffusion coefficient; $A_V$ = vertical turbulent diffusion coefficient; and $g$ = gravitational acceleration. Term 1 above accounts for unsteadiness of flow; Term 2 accounts for nonuniformity of flow; Term 3 accounts for Coriolis accelerations; Term 4 accounts for fluid pressure gradients arising from gradients in the water surface elevation; Term 5 accounts for shearing forces per unit mass due to velocity gradients in the horizontal and Term 6 accounts for shearing forces per unit mass due to velocity gradients in the vertical.

Before the equation set can be solved for the dependent variables, the turbulent diffusion coefficients must be specified. Numerous approaches exist (*cf.* Nezu and Nakagawa, 1993) ranging from "zero-equation" turbulence models that specify constant coefficients to "two-equation" models that equate $A_V$ to the square of the turbulence energy per unit mass and to the inverse of its rate of dissipation. Turbulence production and dissipation in turn are computed at all nodes using transport equations for the turbulence.

In selected applications the above equation set can be considerably simplified. For example, if only a cross-sectional average description of the flow in a rectangular channel is needed, the Coriolis term may be dropped and equations 1–4 integrated to yield:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}QV+gA\frac{\partial h}{\partial x}+\frac{fWV^2}{8}+gA\frac{\partial b}{\partial x}=0 \qquad \text{(Eq. 5)}$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+q_l=0 \qquad \text{(Eq. 6)}$$

where $Q$ = water discharge; $V$ = cross-section average velocity; $A$ = cross-section area; $h$ = water depth; $f$ = friction factor; $W$ = channel width; $b$ = bed elevation; and $q_l$ = lateral inflow per unit length of channel. Equations 5 and 6 can be simplified further by assuming the flow is steady and uniform provided that the ratios $V/gST$ and $h/SL$ are much less than 1 (Paola, 1996), where $S$ is the bed slope, $T$ is a time scale over which the unsteadiness occurs, and $L$ is a length scale over which the channel nonuniformity occurs. It should be noted however, that if the application requires dynamical adjustments in channel width, a 2D formulation is necessary at minimum.

## Shear stress module

The suspended load is determined by the sediment concentration and velocity distributions over the vertical, both of which depend upon the total turbulence-averaged bed shear stress $\tau_0$, exerted by a flow on its bed and banks. The bedload on the other hand, should be computed using only the skin friction component of the bed shear stress, $\tau_0'$, and should not include the bedform shear stress, $\tau_0''$, i.e., that portion of the fluid drag expended exciting roller vortices on the lee sides of dunes. The skin friction component is called the *effective bed shear stress* and various schemes are available to compute it (e.g., Einstein and Barbarossa, 1952; Kazemipour and Apelt, 1983). For example, in the case of equation 5 where the mean properties of the flow are of interest, the effective bed shear stress law may be computed from the quadratic shear stress law as:

$$\tau_0'=\frac{f}{8}\rho V^2 \qquad \text{(Eq. 7)}$$

where $f$, the Darcy–Weisbach friction factor for turbulent flows, is calculated using the Colebrook–White formula. Alternatively, if the flow is steady and uniform, the total turbulence-averaged bed shear stress, given by:

$$\tau_0=\rho gRS \qquad \text{(Eq. 8)}$$

where $R$ = hydraulic radius and $S$ = bed slope, may be reduced by subtracting the bedform shear stress, the latter equal to:

$$\tau_0''=\frac{1}{8}\rho V^2\frac{s^2}{lh} \qquad \text{(Eq. 9)}$$

where $s$ = dune height and $l$ = dune length.

Although most sediment transport models use the temporal mean fluid shear stress to represent the fluid forces on grains, in reality the local instantaneous bed shear stress fluctuates dramatically due to flow turbulence. Some sediment transport models incorporate this variation (e.g., van Niekerk *et al.*, 1992; Bridge and Bennett, 1992) by computing a Gaussian distribution of instantaneous effective shear stresses.

## Bedload transport module

The bed material load consists of all those grains in transport that are directly supplied by, and interchange with, the alluvial bed, whether traveling as bedload or suspended load. Its opposite is wash load. For a given flow strength and bed material it is assumed that each size fraction will be transported at a fixed rate, the sum of which is called the sediment transport capacity of the flow. Prediction of the bed material load at capacity usually proceeds by computing the bedload and suspended load independently.

As discussed elsewhere (see entries in this volume on *Sediment Transport*), bedload refers to all those sliding, rolling, and saltating grains supported at least in part by collisions with other grains or contact with the bed. In water, the grains travel within a few grain diameters of the bed as a low-concentration, dispersed, grain flow.

Grains are considered to be in motion when:

$$\Theta' > \Theta_{ci} \qquad \text{(Eq. 10)}$$

in which $\Theta'$ = the dimensionless effective bed shear stress of the local flow and $\Theta_{ci}$ = the critical shields parameter for the ith grain size and density in question. Accurate prediction of bedload fluxes depends strongly upon knowing these critical shear stresses.

Research over the last two decades (*cf.* Komar, 1996) shows that:

$$\Theta_{ci} = \Theta_{c50}\left(\frac{D_i}{D_{50}}\right)^{-m} \qquad \text{(Eq. 11)}$$

where $\Theta_{c50}$ = the critical shields parameter of $D_{50}$, the median size in the bed size distribution, $D_i$ = the grain size in question, and $m \approx 0.65$ for beds coarser than sand.

Once grains are entrained, they may pass directly into the suspended load. Grains are moving as bedload when:

$$w \geq Bu_*' \qquad \text{(Eq. 12)}$$

where $w$ = the grain fall velocity (see entry in this volume on grain fall velocity), $B = 0.8$, and $u_*'$ = the local effective shear velocity.

The weight or volume transport rate of bed fractions meeting the criteria of equations 11 and 12 may be calculated using one of many formulas (see reviews by Gomez and Church, 1989; Yang and Wan, 1991). Most can be shown to reduce to a function of the form:

$$i_{bi} = aP_i(\Theta' - \Theta_{ci})^b \qquad \text{(Eq. 13)}$$

where $i_{bi}$ = bedload transport rate per unit width of the ith fraction at capacity; $a$ is roughly a constant, $P_i$ = volumetric proportion of the ith fraction in the bed, and $1 \leq b \leq 2$. Note that as the various size fractions are differentially entrained, the bed size distribution evolves, thereby modifying the bedload transport rates through the coefficient $P_i$.

## Suspended load transport module

The suspended load consists of all those grains borne aloft in the flow by an upwards-directed turbulence momentum flux. Operationally, the suspended load consists of all moving grains for which equation 12 is untrue. Here too, the researcher can choose among numerous formula (see entries in this volume on sediment transport). The most basic conception assumes that if the vertical profiles of both sediment concentration $C(z)$, and forward velocity $u(z)$, are known, the volumetric discharge of suspended grains passing through a cross section of unit area at height $z$ is given by $C(z)u(z)$. Integration of this quantity over the depth yields the suspended load transport rate:

$$i_{si} = \int_a^h C_i(z)u(z)\,dz \qquad \text{(Eq. 14)}$$

*where* $i_{si}$ = volumetric suspended load transport rate per unit width of the ith fraction moving in the $x$-direction, and $a$ = the height off the bed at which a reference concentration is known.

The concentration function is defined by the *Rouse equation*:

$$\frac{C_i(z)}{C_i(a)} = \left[\frac{(a)(h-z)}{(z)(h-a)}\right]^R \qquad \text{(Eq. 15)}$$

or more recently, by the van Rijn equation (van Rijn, 1984), where $R$ = the Rouse Number. In either case, a reference concentration $C_i(a)$, is needed for the integration. Some researchers (e.g., van Niekerk *et al.*, 1992) take the reference height as the top of the moving bed layer and the reference concentration as the concentration of the ith fraction in the subjacent bedload as defined by a function of the form given by equation 13. Others, such as van Rijn, point out that in the presence of bedforms another approach is needed, van Rijn takes the reference height as one-half the dune height or the equivalent roughness height if bedform dimensions are not known and computes the concentration at that height as a function of excess effective shear stress.

The velocity profile traditionally is defined by the law of the wall for hydraulic rough flow conditions:

$$\frac{u(z)}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad \text{(Eq. 16)}$$

where: $u_*$ = flow shear velocity; $\kappa$ = von Karman's constant; and $z_0$ = 3.3 percent of the equivalent roughness height of Nikuradse.

Predictions of suspended load flux by equation 14 are suitably accurate provided the concentrations do not increase to values that dampen turbulence.

## Bed module

The core of a sediment transport model is its bed module. The bed is both a source and sink of the various size fractions in transport and it dynamically responds to and modifies the overlying flow field by changing its elevation and roughness. These roles can be described by an equation accounting for the mass fluxes of grains to and from the bed. It is a simple statement of conservation of mass of the bed, often called the *Exner equation*:

$$\frac{\partial}{\partial t}Tb_i = -\frac{1}{(1-p)\gamma'}\left(\frac{\partial}{\partial x}T(i_{bi}+i_{si})\right) + q_b \qquad \text{(Eq. 17)}$$

where: $T$ = width of the active bed, usually assumed to be channel width; $b_i$ = bed elevation attributable to the ith size-density fraction; $p$ = bed porosity; $\gamma'$ = immersed specific gravity of grains; $(i_{bi} + i_{si})$ = the immersed weight transport rates per unit width of the bedload and suspended loads; $q_b$ = volumetric lateral sediment inflow per unit along-stream distance; and it is assumed for simplicity that the application is 1D. Equation 17 expresses how spatial gradients in transport rates of the various size fractions give rise to temporal changes in bed elevation. If the changes in bed elevation are nonuniform, bed slopes and cross sectional areas evolve, thereby changing the flow field. Note that per unit area, the relative proportions of the $b_i$ represent the proportions of the various size fractions in the static bed, thereby allowing computation of a new bed grain size distribution and hydraulic roughness.

In practice, equation 17 is applied to an upper layer of the alluvium called the *active layer*, in recognition of the fact that over time scales of minutes to hours there is a finite thickness of alluvium exposed to the flow. The active layer may be conceived as a layer of mixing between the traction carpet and the static bed. The thickness of the active layer has been taken variously as the height of dunes present on the bed, the thickness of the armor layer (and hence some multiple of a characteristic grain size of the bed), or a function of excess shear stress. As grains are removed from the active layer on its upper surface, grains are added from below in proportion to their concentrations in the subjacent layer. During deposition, grains pass out of the bottom of the active layer in proportion their concentrations in the layer.

## Solution of equation set

The computational modules described above require initial and boundary conditions to form a closed set of equations. In addition, if the application involves channelized flow, either the alongstream channel widths must be specified or an additional function added to relate width to the state variables. Initial conditions include the geometry and bed textures of the geomorphic domain of interest and flow velocities and sediment transport rates everywhere in the domain (both usually taken to be zero for lack of better information). To avoid errors arising from bogus initial conditions, it is common practice to "spin-up" a model before interpreting the results. Boundary conditions include temporally evolving water and sediment hydrographs along upstream open boundaries and (typically) water surface elevations along downstream open boundaries. Lateral inflows of sediment and water along closed boundaries also must be specified.

Because the equation set is analytically unsolvable, the time-space domain is subdivided into a finite number of nodes or elements, and solutions are obtained at discrete points in space and discrete times. The flow chart of MIDAS (van Niekerk *et al.*, 1992), provides a typical example of computational flow for a 1D case (Figure N13). After the user has specified the initial and boundary information, the flow field at time $t + \delta t$ is computed across the whole domain by some combination of equations 1 through 6. The effective shear stresses are calculated next from equations 7 through 9. Starting at the upstream end of the domain, the bedload transport rates are computed from equations 10 through 13, thereby providing the reference concentrations for the suspended load computation using equations 14 through 16. After the bed material load at node 1 has been computed, equation 17 is solved for changes in bed elevation at that node arising from erosion or deposition of each size fraction. If the mass of any size fraction to be eroded is greater than is available in the active layer, then that fraction's bedload transport rate (and consequently its suspended load transport rate) are incrementally reduced until mass is conserved. Computation proceeds through the domain, after which the time step is incremented, the flow field is recomputed taking into account the updated water depths and hydraulic roughnesses, and the sediment transports are recomputed in light of the new flow field.

This algorithm is not the only possible computation method. Although this uncoupled approach is the most common, a few models such as CH3D-SED (Gessler *et al.*, 1999) simultaneously solve for all dependent variables in a fully-coupled solution. The advantage of a coupled solution is that uncoupled models are restricted to short time steps so that the hydrodynamic solution scheme adjusts to small changes in the bed.

## An example

To gain an appreciation of model capabilities, consider a comparison of predictions from the sediment-routing model MIDAS (Table N1) with flume data collected by Little and Mayer (1972). Little and Mayer investigated the effects of sediment gradation on channel armoring. A nonuniform bed of sand and gravel was placed in a flume 12.2 m long, 0.6 m wide, and 0.1 m high. Clear water was passed over the bed to produce bed degradation and armoring. The eroded sediment was caught by screen separators at the downstream end of the flume, and at regular intervals was dried, weighed, and stored for later sieving. When the total transport rate was 1 percent of the initial transport rate and the armoring was thought complete, the flume was drained and the armor layer was sampled using molten beeswax as described by the authors. For numerical modelling, the flume was divided into eight sections and solutions of the MIDAS equation set were computed for every section every minute.

The computed and the measured total transport rates (Figure N14) show good agreement, the computed values being within a factor of 2 of the measured values at all times. Temporary divergence of the two curves arises because turbulence produces random and intermittent movement of the bed particles. After 75.5 hours of flow, the size distributions of the original sediment, the bed-armor sediment, and the total eroded sediment (Figure N15) show that the numerically simulated armor layer is slightly finer than observed, although the difference in mean grain sizes is only 2.7 mm versus 3 mm. The numerically simulated and physically observed grain-size distributions of the transported sediment almost coincide.

## Unresolved problems

Although much progress has been made in sediment transport models, the accuracy of predictions in many applications is still regrettable. Bedload functions are still prone to order of magnitude errors (*cf.* Gomez and Church, 1989; Yang and Wan, 1991), and present formulations need to be tested in extreme events when much of the sediment transport occurs in many geomorphic systems. These errors are compounded when computing sediment flux divergences in equation 17. Also, suspended load formulations break down at hyper-concentrations such as seen in many rivers draining loess provinces and do not yet account for the wash load. There is

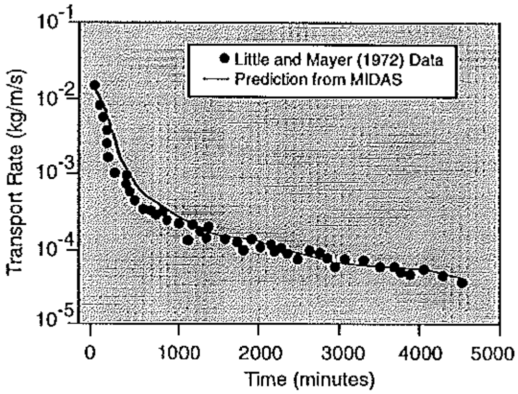


**Figure N14** Comparison of observed sediment transport rates from a flume study of bed armoring by Little and Mayer (1972) with predictions from the sediment transport model MIDAS (van Niekerk *et al.*, 1992).

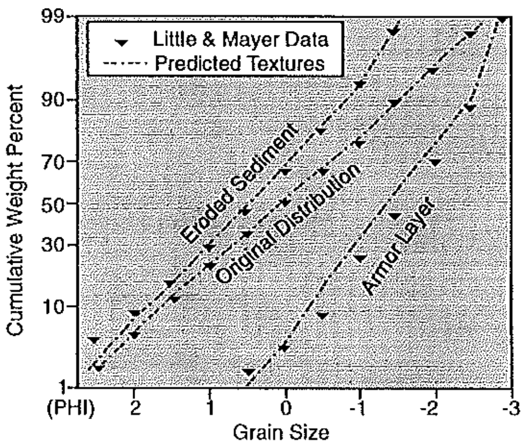


**Figure N15** Comparison of observed textures from a flume study of bed armoring by Little and Mayer (1972) with predictions from the sediment transport model MIDAS (van Niekerk *et al.*, 1992).

also a pressing need to treat channel pattern changes and dynamic adjustments in channel hydraulic geometries. Secondary flows are commonly assumed to be negligible, yet in natural channels, and particularly during overbank flows, lateral gradients of flow depth and friction factor induce significant lateral velocity gradients. Although not much as been said about coastal ocean sediment transport models, a better understanding of the basic physics of combined oscillatory and uni-directional flows is needed and the processes of sediment aggregation, flocculation, and disaggregation in marine waters must be better understood.

## A final thought

Given the work yet to be done, it is sobering to realize that the most severe test yet of numerical sediment transport modeling is being carried out right now on the Yangtze River in China. Construction of the Three Gorges Dam began in 1994 and is scheduled to take 20 years. It will be the largest hydroelectric dam in the world, stretching nearly a mile across and towering 575 feet above the world's third longest river. Its reservoir will stretch over 350 miles upstream and force the displacement of 1.2 million people. The role that numerical sediment transport modeling has played in the dam's conception, feasibility studies, and design is unprecedented and the predictions are controversial. Physical and in particular, mathematical modeling of sedimentation was conducted by the Yangtze Valley Planning Office (China) and reviewed by the Yangtze Joint Venture (Canadian International Development Agency). Dr Luna Leopold, a respected elder statesman of fluvial engineering in the United States has written, "The sedimentation conditions at various times during the first 100 years of operation have been forecast by use of mathematical models and physical analogues that involve many assumptions of unverified reliability". Let us hope our faith in numerical models of sediment transport and deposition is justified.

Rudy L. Slingerland

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# S

## GROVE KARL GILBERT (1843–1918)

One of the greatest American geologists of the nineteenth century—a man who should be ranked with Lyell, Agassiz, and Smith—is Grove Karl Gilbert, born May 6, 1843 in Rochester, NY, and who died May 1, 1918 while preparing for another field season in Utah. His intellectual contributions were theoretical and institutional, ranging from the concept of dynamic equilibrium of landscapes to founding member and Chief Geologist of the United States Geological Survey. He was one of the premier scientific explorers of the American West and it is not coincidental that his lifetime is called the heroic age of American geology.

Born the son of a self-taught portrait painter, Gilbert was the youngest of three children. He received a classical education studying at home and from the University of Rochester where he emphasized Greek and Latin; he took but one geology course. After a failed attempt at teaching school on the Michigan frontier, he landed a job at Cosmos Hall, the famous distributor of natural history artifacts run by Henry A. Ward. This in turn led to a position with the Ohio Geological Survey as a volunteer, where he came under the tutelege of John Strong Newberry. Two years later Newberry recommended him for the position of geologist on the US Army's Geographical Survey West of the 100th Meridian. He remained an employee of the US Government for the rest of his life, joining the Powell Survey in 1875, and the fledging United State Geological Survey in 1879.

Gilbert's principal contributions to sedimentology are contained in his four great monographs: *Report on the Geology of the Henry Mountains* in 1877; *Lake Bonneville*, 1890; *The Transportation of Debris by Running Water*, 1914; and *Hydraulic-Mining Debris in the Sierra Nevada*, 1917. In the third and final part of the Henry Mountains report he erected the foundations of modern geomorphology. Conceiving of a stream as an engine which performs work and applying the laws of conservation of energy and least action, he codified three laws of land sculpture and invented the fruitful concept of dynamic equilibrium of landscapes and its derivitive, the graded stream. He also presented the concept of bedload as a corrasion tool in bedrock streams and articulated for the first time the conditions under which streams will form lateral planation surfaces.

In his Lake Bonneville studies the objective was twofold: "the discovery of the local Pleistocene history and the discovery of the processes by which the changes constituting that history were wrought." Here is the first description of the origin of coastal features such as spits, bars, and wave-cut terraces as a product of the balance between wave energy and sediment supply as it affects littoral drift and the first sedimentologic description of the delta type which still bears his name. Its everlasting contribution however, was primarily methodological. In this one quarto volume Gilbert showed how sedimentary processes could be deduced from geomorphic forms using the proper application of mechanical laws.

Gilbert's monograph on bedload transport (with E. C. Murphy) is a seminal document in experimental sedimentology. It is the first systematic attempt to formulate the functional relationships between bedload flux and flow energetics, the only exception possibly being the work of C. Lechalas in 1871. The experiments were conducted in four flumes of varying sizes. In each, the capacity of the flow was measured as a function of seven variables: discharge, slope, fineness of debris, depth, width, and to a lesser extent, mean velocity and channel curvature. Although Gilbert was never able to reduce the data to a rational theory of bedload transport, he succeeded in formulating the basic questions and concepts. Besides providing practical formulae relating capacity to discharge, slope, and width/depth ratio, he described the particle dynamics of the moving bedlayer, the threshold of motion as a function of grain diameter, and the role played by fines in increasing the capacity of the coarse fraction in bimodal mixtures. While others, especially French engineers, had conducted flume experiments before Gilbert, his methodology, mathematical formulations, and physical explanations were unrivaled. The experimental design was so well conceived and the observations so meticulously taken, the data are still used today.

In his last monograph Gilbert applied these flume results to address the natural and man-made problems arising from excess sediment supply to the Sacramento River system. Using his idea of a graded stream, he predicted the effectiveness of various engineering structures to control flooding along its course. And in a final rhetorical flourish he predicted that the tidal bar at the mouth of the Golden Gate would move inland as a consequence of reduction in tidal prism as the bay was filled by mining debris and agricultural sediment runoff. The power of this work was not in the social change it effected, but in the template it provided for subsequent conservation literature.

In separate contributions he published on the origin of bedforms, in particular ripples marks, ripple drift lamination, and "giant wave" ripples, from which he attempted to deduce ancient water wave heights.

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## Bibliography

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