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The contents of this paper reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Hydrology, Hydraulics and Water Quality.

Computer-Based Prediction of Alluvial Riverbed Changes

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ABSTRACT

Recent investigations and research programs at the Iowa Institute of Hydraulic Research have involved both the analysis and development of computer-based simulation techniques for alluvial riverbed evolution. The primary use of such techniques is in the prediction of riverbed aggradation and degradation caused by perturbations in the river's equilibrium geometry and sediment inflow supply over extended reaches. In this paper the mathematical basis of the problem is reviewed and several general numerical approaches and associated difficulties are described. Seven published programs are then described, and their performance when applied to three actual field situations is compared. The conclusions point out a critical dependence on field data and identify the need for further research in understanding physical mechanisms such as sediment sorting, armoring, scour, and deposition.

Mother Nature, in providing the Earth with a system of drainage channels to return surface waters to the sea, has endowed man in general, and river engineers in particular, with both a blessing and a curse. The blessing is that rivers whose channels are formed of loose, noncohesive alluvium are able to adjust their geometry to carry widely varying discharges with only moderate changes in water-surface elevation. The curse is that river engineers have found this self-regulating mechanism extremely difficult to understand and accommodate in their projects.

The sheer complexity of alluvial river response, which involves dozens of relevant variables and even ambiguity as to which are the dependent and independent ones, has defied attempts to formulate a coherent, reliable, "desktop" methodology for alluvial river design. Although field experience and laboratory tests have led to the establishment of fairly reliable procedures for the prediction of local scour around bridge piers, bank stability, and other such local phenomena, no such procedures exist for the analysis of alluvial riverbed and bank changes over long river reaches and extended periods of time.

The design engineer's interest in alluvial river response is generally focused on anticipating how the riverbed and water-surface elevations will change if an existing stable or equilibrium situation is perturbed. This perturbation may be the occurrence of an unusually large annual flood that temporarily scours the bed and banks to accommodate the higher flow before returning to normal conditions. Or the perturbation may be a permanent change in river discharge patterns and geometry caused by upstream regulation of flows or bank stabilization and channelization. The first type of perturbation is often susceptible to simulation using a physical scale model. Although difficult problems of scaling laws and with the interpretation of results arise, such physical models, in the hands of experienced modelers, can yield valuable information on local scour and deposition around structures. However, the sheer expense and space requirements of physical scale models generally disqualify them for simulation of long-term, large-distance riverbed response to the second type of perturbation. This is where numerical, computer-based models, which can simulate both short- and long-term response, find their natural area of application.

Numerical models of alluvial river response are the natural outgrowth of rigid-boundary, unsteady flood-propagation models that have proven to be so useful in engineering design. These unsteady flow models have succeeded because they are based on mathematical descriptions that incorporate all the important physical processes involved and use reliable, carefully implemented numerical methods to obtain approximate solutions to the appropriate partial-differential equations. However, alluvial river-response models have enjoyed nowhere near the success of their rigid-boundary cousins, precisely because of the weaknesses in our understanding and mathematical formulation of the relevant physical processes. Notwithstanding this fundamental difficulty, design engineers have an immediate need for reliable numerical simulations, and hydraulic research engineers have targeted alluvial river hydraulics as a prime area for continuing fundamental and applied research. Out of this fortunate confluence of interest have arisen a variety of simulation techniques and industrialized software systems, as well as many apparently successful simulations of prototype situations.

The remainder of this paper is devoted to brief descriptions and critical analyses of several of the currently available software systems for alluvial river simulation. All are limited to one-dimensional simulation, in which it is assumed that river response can be described in terms of the average longitudinal flow, without detailed knowledge of secondary currents, backwater eddies, flow patterns in the immediate vicinity of structures, and so forth. At this time (1984), it would appear that engineering use of two- and three-dimensional simulation must await the development of a more complete understanding of the physical processes involved.

MATHEMATICAL REPRESENTATION OF ALLUVIAL RIVERBED EVOLUTION

The most basic one-dimensional description of water and sediment flow in an alluvial river consists of four relations (1):

Conservation of water

$$(\partial h/\partial t) + (\partial q/\partial x) = Q_\ell/B \tag{1}$$

Conservation of water momentum

$$(\partial u/\partial t) + [u(\partial u/\partial x)] + [\underline{g}(\partial h/\partial x)] + [\underline{g}(\partial z/\partial x)] + \underline{g}S_f = M_\ell/\rho Bh \tag{2}$$

Conservation of sediment

$$(1-n)[\tilde{B}(\partial z/\partial t)] + (\partial G/\partial x) = G_\ell \tag{3}$$

Sediment-transport law

$$f(G, S_f u, h, D_{50}, \ldots) = 0 \tag{4}$$

where

- h = water depth,
- q = water discharge per unit channel width ($q = uh$),
- u = depth-averaged water velocity,
- Q_ℓ = lateral water-inflow rate per unit length,
- B = channel width,
- $\underline{g}$ = gravitational acceleration,
- S_f = energy gradient,
- M_ℓ = contribution to longitudinal momentum from lateral water inflow,
- ρ = water density,
- $\underline{n}$ = sediment porosity,
- $\tilde{B}$ = channel width affected by sediment transport,
- z = bed elevation,
- G = volumetric sediment-transport rate,
- G_ℓ = lateral sediment-inflow rate per unit length, and
- D_{50}, ...symbolically represents all sediment properties that determine the amount transported and the shear stress at the riverbed.

Solutions to Equations 1 through 4, if they could be obtained for appropriate initial and boundary conditions, would produce the time and one-dimensional space variation of velocity $u(x,t)$, depth $h(x,t)$, bed elevation $z(x,t)$, and sediment transport rate $G(x,t)$. However, any implementation of a conceptual model based on these equations also requires assumptions about how erosion or deposition is distributed across the width of the channel, as well as a quantifiable conceptual model relating the composition (size distribution) of sediment in the bed alluvium to the composition of sediment being transported. Numerical models are more often distinguished one from another by the way they treat such processes than by their solution of the basic equations.

Equations 1 through 4 form a nonlinear partial-differential system that in general cannot be solved analytically. Approximate numerical methods can be used to solve these equations, but such methods are often tedious and expensive, especially when Equation 4 incorporates the interdependence of sediment-transport rate and flow resistance. Consequently, use is often made of the fact that the typical time scale of liquid wave-propagation phenomena is much shorter than the time scale of longitudinal bed-profile modification (1). The propagation time of a flood peak along a 100-km reach may be of the order of 1 or 2 days, whereas it would take several years for a bed-level perturbation to cover such a distance. Whenever this is the case, the system of Equations 1 through 4 can be simplified by assuming that the water flow remains quasi-steady during a certain interval of time; or, in other words, that water-wave propagation effects are of secondary importance for sediment-transport phenomena.

When this quasi-steady water-flow assumption is justified, Equation 2 for unsteady conservation of water momentum reduces to the familiar "backwater equation," an equivalent statement of steady-state momentum or energy conservation:

$$[u(\partial u/\partial x)] + [\underline{g}(\partial h/\partial x)] + [\underline{g}(\partial z/\partial x)] + \underline{g}S_f = M_\ell/\rho Bh \tag{5}$$

The mathematical problem is then reduced to one of solving just the nonlinear partial-differential system of Equations 3, 4, and 5 in each time interval over which the water discharge is assumed to be nonvarying in time, be it for several hours during a rising flood hydrograph or several years if the effects of a single dominant discharge are of interest.

There are two general types of sediment-transport and flow-resistance formulae as represented symbolically by Equation 4. In the first type, the energy gradient S_f is taken to be an explicit function of known flow roughness and other parameters, and the sediment-transport rate G is an explicit function, albeit indirect and often complex, of the flow. In the second general type of Equation 4, the effects of bed forms, changing bed-material composition, and bed armoring on both flow resistance and sediment-transport formulae are taken into account in an attempt to represent the known interdependence of flow resistance and sediment transport (2, pp. 114-126).

NUMERICAL SOLUTION OF GOVERNING EQUATIONS

Virtually all published software systems for the solution of the water- and sediment-flow equations use one form or another of the finite-difference method, in which time and space derivatives are approximated by differences of nodal values of grid functions that replace the continuous functions, leading to a system of algebraic equations. Some authors have used the finite-element method, but in one dimension there does not appear to be any strong reason for doing so. In any case, the quality and reliability of numerical models for bed evolution are determined primarily by the sediment-transport formulation and mechanisms adopted for sorting, armoring, and so forth. The particular numerical method used, as long as it is consistent with the partial-differential equations and is stable, has only a secondary effect on simulation quality.

Whether the full unsteady set of Equations 1 through 4 or the quasi-steady set of Equations 3 through 5 is solved numerically, two basic approaches are possible: coupled or uncoupled (1). In the coupled case, a simultaneous solution of both water and sediment equations is sought. This is evidently the physically proper way to proceed, because the water-flow and sediment-transport processes occur simultaneously. However, the simultaneous solution may involve certain computational complications, especially when the sediment-transport flow-resistance equation (4) involves not just an analytic mathematical expression but a whole series of procedures and computations to simulate armoring, sorting, bed forms, and so forth.

The uncoupled procedure has arisen essentially to circumvent the computational difficulties of the coupled approach. The uncoupling of the liquid and solid transport occurs during a short computational time step, Δt. First the water-flow equations are solved to yield new values of depth and velocity throughout the reach of interest, assuming that neither the bed elevation nor the bed-sediment characteristics change during the time step. Then the depths and velocities are taken as constant, known inputs to the sediment continuity and transport equations (3 and 4); these equations then become relatively easy to solve numerically, yielding the new bed elevations. When the overall model includes bed-sediment sorting or armoring, these processes are simulated in a third uncoupled computational phase using new depths, velocities, and bed elevations as known inputs. Although it is difficult to quantify the error associated with this artificial uncoupling of simultaneous, mutually dependent processes, it is intuitively obvious that the uncoupling is justified only if bed elevations and bed-material characteristics change very little during one time step. Experience in the use of uncoupled models, with both the unsteady and quasi-steady water-flow equations, has shown that the uncoupling is not a serious obstacle to successful simulation.

Another hybrid approach involves an iterative application of the uncoupled approach within one time step. The computational practicalities of the uncoupling are retained, but the water and sediment processes are allowed to interact through iterative coupling until the algebraic equivalents of the water- and sediment-flow equations are truly simultaneously satisfied at the end of the time step. Additional computational cost would appear to be the only reason (and a weak one at that) not to iteratively couple the equations.

ARMORING AND SORTING

Another distinguishing feature of numerical bed-evolution models is the representation of sediment sorting and bed-surface armoring. Alluvial sediments are rarely of uniform grain size. A broad range of sizes are represented, from gravels and coarse sands down to fine silt and clay in varying proportions. Finer particles are preferentially entrained into the flow as erosion occurs, so that the material remaining on the bed contains a progressively higher proportion of coarser material. This so-called sorting process tends to increase the mean bed-material size as degradation occurs, thus affecting the sediment-transport rate, river regime (existence of ripples and dunes), and flow resistance through both particle roughness and bed-form effects (3). If the original bed material contains a high enough proportion of large, nonmovable materials (coarse gravel, cobbles, and small boulders), an interlocking armor layer may form on the surface, arresting further degradation. These processes are qualitatively reversed during deposition, but become even more difficult to quantify.

No computer-based models presently available incorporate a general, adequate treatment of sorting and armoring processes. Nevertheless, some models attempt to simulate their effects on bed evolution; others ignore them completely. Thus another important distinguishing feature of computer-based models is the degree to which they incorporate sorting and armoring effects.

PERFORMANCE OF SELECTED MODELS

Numerical modeling of alluvial river flows has become very popular in recent years because of the advancement of digital-computer technology. However, the number of computer-based, alluvial riverbed prediction models that are readily available for application to prototype cases seems to be quite small. Most of the available models have been developed for specific rivers under particular flow and alluvial riverbed conditions, and many of them are, to some extent, well tuned or calibrated for those particular rivers. In this section, attention will be focused only on those models that are related to the investigations conducted at the Iowa Institute of Hydraulic Research (IIHR) in the last few years (4-7).

The assessment of the selected models is made for two different groups: short-term models and long-term models. The short-term models are best suited to compute changes in alluvial riverbed level during a relatively short time period. They are suited for a single-flood event because of the relatively high cost of backwater computation using either unsteady flow equations or a rather complex fixed-bed water-routing model such as HEC-2 (8). On the other hand, the long-term models employ simpler implementations of steady-state flow equations, and thus are suited for long-term prediction of riverbed level for multiple-flood events over multiple years. However, it should be recognized that the short-term models can also be applied for long-term prediction if variable time steps are employed. In that case a shorter time step is used for highly unsteady flows and a longer time step is used otherwise.

Short-Term Models

HEC2SR (HEC-2 with Sediment Routing)

The known-discharge, uncoupled, water- and sediment-routing model was developed by Simons, Li and Associates (SLA) for simulating watershed sediment yield and the attendant riverbed aggradation and degradation in a river system (9). The model uses the HEC-2 fixed-bed, backwater-computation program developed by the U.S. Army Corps of Engineers (COE), Hydrologic Engineering Center (HEC) (8) for water routing. HEC-2 solves one-dimensional, steady-state, gradually varied flow using the flow-continuity and flow-energy equations (1 and 5). HEC-2 accounts for various kinds of flow encroachments, such as bridge constrictions and multiple channels, and allows for nonuniform distribution of the bed-roughness coefficient across the channel.

Once various hydraulic parameters are determined by the HEC-2 computation, the bed-material and wash-load discharges are estimated for each computational reach. The model uses the Meyer-Peter and Mueller formula (10) for the bed-load discharge computation and the Einstein formula (11) for the suspended-load discharge. The combined bed-material transport rates are further corrected for wash-load effects using Colby's empirical relationships (12). The sediment-volume change determined from the balance between the sediment inflow and outflow of each subreach is distributed uniformly along the reach. Therefore, the sediment-routing model that solves the sediment-continuity equation (3) cannot predict local scour or deposition patterns. However, dredging effects can be incorporated during the computation of the sediment-volume change. The change in cross-sectional profile is determined by a weighting factor based on flow conveyances in adjacent lateral subsections. Armoring effects and changes of bed-material composition are considered during each sediment-routing phase. After the sediment-routing phase, hydraulic and bed-profile data in the HEC-2 data file are updated, and the water- and sediment-routing computation for the next time step begins.

Because of the high cost of backwater computation, the model is not suitable for the long-term prediction of riverbed changes. The model is purely one dimensional and accounts for neither lateral channel migration nor secondary flows.

UUWSR (Uncoupled, Unsteady Water and Sediment Routing)

This model was developed at Colorado State University by Tucci, Chen, and Simons (13) for simulating one-dimensional, gradually varied, unsteady, water and sediment flows in complicated river networks. The model first solves the unsteady flow-continuity and flow-momentum equations (1 and 2) by an unconditionally stable, four-point, implicit, finite-difference scheme assuming a fixed bed during one time step. It is assumed that the bed-roughness coefficient for the unsteady flow is the same as that for a steady flow. Three types of boundary conditions may be used: upstream discharge hydrograph, upstream stage hydrograph, and downstream stage-discharge rating curve. The water-routing model also considers the effects of tributary confluences and dams on water-surface profiles in the study reach.

The computed flow information is used to compute the sediment-transport capacity, G, which is given by

$$G = a\,u^b\,h^c \tag{6}$$

where a, b, and c are empirical regression coefficients determined either from field data or by generating data using the Meyer-Peter and Mueller formula and Einstein's bed-load function for bed-load and suspended-load discharges, respectively. Computed sediment discharges are then applied to the sediment-continuity equation (3) to compute the change in the cross-sectional area by means of an explicit finite-difference scheme. Changes in bed-material composition are not taken into account. It should be noted that steady-state conditions are assumed at confluences and dams of the study reach. The model is able to simulate, with minimal computer cost, a complex river-network system in which islands, meander loops, and tributaries are connected to the main channel. The model can also account for effects of hydraulic structures such as dikes, locks, and dams. The flood-wave movement in a long reach can be simulated by this unsteady flow-routing model.

FLUVIAL-11

This uncoupled model was developed at San Diego State University in 1976 by Chang and Hill (14) to simulate one-dimensional, unsteady, gradually varied, water and sediment flows for channels with erodible banks. FLUVIAL-11 first solves the unsteady, flow-continuity and flow-momentum equations (1 and 2) in one time step by neglecting storage effects due to unsteady flow. The model uses an implicit, central-difference, numerical scheme in solving for the two unknown variables of water discharge and cross-sectional area. The flow information is then used to compute the bed-material discharge at each section using either the Graf formula (15) or the Engelund-Hansen formula (16).

The net change in cross-sectional area is next obtained by solving the sediment-continuity equation (3) using a backward-difference scheme for space and a forward-difference scheme for time. The computed cross-sectional area change is then adjusted for the effects of channel width, cross-sectional profile, and lateral channel migration. Width adjustments are made in such a manner that the spatial variation in power expenditure per unit channel length is reduced along the reach by a trial and error technique. Further adjustment of cross-sectional area is made to reduce the spatial variation in power expenditure along the channel. The effect of lateral channel migration is determined by solving the sediment-continuity equation in the transverse direction, which incorporates the effect of radius of curvature of the river bend into the transverse component of the sediment-transport rate. FLUVIAL-11 in unique because of its capability to predict changes in erodible channel width, changes in channel-bed profile, and lateral migration of a channel in bends.

Examples of Short-Term Model Performance

A National Research Council study committee conducted an investigation for the Federal Emergency Management Agency (FEMA) during 1981-1983 to determine whether riverbed degradation during flood passage has an effect on the flood stage that should be incorporated into the calculation of flood-zone limits (4). The study involved application of several flow- and sediment-routing models for alluvial streams to study reaches of the San Lorenzo, San Dieguito, and Salt rivers. These rivers were selected because they have historically experienced flash-flood-type events with appreciable riverbed changes and channel migration during floods. In the National Research Council study, the same input data for each river were furnished to the participating modelers and principal computational results were submitted by the modelers to the committee for evaluation. Only two cases of numerical simulation that are pertinent to the topic of this paper are presented in the National Research Council study results.

The first example is for the San Lorenzo River, which is located in Santa Cruz County in northern California and flows into the Pacific Ocean at Monterey Bay. The approximately 4.7-mile-long study reach comprises two different subreaches: the relatively steep upper-half reach and the 2.4-mile-long lower-half reach with a much smaller slope. The input data included hydrographs for the February 16-20, 1980, flood, preflood channel cross-sectional profiles coded in HEC-6 format, suspended-sediment discharge rating curves by particle sizes collected upstream from the upper-reach boundary, and bed-material composition data coded in HEC-6 format. The peak discharge was 12,800 cfs, and the median bed-material size varied between 0.34 mm at the downstream and 0.93 mm at the upstream boundary. The downstream boundary condition reflected tidal effects. The thalweg profiles at the peak discharge computed by HEC2SR, UUWSR, and FLUVIAL-11 are shown in Figure 1 together with the initial thalweg profile. As seen in the figure, UUWSR and FLUVIAL-11 predicted significant changes in thalweg elevation compared with the HEC2SR prediction. The general agreement of predictions of thalweg elevations among the three models is seen to be limited to extremely small portions of the study reach. Longitudinal distributions of the total-load discharge, mean flow velocity, and median bed-material size at peak flow were also found to differ significantly among the three models.

The second example is for the San Dieguito River, which flows through San Diego County in southern California. The 2-mile-long reach was studied for two peak flows of 4,400 cfs and 22,000 cfs. The San Dieguito River channel has a wide, flat cross section with highly erodible banks, and had been disturbed extensively, before the simulated floods, by sand-mining activities and construction of the Via de Santa Fe bridge. The channel bed is composed primarily of sand-range materials. The duration of each flood was approximately 2 days.

Thalweg elevations computed at a peak discharge of 22,000 cfs by HEC2SR, UUWSR, and FLUVIAL-11 are plotted in Figure 2 (no observed profile after 2 days was available). FLUVIAL-11 predicted a generally aggrading thalweg pattern over the entire reach, and the two Colorado State models predicted an aggradation pattern for the upper reach and a degradation pattern for the lower reach. The FLUVIAL-11 prediction of riverbed aggradation is believed to be due to the effect of a channel-widening module in the model. The prediction gap among these models is seen to amount to about 20 feet at a river distance of 3,600 ft at the Via de Santa Fe bridge.

Long-Term Models

KUWASER (Known-Discharge, Uncoupled, Water and Sediment Routing)

The KUWASER model was developed in 1979 at Colorado State University by Simons, Li, and Brown (17). The water discharge is taken as steady during a specified time interval, so that water-flow routing consists of simply solving the backwater equation (5) with an additional term for explicit representation of energy losses other than those caused by bed-shear stress. Equation 3 is solved by first computing the sediment volume to be removed or added to each reach, then allocating 25 percent of this volume to the upstream half of the reach and 75 percent to the downstream half. Cross-sectional changes are computed in a quasi-two-dimensional manner by allocating the volume change across the channel in direct proportion to the local longitudinal hydraulic conveyance factor. Lateral channel boundaries are assumed to be fixed (nonerodible banks); neither hydraulic-sorting nor bed-armoring processes are taken into account explicitly, though their effects may appear indirectly in the regression coefficients a, b, and c, in Equation 6.

KUWASER uses an empirical sediment-transport function. Flow resistance is uncoupled from bed

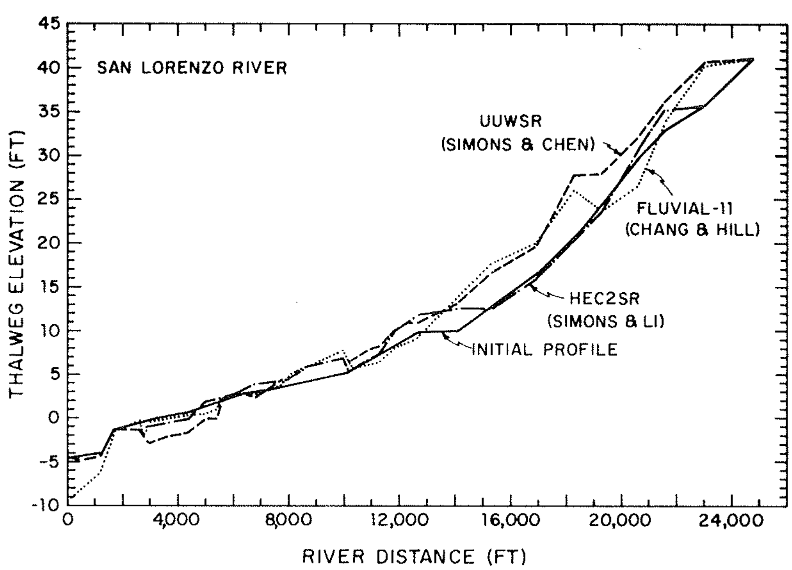

FIGURE 1 Comparison of computed thalweg elevations for the San Lorenzo River.

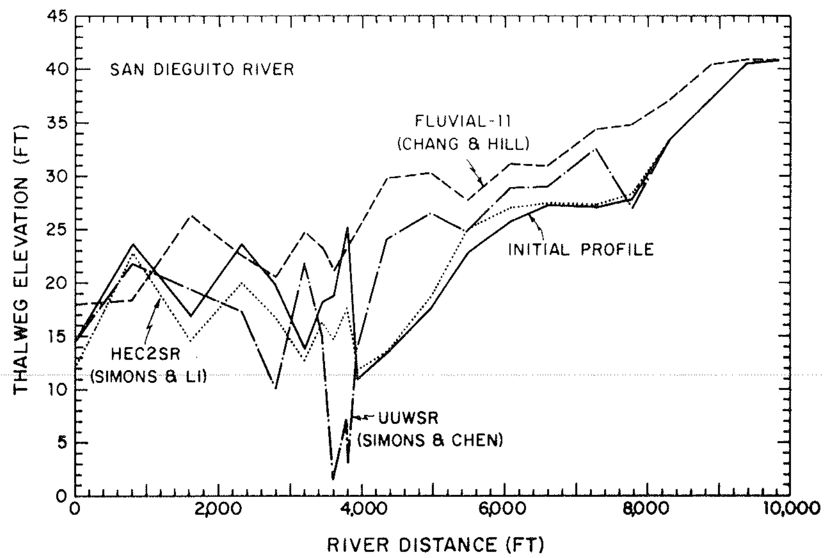

FIGURE 2 Comparison of computed thalweg elevations for the San Dieguito River.

evolution through use of simple Manning-Strickler equations for energy loss.

The use of KUWASER is limited to subcritical flows and channels without extremely irregular grade and geometry. However, it has the capability to model the mainstem and tributaries of a river system and can simulate divided flow associated with bars, islands, or channel breaches.

HEC-6 (Hydrologic Engineering Center)

The HEC-6 program was developed at the Hydrologic Engineering Center of the U.S. Army Corps of Engineers in 1977 (18,19). The quasi-steady backwater equation (5) is used to compute water-flow conditions uncoupled from the sediment-continuity equation, with expansion and contraction losses explicitly taken into account. The Manning-Strickler equation is used to compute energy loss caused by bed and bank roughness; roughness coefficients must be specified as input data, though they can be allowed to vary with discharge or stage.

The sediment-continuity equation (3) is solved using an explicit finite-difference scheme, with sediment-transport capacities determined from water-flow conditions previously determined in the uncoupled backwater computation. The entire movable-bed portion of the channel is assumed to aggrade or degrade uniformly. Sediments are routed by individual size fraction, which makes possible a detailed accounting of hydraulic sorting and development of an armored layer. Bank lines are assumed to be stable and fixed in the HEC-6 computation.

HEC-6 offers a choice of five sediment transport functions in Equation 4: Laursen's relationship, as modified by Madden for large rivers (20); Toffaleti's formula (21); Yang's stream-power formula (22); DuBoys' formula (23); and a special relationship between unit-width sediment-transport capacity and the product of the depth and energy slope developed for the particular river reach under study. In all these relations, it is assumed that sediment-transport capacity can be determined independently of flow conditions; that is, Equation 4 does not explicitly include the coupling of flow resistance and sediment transport through bed-form development.

HEC-6 is strictly a one-dimensional model with no provision for simulating the development of meanders or specifying a lateral distribution of sediment-transport rate across the section. The model is not suitable for rapidly changing flow conditions but can be applied to predict reservoir sedimentation, degradation of the streambed downstream from a dam, and long-term trends of scour or deposition in a stream channel, including the effects of dredging.

CHAR II (Charriage dans les Rivieres)

The CHAR II modeling system was developed by the French consulting engineering firm SOGREAH in the early 1970s (1,24,25). It is a coupled, quasi-steady model, simultaneously solving Equations 3 and 5 using an implicit finite-difference scheme. Energy losses caused by bed roughness are based on the Manning-Strickler equation, with overall section conveyances computed as the sums of individual rectangular sections following Chow's method (26). Localized energy losses and hydraulic works are modeled with the appropriate equations discretized between two adjacent computational points.

CHAR II considers banks to be nonerodible. Degradation and aggradation volumes are assumed to be uniformly distributed across the wetted channel section. No procedures for hydraulic sorting or armoring are included in the methodology, which considers only a single representative size fraction.

Sediment transport in the present version of CHAR II is limited to bed load, computed with either the Meyer-Peter and Mueller, Engelund-Hansen, DuBoys, or Einstein-Brown formulae (2) for Equation 4. Hydraulic roughness and sediment transport are uncoupled in CHAR II; SOGREAH's CHAR IV program, although less industrialized than CHAR II, does take this coupling into account through use of the full Einstein method (11).

CHAR II is designed for simulation of long-term riverbed evolution and sedimentation in reservoirs. A mainstem river and its tributaries can be modeled simultaneously with a variety of hydraulic works. The method is not inherently limited to bed-load transport because users can relatively easily add subroutines to compute total load using methods of their choice.

IALLUVIAL (Iowa ALLUVIAL River Model)

The IALLUVIAL program was developed between 1979 and 1982 by Karim and Kennedy at IIHR (6). It is formally classified as an iteratively coupled, quasi-steady model; in each time step Equation 5 is solved with bed elevations fixed; then Equation 3 is solved, using sediment-transport capacities determined as an integral part of the solution of Equation 5, to compute bed-elevation changes. Hydraulic sorting and armoring are then computed in a third phase. The entire procedure is iteratively repeated in each time step until the finite-difference analogues of Equations 3 and 5 are simultaneously satisfied at the end of the time step, although in most applications a single iteration (uncoupled) is sufficient.

The sediment-continuity equation includes sediment contributions from bank erosion and tributaries, and the effects of bank-line geometry changes can be simulated by explicit introduction of known width changes with time. The effects of dredging, cutoffs, and vertical variations in bed-sediment composition are taken into account in the computation.

IALLUVIAL is based on the total load transport model (TLTM) of Karim and Kennedy (27). This system of nonlinear equations, developed through dimensional reasoning and regression analysis of extensive laboratory and field data, specifically incorporates the coupling between sediment-transport capacity and hydraulic-energy losses; thus Equation 4 becomes an integral part of Equation 5.

Although TLTM computes transport capacity based on a mean sediment size, another empirical relationship (27) is used to allocate the total load among the size fractions present on the bed surface. Thus a detailed accounting of hydraulic sorting and armoring processes is included in the program (3).

IALLUVIAL is best suited for the prediction of long-term bed changes following a perturbation to the mainstem river. It has recently been used for extensive study of Missouri River degradation following upstream regulation and channelization (7).

Examples of Long-Term Model Performance

The first example is the performance of KUWASER, HEC-6, and CHAR II when applied to the pool 20 reach of the Mississippi River (RM 343.2-364.2) between Keokuk, Iowa, and Canton, Missouri (5). Periodic, high-cost maintenance dredging has been necessary to maintain the 9-ft depth along the barge passageway in the vicinities of Fox and Buzzard Islands (RM 355-6 and RM 349-50) of pool 20 because of localized shoaling problems. To understand the basic mechanisms responsible for the shoaling problems, two field studies were conducted to obtain detailed information about the flow and sediment-transport characteristics along the shoaling reaches. On the basis of the field data collected, detailed geometric, hydrologic, and sediment-input data were prepared and the three models, KUWASER, HEC-6, and Char II, were tested at Colorado State University, IIHR, and SOGREAH, respectively.

Simulation runs of these models were made for a 28-month period between May 1976 and August 1978. Figure 3 shows the initial, computed, and measured thalweg elevations. The degree of agreement between the computed and measured values is seen to be of almost the same order for each model. It should be noted that KUWASER used a 5-day time step for a water discharge over 100,000 cfs, a 10-day time step for a discharge between 50,000 cfs and 100,000 cfs, and a 30-day time step for a discharge below 50,000 cfs. HEC-6 used monthly averaged flow quantities, and CHAR II used a temporal computation interval ranging between 6 hr and 5 days.

The second example is the application of the IALLUVIAL model to the Missouri River from Gavin's Point Dam down to Omaha. Extensive channelization of most of this 200-mile reach, and virtual complete shut-off of upstream sediment supply by the closure of Gavin's Point Dam, has resulted in severe bed degradation of up to 8 ft in the period 1957-1977. Bed-surface armoring and bed-material coarsening caused by hydraulic sorting appear to be fundamentally important factors in the river's approach to a new equilibrium. IALLUVIAL's incorporation of these phenomena grew out of its specific development goal of becoming a Missouri River prediction model.

Figure 4 shows a comparison of measured and predicted bed and water-surface elevation changes for the 20-year study period (6). This successful simulation of past results has led to further refinements of the input-data set and a program of prognosis simulations to predict river behavior for the next 20 years under various river-management scenarios (7).

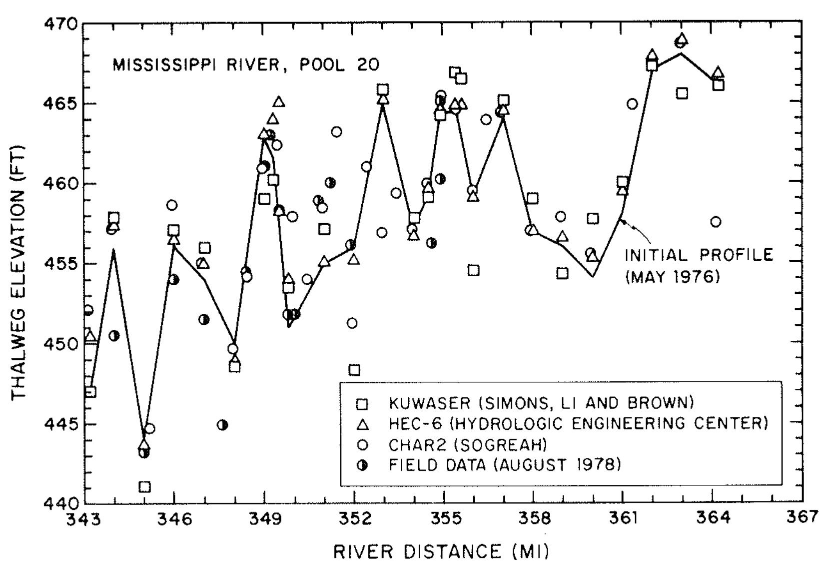

FIGURE 3 Comparison of computed thalweg elevations and several spot measurements for pool 20, Mississippi River.

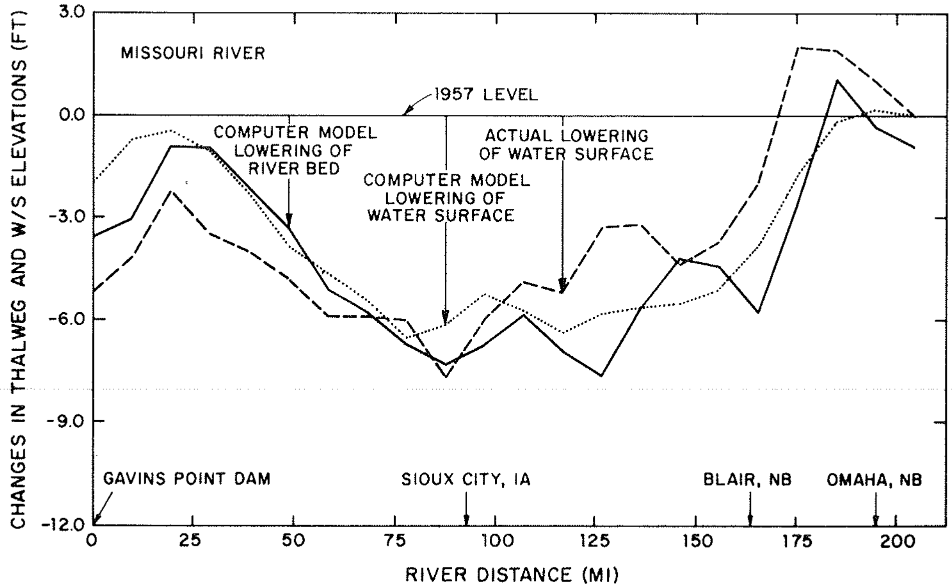

FIGURE 4 Comparison of observed and computed (IALLUVIAL) riverbed degradation and water-surface elevations (36,000 cfs) for the Missouri River.

ASSESSMENT OF STATE-OF-THE-ART ABILITY

Common to all alluvial river-flow models are requirements for the following input information: (a) accurate initial conditions, including a cross-sectional profile and bed-material size distribution at each computational cross section; (b) accurate boundary conditions such as water and sediment inflows along the boundaries, quantitative expressions of bed-load and suspended-load discharges, size distributions of boundary-sediment input, and stage hydrographs at the upstream and downstream boundaries; and (c) bed-roughness characteristics at each computational point. It is clear that a computer simulation would be meaningless without the first and second requirements, and the lack of the third requirement would yield an erroneous estimation of flow characteristics, resulting in erroneous feedback of flow information to the riverbed.

The exclusion of even one of these three requirements may lead to serious errors in computer simulations. However, one can hardly be provided with a complete set of input data in any prototype numerical application. Therefore, a great number of assumptions often have to be made to fill the gap in the input data. Even if adequate data are provided for a study river, there still remains a need to calibrate and verify the model by means of field data. In most natural rivers, only extremely limited field data are available for high flood stages at which major riverbed changes occur, and, consequently, adequate calibration or verification of the models normally cannot be obtained. In this sense, the capability of the alluvial river-flow models can best be assessed according to how accurately they can predict riverbed changes with limited sources of input data. A numerical modeler should be aware of which input information is most important to the final result of predicting riverbed changes.

The National Research Council study (4) pointed out that a principal deficiency of most of the available numerical models described in this paper is their inability to accurately predict channel roughness when calibration data are insufficient. It was in the calculation of sediment-discharge capacities that the various models examined differed most widely. A reliable sediment-transport formula is a prerequisite to reliable estimates of channel-geometry changes because riverbed degradation and aggradation are computed from streamwise gradients in the sediment-transport capacity of streams as the sediment-continuity equation states. The bed-armoring process during channel degradation is also not well understood and has not been adequately formulated. Armoring and the resulting coarsening of the bed-material size have a direct effect on the sediment-transport capacity and the channel-bed roughness or friction factor and thereby impact on the mean velocity, depth, and friction slope of the flow. Bed-degradation processes are generally slowed by bed armoring.

RESEARCH NEEDS

The surprisingly large discrepancies among the computed results described earlier may be taken as symptomatic of inadequate input and calibration data. However, it also may be true that any modeler would be able to simulate observed changes in thalweg elevation exactly by adjusting the model's "tuning knobs" (calibration parameters) if there were fully adequate river data available. At present no alluvial riverbed model seems mature enough to answer the question: What are the input and calibration data required for the model to yield convincing, reliable results? Simple artificial adjustments of the tuning knobs in the numerical simulation, based on the availability of plentiful data, does not appear to be a satisfactory way of predicting riverbed changes.

The most important overall need is for better interpretation of physical processes and their incorporation in the numerical models. Numerical techniques for solution of the governing equations are now adequately developed for accurate prediction of alluvial riverbed profiles if an accurate sediment-transport function and a bed-roughness predictor were available. Improvement in model reliability requires further research in the areas described hereafter.

First, there is a strong need for a very reliable sediment-transport relation because alluvial riverbed changes are the result of a streamwise gradient in the stream's sediment-transport capacity.

Second, the bed-armoring process during channel degradation is not well understood and has not been adequately formulated in a conceptual model. Armoring and coarsening of the bed-material size have a direct effect on the sediment-transport capacity and the bed-friction factor, and consequently affect the velocity, depth, and energy slope of the flow.

Third, there is a need to develop a better friction-factor predictor that depends on flow depth and velocity and sediment discharge.

Fourth, there is a need to incorporate into models the bank-erosion and channel-migration effects of channel widening.

Fifth, it is unlikely that an alluvial riverbed model that is applicable to all types of rivers will be forthcoming in the near future. Instead, each model will be most dependable for rivers of the type for which it was developed. Therefore, there is a need for an effort to classify natural rivers in terms of their hydraulic and geomorphologic characteristics, to guide engineers in the selection and application of a model that uses formulations of sediment discharge, channel roughness, channel widening, and so on that are most appropriate for their study cases.

If there is one important message to be drawn from this catalog of deficiencies, it is the following: Model developers and users must not let their preoccupations with improvements in numerical methods, user friendliness, program generalization, and other pleasant but peripheral concerns cause them to lose sight of the central and often unpleasant need to obtain a better understanding and conceptual formulation of the basic physical processes of alluvial riverbed evolution.

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Publication of this paper sponsored by Committee on Hydrology, Hydraulics and Water Quality.