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Computer-Based Prediction of Alluvial River-Bed Changes

An Assessment of the State-of-the-Art

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by

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I. INTRODUCTION

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 in such a way as to carry widely varying discharges with only moderate changes in water surface elevation. The curse is that the river engineer has found this self-regulating mechanism extremely difficult to understand and accommodate in his projects.

The sheer complexity of alluvial river response, involving dozens of relevant variables, and even ambiguity as to which are the dependent and independent ones, has defied the formulation of 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 prediction of local scour around bridge piers, bank stability, and other such local phenomena, no such procedures exist for analysis of alluvial river-bed 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 river-bed 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 which 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 due to upstream regulation of flows and/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 results interpretation 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 river-bed response to the second type of perturbation mentioned above. This is where numerical, computer-based models find their natural area of application.

Numerical models of alluvial river response are the natural outgrowth of rigid-boundary, unsteady flood-propagation models which have proven to be so useful in engineering design. These unsteady flow models have succeeded because they are based on mathematical descriptions which 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 article 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, etc. At this juncture (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.

II. MATHEMATICAL REPRESENTATION OF ALLUVIAL RIVER-BED EVOLUTION

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

Conservation of water:

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

Conservation of water momentum:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} + g \frac{\partial z}{\partial x} + g S_f = M_\ell / \rho B h \tag{2}$$

Conservation of sediment:

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

Sediment-transport law:

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

in which h = water depth; q = water discharge per unit channel width (q = uh); u = depth-averaged water discharge; Q_ℓ = lateral water-inflow rate per unit length; B = channel width; g = gravitational acceleration; S_f = energy gradient; M_ℓ = contribution to longitudinal momentum from lateral water inflow; ρ = water density; 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 $D_{50}, \ldots$ symbolically represents all sediment properties which determine the amount transported and the shear stress at the

river bed. Solutions to Eqs. (1) to (4), if they could be obtained for appropriate initial and boundary conditions, would produce the time and 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 as to how erosion or deposition are 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) to (4) form a nonlinear partial-differential system which in general cannot be solved analytically. Approximate numerical methods can be used to solve them, but such methods are often tedious and expensive, especially when Eq. (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. The propagation time of a flood peak along a 100 km reach may be of the order of one or two days, while it would take several years for a bed-level perturbation to cover such a distance. Whenever this is the case, the system of Eqs. (1) to (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, Eq. (2) for unsteady conservation of water momentum reduces to the familiar "backwater equation", an equivalent statement of steady-state momentum and/or energy conservation:

$$u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} + g \frac{\partial z}{\partial x} + gS_f = M_\ell / \rho Bh \qquad (5)$$

The mathematical problem is then reduced to one of solving just the nonlinear partial-differential system of Eqs. (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/flow-resistance formulae as represented symbolically by Eq. (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 then the sediment-transport rate G is an explicit function, albeit indirect and often complex, of the flow. In the second general type of Eq. (4), the effects of bed forms, changing bed-material composition, and bed armoring on both flow resistance and sediment-transport forumlae are taken into account in an attempt to represent the known interdependence of flow resistance and sediment transport (Vanoni, 1975, pp. 114-126).

III. NUMERICAL SOLUTION OF THE GOVERNING EQUATIONS

Virtually all published software systems for 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 which 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 is determined primarily by the sediment-transport formulation and mechanisms adopted for sorting, armoring, etc. The particular numerical method used, as long as it is consistent with the partial-differential equations and stable, has only a secondary effect on simulation quality.

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

The uncoupled solution 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 changes during the time step. Then the depths and velocities are taken as constant, known inputs to the sediment continuity and transport Eqs. (3) and (4), which then become relatively easy to solve numerically, yielding the new bed elevations. When the overall model includes bed-sediment sorting and/or armoring, these processes are then simulated in a third uncoupled computational phase using new depths, velocities, and bed elevations as known inputs. While 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 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.

A third 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.

IV. 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 thus 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. If the original bed material contains a high enough proportion of large, non-movable materials (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, while others ignore them completely. Thus another important distinguishing feature of computer-based models is the degree to which they incorporate sorting and armoring effects.

V. PERFORMANCE OF SELECTED MODELS APPLIED TO PROTOTYPE SITUATIONS

A. Background

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 river-bed 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 river-bed conditions, and many of them are, to some extent, well-tuned or calibrated for those particular rivers. In this chapter, attention will be focused only on those models which are related to the investigations conducted at the Iowa Institute of Hydraulic Research (IIHR) in the last few years (National Research Council, 1983; Nakato and Vadnal, 1981; Karim and Kennedy, 1982; Holly and Karim, 1983). The assessment of the selected models will be made for two different groups: short-term models and long-term models. The short-term models are best suited to compute changes in alluvial river-bed 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 (Hydrologic Engineering Center, 1981). 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 river-bed 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 which a shorter time step is used for highly unsteady flows and a longer time step is used otherwise.

B. Short-Term Models

a. 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 river-bed aggradation and degradation in a river system (SLA, 1980). The model utilizes the HEC-2 fixed-bed, backwater-computation program developed by the U.S. Corps of Engineers (COE), Hydrologic Engineering Center (HEC) (HEC, 1981) for water routing. HEC-2 solves one-dimensional, steady-state, gradually-varied flow using the flow-continuity and flow-energy Eqs., (1) and (5). HEC-2 accounts for various kinds of flow encroachments such as bridge constrictions, multiple channels, etc., 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 (Meyer-Peter and Mueller, 1948) for the bed-load discharge computation and the Einstein formula (Einstein, 1950) for the suspended-load discharge. The combined bed-materal transport rates are further corrected by the wash-load discharge using Colby's empirical relationships (Colby, 1957). 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 which solves the sediment-continuity Eq. (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-section 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 compututation, the model is not suitable for the long-term prediction of river-bed changes. The model is purely one dimensional and accounts for neither lateral channel migration nor secondary flows.

b. UUWSR (Uncoupled, Unsteady Water and Sediment Routing)

This model was developed at Colorado State University by Tucci, Chen, and Simons (Simons and Chen, 1979) 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 Eqs, (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

$$G = a\, u^{b}\, h^{c} \qquad (6)$$

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 Eq. (3), to compute the change in the cross-section 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, etc. The flood-wave movement in a long reach can be simulated by this unsteady flow-routing model.

c. FLUVIAL-11

This uncoupled model was developed at San Diego State University in 1976 by Chang and Hill (Chang and Hill, 1976) 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 Eqs. (1) and (2) in one time step, by neglecting storage effects due to unsteady flow. The model utilizes an implicit, central-difference, numerical scheme in solving for the two unknown variables of water discharge and cross-section area. The flow information is then used to compute the bed-material discharge at each section using either the Graf formula (Graf, 1968) or the ~~Engelund-Hansen formula~~ YANG (Engelund and Hansen, 1967).

The net change in cross-section area is next obtained by solving the sediment-continuity Eq. (3), using a backward-differ-

ence scheme for space and a forward-difference scheme for time. The computed cross-section area change is then adjusted for the effects of channel width, cross-section 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-section 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 is 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.

C. Examples of Short-Term Model Performance

A National Research Council (NRC) study committee conducted an investigation for the Federal Energy Management Agency (FEMA) during 1981-1983 to determine whether river-bed degradation during flood passage has an effect on the flood stage that should be incorporated into the calculation of flood-zone limits (National Research Council, 1983). 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 river-bed changes and channel migration during floods. In the NRC 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. From the NRC Committee's study results, only two cases of numerical simulation which are pertinent to the topic of this paper are presented.

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-mi long study reach comprises two different subreaches: the relatively steep upper-half reach and the 2.4-mi long lower-half reach with a much smaller slope. The input data included hydrographs for the February 16-20, 1980 flood, preflood channel cross-section 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 end to 0.93 mm at the upstream boundary. The downstream boundary condition reflected the 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 predic-

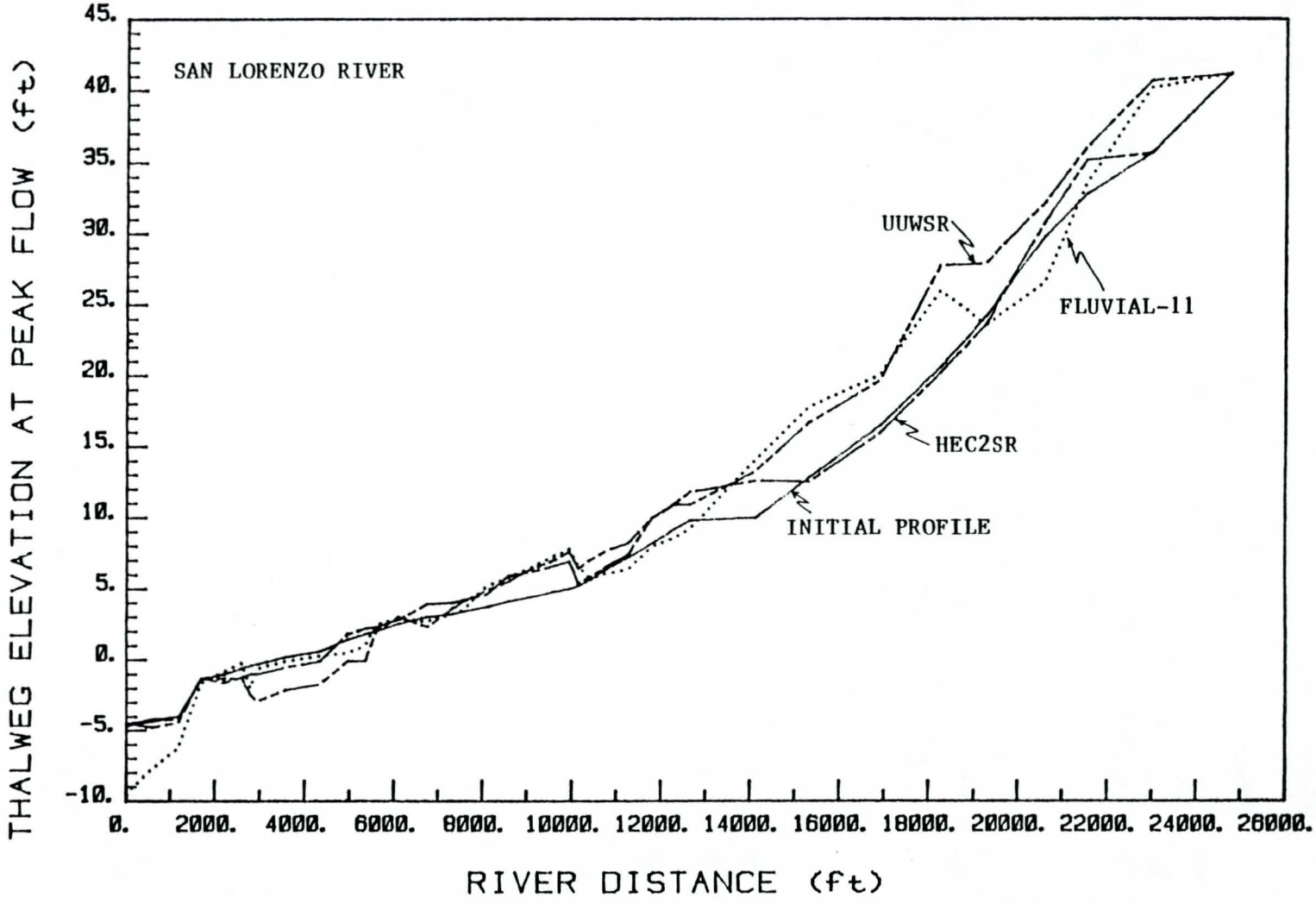

Figure 1 Comparison of computed thalweg elevations for the San Lorenzo River (HEC2SR, UUWSR, and FLUVIAL-11)

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

Thalweg elevations computed at a peak discharge of 22,000 cfs by HEC2SR, UUWSR, and FLUVIAL-11 are plotted in figure 2. FLUVIAL-11 predicted a generally aggrading thalweg pattern over the entire reach, while 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 ft at a river distance of 3,600 ft where the Via de Santa Fe bridge is located.

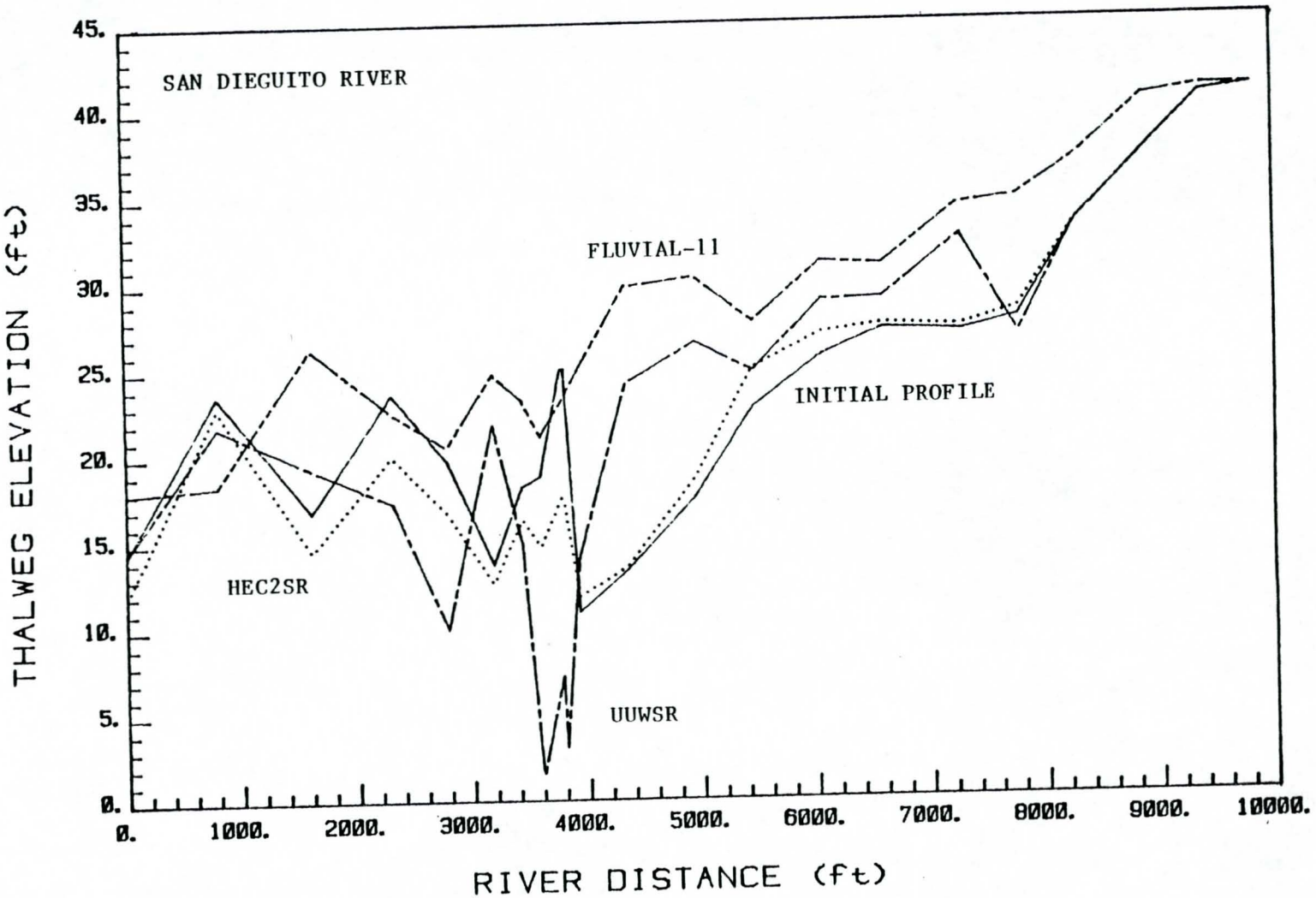

Figure 2 Comparison of computed thalweg elevations for the San Dieguito River (HEC2SR, UUWSR, and FLUVIAL-11)

D. Long-Term Models

a. KUWASER (Known discharge, Uncoupled, Water and SEdiment Routing)

The KUWASER model was developed in 1979 at Colorado State University by Simons, Li, and Brown (Simons, Li, and Brown, 1979). The water discharge is taken as steady during a specified time interval, so that water-flow routing consists in simply solving the backwater Eq. (5), with an additional term for explicit representation of energy losses other than those due to bed-shear stress. Equation (3) is solved by first computing the sediment volume to be removed or added to each reach, then allocating 25% of this volume to the upstream half of the reach and 75% to the downstream half. Cross-section 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 Eq. (6).

KUWASER uses an empirical sediment-transport function. Flow resistance is uncoupled from bed evolution through use of a 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 main stem and tributaries of a

river system, and can simulate divided flow associated with bars, islands, or channel breaches.

b. HEC-6

The HEC-6 program was developed at the Hydrologic Engineering Center of the U.S. Army Corps of Engineers in 1977 (Hydrologic Engineering Center, 1977; Thomas and Prasuhn, 1977). The quasi-steady backwater Eq. (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 due to bed and bank roughness; roughness coefficients must be specified as input data, though they can be allowed to vary with discharge and/or stage.

The sediment-continuity Eq. (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. Banklines are assumed to be stable and fixed in the HEC-6 computation.

HEC-6 offers a choice of five sediment transport functions in Eq. (4): Laursen's relationship, as modified by Madden for large rivers (Laursen, 1958); Toffaleti's formula (Toffaleti,

1968); Yang's stream-power formula (Yang, 1973); DuBoy's formula (Brown, 1950); 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 from flow conditions, i.e., Eq. (4) does not explicitly include the coupling of flow resistance and sediment transport through bed-form development.

HEC-6 is a strictly 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.

c. CHAR II (CHARriage dans les Rivieres)

The CHAR II modeling system was developed by the French consulting engineering firm SOGREAH in the early 1970's (Cunge and Perdreau, 1973; Cunge, Holly, and Verwey, 1981; SOGREAH, 1978). It is a coupled, quasi-steady model, simultaneously solving Eqs. (3) and (5) using an implicit finite-difference scheme. Energy losses due to bed roughness are based on the Manning-Strickler equation, with overall section conveyances

computed as the sums of individual rectangular section following Chow's method (Chow, 1959). 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, Englund-Hansen, DuBoys, or Einstein-Brown formulas (Vanoni, 1975) for Eq. (4). Hydraulic roughness and sediment transport are uncoupled in CHAR II, although SOGREAH's CHAR IV program, while less industrialized than CHAR II, does take this coupling into account through use of the full Einstein method (Einstein, 1950).

CHAR II is designed for simulation of long-term river-bed evolution and sedimentation in reservoirs. Both 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, as the user can relatively easily add subroutines to compute total load using a method of his choice.

V.C.4. IALLUVIAL (Iowa ALLUVIAL river model)

The IALLUVIAL program was developed during 1979 and 1982 by Karim and Kennedy at IIHR (Karim and Kennedy, 1982). It is for-

mally classified as an iteratively coupled, quasi-steady model; in each time step Eq. (5) is solved with bed elevations fixed, then Eq. (3) is solved, using sediment-transport capacities determined as an integral part of the solution of Eq. (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 Eqs. (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, cut-offs, 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 (Karim and Kennedy 1981). 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 Eq. (4) becomes an integral part of Eq. (5).

Although TLTM computes transport capacity based on a mean sediment size, another empirical relationship (Karim and Kennedy, 1981) 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 (Karim, Holly, and Kennedy, 1983).

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 (Holly and Karim, 1983).

E. 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 (Nakato and Vadnal, 1981). 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. In order to understand the basic mechanisms responsible for the shoaling problems, two field studies were conducted to obtain detailed information related to 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 time 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 almost of 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 utilized monthly-averaged flow quantities and CHAR II utilized a temporal computation interval ranging between 6 hrs and 5 days.

The second example concerns 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-m 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 due to 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 measured and predicted bed and water-surface elevation changes for the 20-year study period (Karim and Kennedy, 1982). This successful simulation of past results has led to further refinements of the input-data set and

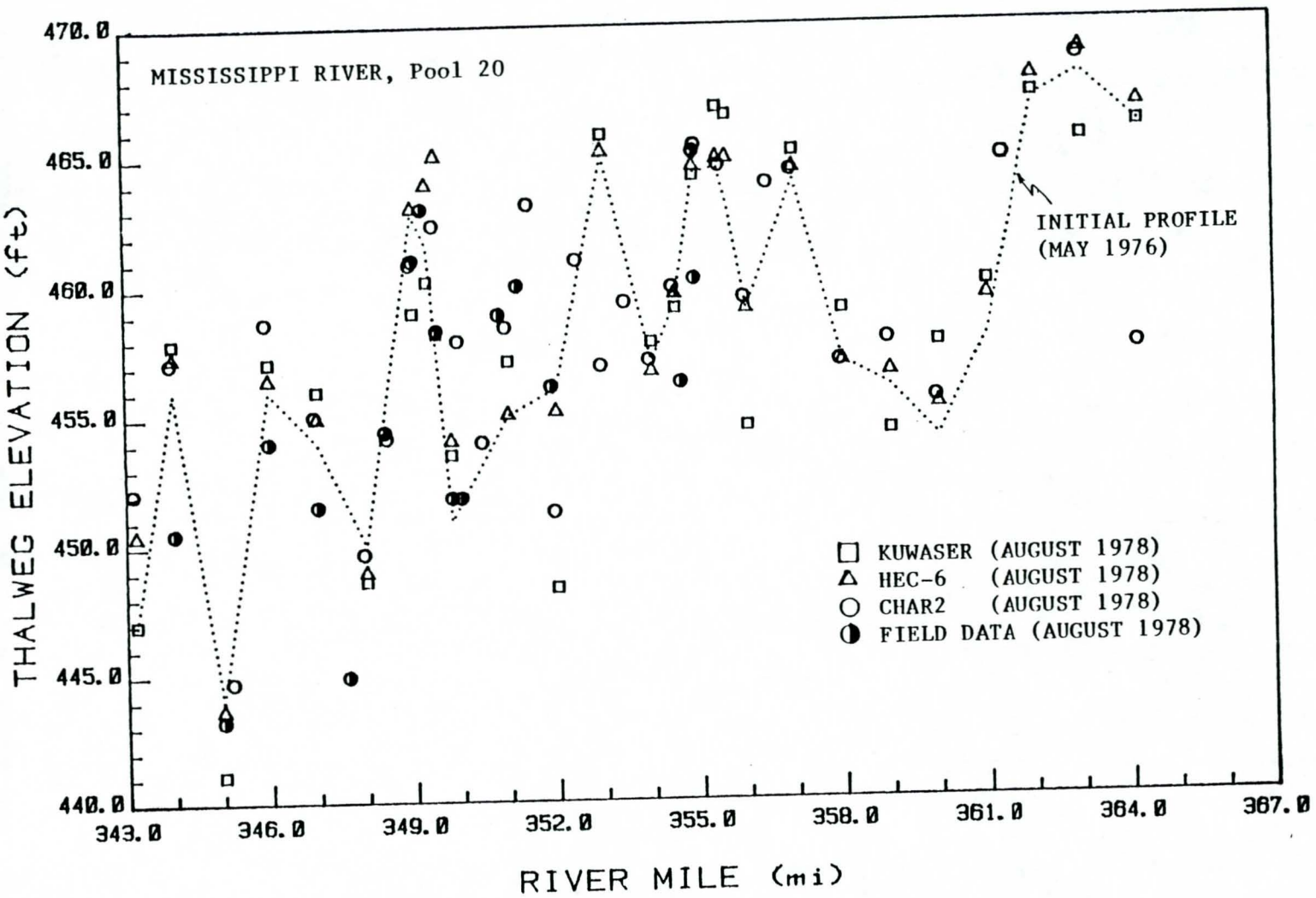

Figure 3 Comparison of observed and computed thalweg elevations for the Mississippi River (KUWASER, HEC-6, and CHAR2)

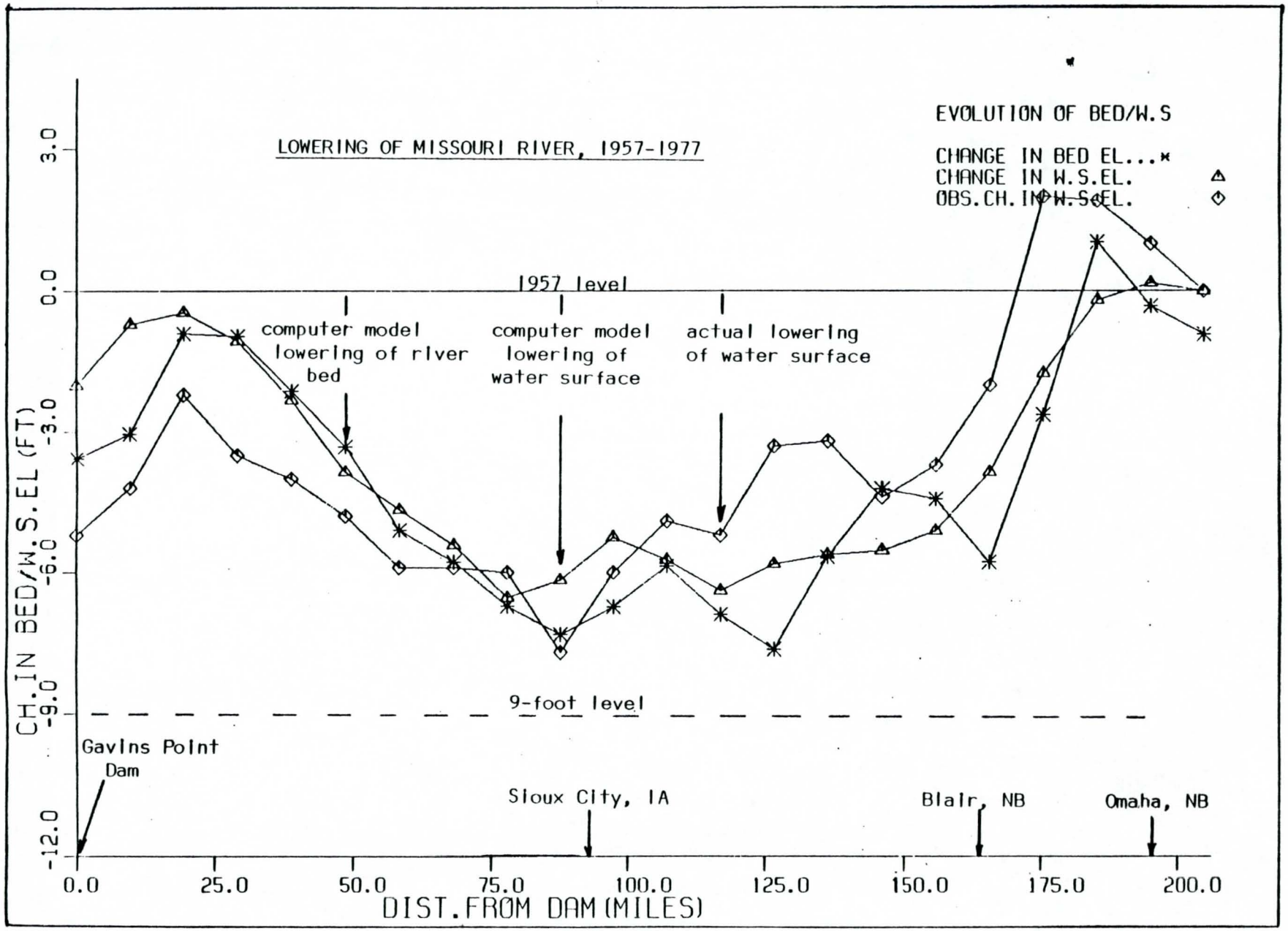

Figure 4 Comparison of observed and computed river-bed degradation for the Missouri River (IALLUVIAL)

a program of prognosis simulations to predict river behavior for the next twenty years under various river-management scenarios (Holly and Karim, 1983).

VI. ASSESSMENT OF STATE-OF-THE-ART ABILITY

Computer-based alluvial river-flow models account for changes in river-bed elevation which occur when the sediment-transport capacity of the flow at the upstream boundary of a reach differs from that at the downstream boundary. The sediment-transport imbalances occur along the river reach when there is a change in flow characteristics or the sediment supply to the reach is changed without accompanying changes in the sediment-transport capacity. Alluvial river-flow models compute changes in river-bed elevation using the sediment-continuity equation, and determine the new flow characteristics on the basis of the altered bed elevation and slope by means of the flow-continuity and the flow-momentum (or energy) equations. Interaction or feedback between a changing river bed and its flow field is handled by different numerical schemes. However, common to all alluvial river-flow models are requirements for the following input information: (1) accurate initial conditions, including a cross-section profile and bed-material size distribution at each computational cross section; (2) 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 (3) 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 river bed.

The exclusion of even one requirement listed above 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 close 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 river-bed 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 river-bed 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 the river-bed changes.

The NRC study (National Research Council, 1983) pointed out that a principal deficiency 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 river-bed degradation and aggradation are computed from streamwise gradients in the sediment-transport capacity of streams as the sediment-continuity equations 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.

VII. RESEARCH NEEDS FOR RELIABILITY

In Chapter V, the limitations of the individual model selected are described, and the thalweg elevations computed for the several prototype cases by these models are compared. The surprisingly large discrepances among the computed results 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 his model's "tuning knobs" (calibration parameters) if there were fully adequate river data available. No alluvial river-bed

model seems at this juncture to be mature enough to answer the question: what are the input and calibration data needs 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 predicitng river-bed 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 river-bed profiles if an accurate sediment-transport function and a bed-roughness predictor were available. Improvement in model reliability requires, in our view, further research in the areas described below.

First, there is a strong need for a very reliable sediment-transport relation, alluvial river-bed changes being 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 which depends on flow depth and velocity, and sediment discharge.

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

Fifth, it is unlikely that an alluvial river-bed model which 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 to undertake an effort to classify natural rivers in terms of their hydraulic and geomorphological characteristics, to guide the engineer in selection and application of a model which uses formulations of sediment discharge, channel roughness, channel widening, etc. which are most appropriate for his study case.

If there is one important message to be drawn from the above catalogue of deficiencies, it is in our view the following one. 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 off-unpleasant need to obtain a better understanding and conceptual formulation of the basic physical processes of alluvial river-bed evolution.

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