Modeling General Scour at Bridge Crossings

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ABSTRACT

Modeling of general scour at bridge crossings using a mathematical model for water and sediment routing is described. For a given bridge configuration, general scour that results from imbalance in sediment supply and transport capacity of the river is evaluated based on river channel evolution reflecting the flow and sediment-transport processes. Two case studies are presented to illustrate the prediction of general scour caused by man-made factors including sand mining and flow constriction by a bridge. Depth of general scour is found to be sensitive to channel width; therefore, width formation of the alluvial river plays an important role in scour development.

River-channel scour may be considered as consisting of local scour and general scour. Local scour that occurs around bridge piers and abutments is caused by local obstructions to flow. General scour refers to the change in river-channel configuration provoked by sediment imbalance, due to natural or man-made causes, between the supply and transport capacity of the river. The bridge structure is one such man-made cause if it interferes with the flow pattern. Because general scour at bridge crossings is related to the flow and sediment-transport processes of the adjacent river as a system, evaluation of such scour requires modeling of the river channel for water and sediment routing.

Bridges are often constructed with the span shorter than the channel width, particularly across broad floodplains in semiarid regions. Therefore, the river flow is often constricted at the bridge crossing, resulting in higher velocities and channel-bed scour. Flow constriction at the bridge crossing varies with the discharge or stage. During high flows, the river channel is wide and thus the constriction effect is more pronounced. In this situation, greater general scour at the bridge crossing can usually be expected. During low flows, the channel width may be less than the bridge opening and thus flow constriction no longer exists. Therefore, general scour caused by the constriction effect during the high flood stage may be refilled to the preflood level during the subsequent low-flow period. Because the riverbed cannot be observed during flood stage because of muddy water, such major scours may occur but not be noticed. However, because the bridge footings are affected by the scour, such scour development should be evaluated for bridge design and restoration.

General scour develops when more sediment is removed from an area than is supplied from upstream. This development is accompanied by changes in bed-material composition caused by hydraulic sorting and by other river-channel changes. These changes provide the mechanisms with which the river seeks to establish equilibrium in sediment transport; that is, equal sediment load along the river reach. Net scour at the bridge crossing ceases when equilibrium is established or when bed armoring forms to prevent further scour.

The mathematical model FLUVIAL-11 (1), which was developed for water- and sediment-routing in alluvial channels, is employed for modeling general scour. For a given river channel and bridge configuration, river-channel changes in channel-bed profile, width, and sediment composition can be evaluated using this model for specified flow conditions. The scour depth is directly measured by the channel-bed elevation. Because channel-bed profile is part of river-channel formation, which also involves channel width, evaluation of the scour depth must also consider width changes.

THE MATHEMATICAL MODEL

The mathematical model FLUVIAL-11 has five major components: (a) water routing, (b) sediment routing, (c) changes in channel width, (d) changes in channel-bed profile, and (e) lateral migration of the channel as detailed in previous publications (1,2). This model employs a space-time domain in which the space domain is represented by the discrete cross sections along the river reach and the time domain is represented by discrete time steps. In water routing, the time and spatial variations of the discharge, stage, velocity, energy gradient, and so forth along the reach are obtained by an iterative procedure. At each time step, sediment discharge at each cross section is computed; changes in channel width, channel-bed profile, and lateral migration are obtained and applied to each cross section. The bed-material composition is updated at each time step. Because changes in channel geometry and bed-material composition are slow in comparison with water routing, corrections for them are made separately for each time step.

Width changes are related to energy expenditure. Simulation of width variation is based on the concept of minimum stream power. At a time step, width corrections for all cross sections are such that the total stream power (or rate of energy expenditure) for the reach is minimized. These corrections are subject to the physical constraint of rigid banks and limited by the amount of sediment removal or deposition along the banks within the time step. Total stream power of a channel reach is

$$P = \int_L \gamma Q S dx \tag{1}$$

where

P = total stream power of the reach,
L = length of the reach,
Q = discharge,
S = energy gradient,
γ = specific weight of water and sediment mixture, and
x = distance in the flow direction.

Written in finite-difference form, this equation becomes

$$P = \sum_{i=1}^{N-1} 1/2 \left[\gamma(Q_i S_i + Q_{i+1} S_{i+1}) \Delta x_i\right] \tag{2}$$

where

N = total number of cross sections for the reach,
i = cross-sectional index, and
Δx_i = distance between sections i and i + 1.

Previous studies (2-4) have established that minimum stream power for an alluvial river reach is equivalent to equal power expenditure per unit channel length, that is, constant QS along the reach. A river reach undergoing changes usually has uneven spatial distribution of power expenditure or γQS. Usually the spatial variation in Q is small but that in S is pronounced. Total stream power of a reach decreases with the reduction in spatial variation of QS or S along the reach. Adjustments in channel widths are made in such a way that the spatial variation of QS is minimized subject to the constraints and limitations stated previously. An adjustment in width reflects the river's adjustment in flow resistance, that is, in power expenditure. A reduction in width at a cross section is usually associated with a decrease in energy gradient for the section, whereas an increase in width is accompanied by an increase in energy gradient. Following these guidelines, a technique for width correction has been developed (2).

Width changes in alluvial rivers are characterized by the formation of small widths at degrading reaches and widening widths at aggrading reaches (2-7). Such changes represent adjustment of the river's resistance to equalize power expenditure along its course as described later. A degrading reach usually has a higher channel-bed elevation and energy gradient than do its adjacent sections. Formation of a narrower and deeper channel at the degrading reach decreases its energy gradient because of reduced boundary resistance and lowered elevation. On the other hand, an aggrading reach is usually lower in channel-bed elevation and energy gradient. Widening at the aggrading reach increases its energy gradient because of increased boundary resistance. These adjustments in channel width reduce the spatial variation in energy gradient and total power expenditure of the channel. Because the sediment discharge is proportional to the stream power (8), these adjustments also favor the establishment of channel sediment-load equilibrium.

A river's adjustment in width in relation to power expenditure may also be explained based on the water-surface profile. If the energy gradient is approximated by the water-surface slope, the equal energy gradient is equivalent to the straight water-surface profile. A river reach undergoing changes usually has an uneven water-surface profile, but it constantly seeks to establish a straight profile through adjustments in channel geometry, roughness, and so forth subject to physical constraints such as abutments, rigid banks, and check dams. In this model, the channel geometries are adjusted, subject to the constraints, so that they favor uniformity in the water-surface profile.

SANTA MARGARITA RIVER STUDY

General scour at a bridge crossing caused primarily by the flow-constriction effect may be illustrated by the Santa Margarita River study using the FLUVIAL-11 program. The study reach of the river is near the Basilone Road bridge (Figure 1) at Camp Pendleton, California. Because it is an ephemeral river, the Santa Margarita flows only during floods. The width of flow varies significantly with the discharge. For the 100-year flood, the floodplain is computed to be about 1,000 feet wide, but the channel during low flows may be 10 to 20 feet wide. The Basilone Road bridge has long approach embankments and a span of 200 ft. Except at very high flood stages when flood waters are overtopping the approach embankments, flood flows are confined to the small bridge opening in the broad floodplain.

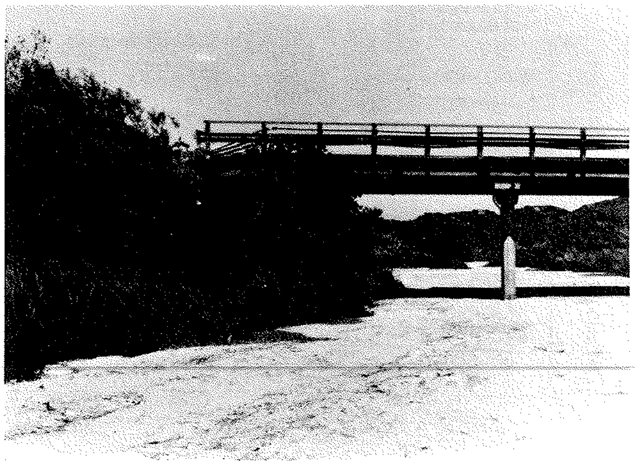

FIGURE 1 Basilone Road bridge on Santa Margarita River.

A major flood with a magnitude approximately that of a 50-year flood occurred in the winter of 1978. A picture taken after this flood (Figure 1) shows no sign of significant channel-bed scour at the bridge crossing. However, evidence of severe scour at this location during the flood was strong (9). For example, muddy flows of very high velocities through the constriction were observed, and bridge abutments were undermined. Eroded bridge abutments were repaired and reinforced after the flood. During inspection excavation of the bridge footings, which reach about 10 feet below the riverbed, a broken reinforced concrete pile was found; its 40-ft lower section was never found. This could be explained only by the fact that this pile section was washed away during the flood.

A simulation study of the Santa Margarita River near the bridge crossing at Basilone Road was done using the FLUVIAL-11 model. The hydrograph of the 50-year flood used in the study is shown in Figure 2. Simulated results shown in Figure 3 include the spatial variations of water surface, channel invert, and mean velocity at different time intervals. At peak discharge (t = 30 hr), maximum channel-bed scour at the bridge crossing is predicted to reach a minimum elevation of 57.3 ft, which means a scour

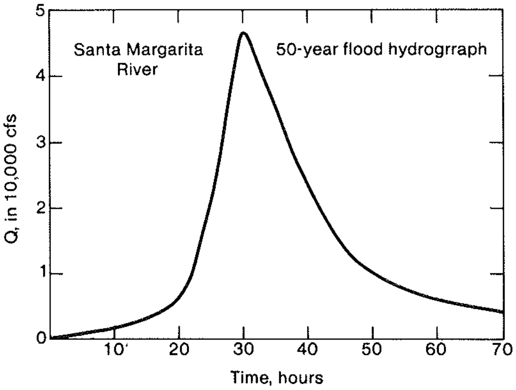

FIGURE 2 Flood hydrograph, Santa Margarita River.

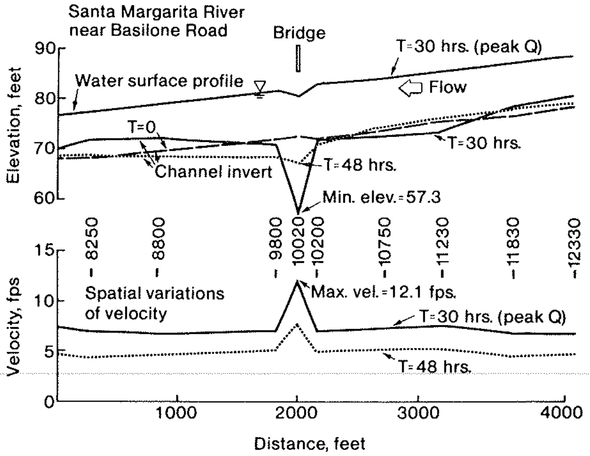

FIGURE 3 Simulated results for 50-year flood.

depth of 15.4 ft from the original bed level. At this discharge, the flood channel has a width about 5 times that of the bridge opening. However, the width of flood flow decreases with discharge during the falling limb of the hydrograph. Thus, as the flow-constriction effect becomes gradually less so does the channel-bed scour at the bridge crossing. In the absence of other factors for general scour, restoration of the channel bed, more or less to its preflood level at the end of the flood, is predicted.

At peak flood, the river reach has an uneven width, primarily because of the small bridge opening. Although at this time the river channel has established a more or less uniform sediment load along the reach, the energy gradient is not constant as indicated by the uneven water-surface profile near the bridge shown in Figure 3. The physical constraint in width at the bridge crossing prevents the formation of a straight water-surface profile through the bridge. This example demonstrates that continuity in sediment transport (i.e., equal sediment load along the reach) does not necessarily mean equal energy gradient or constancy in power expenditure. Therefore, they are independent physical conditions.

SAN DIEGUITO RIVER STUDY

The San Dieguito River at Rancho Santa Fe, California, experienced significant changes in a 2-mile reach (Figure 4) during recent floods. The bridge on Via de Santa Fe Road was damaged (Figure 5) by channel-bed scour and high velocities. Documentation of river-channel changes and flood hydrographs were made by the county of San Diego (10,11); these provide a valuable set of field data for river studies. The study reach is about 4 miles from the ocean and about 5 miles below Lake Hodges Dam. The channel has a wide and flat natural configuration; the natural slope and bed-material size decrease significantly in the downstream direction. Bed material of the study reach varies from coarse sand (d_{50} = 0.85 mm) at the upstream end to fine sand (d_{50} = 0.24 mm) downstream.

The natural channel configuration was changed before recent flood events by man's activities including sand mining and construction of the Via de Santa

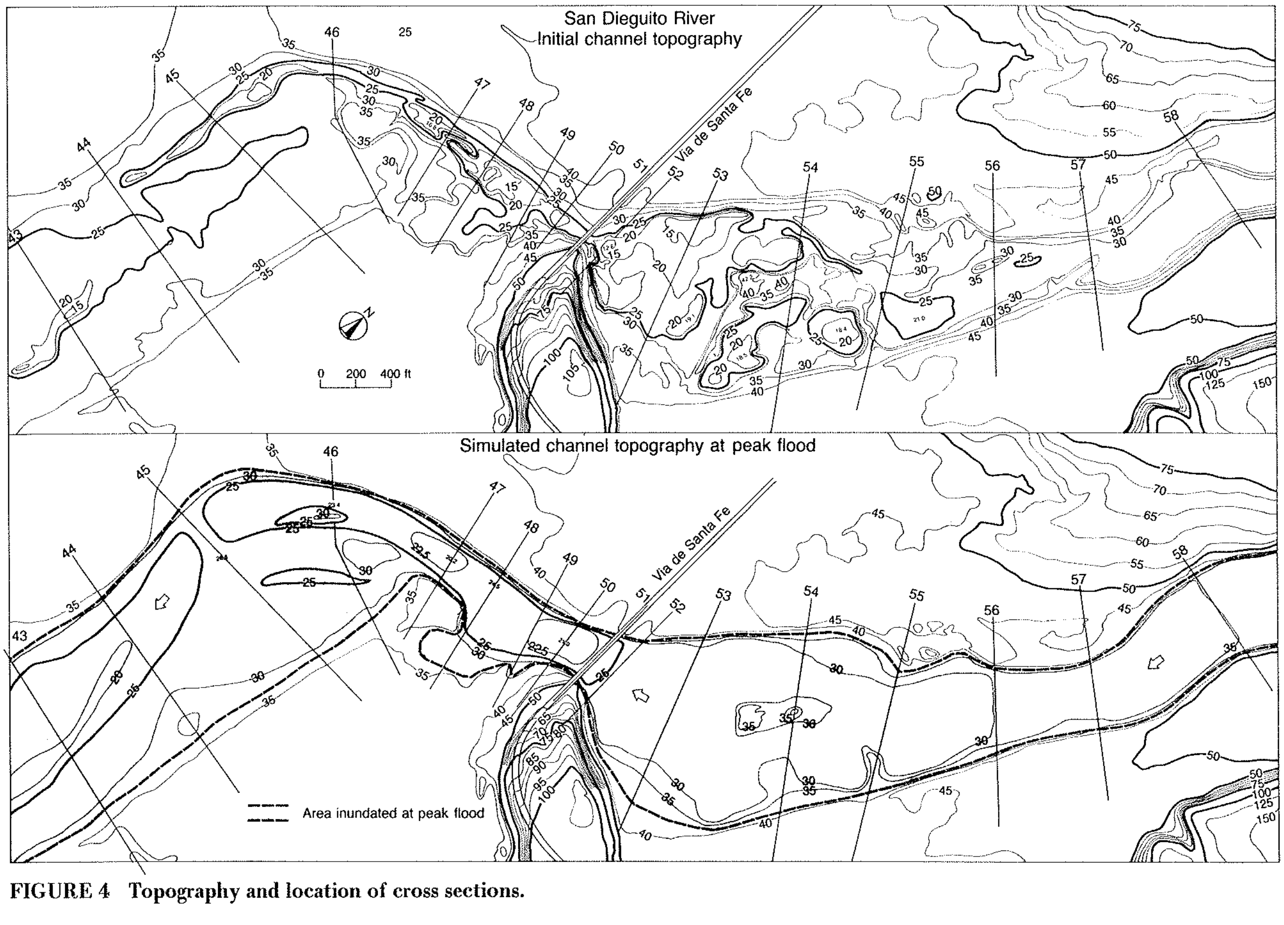

FIGURE 4 Topography and location of cross sections.

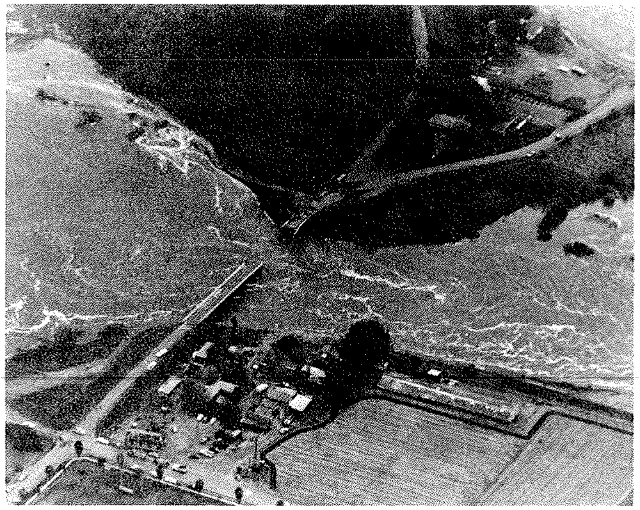

FIGURE 5 Damaged bridge on San Dieguito River.

Fe Road and bridge shown in Figure 4. As a result of sand mining, several large borrow pits, both upstream and downstream of the bridge, with a depth as great as 25 feet were created. The natural wide channel is encroached on by the approach embankment on each side of the bridge (section 51). The river channel has erodible bed and banks; the banks, however, are constrained by the hills at the south bank of section 51 and along the north banks of sections 60 to 63 and by bank protections at the north banks of sections 51 and 58.

Two floods passed through the river in March 1978 (peak flow = 4,400 cfs) and in February 1980 (peak flow = 22,000 cfs) when Lake Hodges spilled. Hydrographs of these floods are shown in Figure 6. Before these events, Lake Hodges had not spilled for 26 years. Significant changes in the river channel were observed after the March 1978 flood. Channel-bed scour occurred near borrow pits and notably at the bridge crossing where measurements were made (Figure 7). Deposition was observed in the borrow pits. Because of limited flood discharge and duration, these borrow pits were only partly refilled. Major changes in the river channel occurred during the greater February 1980 flood. These changes included channel-bed aggradation and degradation, width variation, and lateral migration of the channel (1).

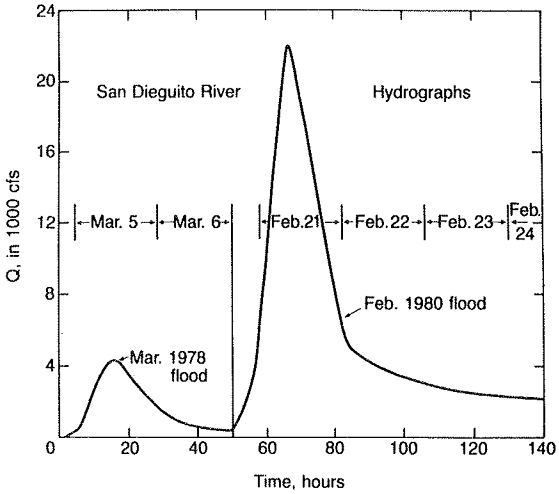

FIGURE 6 Flood hydrographs, San Dieguito River.

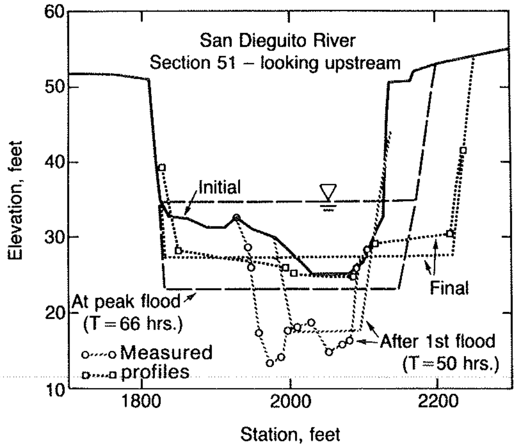

FIGURE 7 Simulated and measured riverbed profiles at bridge crossing.

The mathematical model FLUVIAL-11 was used to simulate river-channel changes in the San Dieguito River during the 1978 and 1980 floods. Graf's equation (12) for bed-material load was used in computing sediment movement. Channel roughness in terms of Manning's n was selected to be 0.035 in consideration of channel irregularity and minor vegetation growth; it was estimated to be 0.04 at the bridge crossing. A combined duration of 140 hours for these two floods was computed using 2,000 time steps.

Simulated results are shown in Figures 4, 7, and 8. River-channel changes, including those in channel-bed profile and channel width, as simulated by the computer model, are described herein. Changes in the longitudinal channel-bed profile (Figure 8) are characterized by aggradation in the borrow pits, erosion of higher grounds, and the gradual formation of a more or less smooth channel-bed profile at the end of the flood. In that process, considerable variation in the longitudinal channel-bed elevation through the downstream portion of the river reach is predicted at peak flood as shown in Figures 4 and 8. The higher channel-bed elevations at sections 45, 46, and 48 are associated with large channel widths, and the lower elevations at sections 47 and 50 are due to their smaller widths. Changes in channel width that occur concurrently with variations in channel-bed elevation are simulated. Width changes are characterized by the gradual widening of the initially narrow sections, notably sections 47, 49, 50, 51, 57, 58, and 59 and reductions in width of initially wide sections, notably sections 53 and 54. Simulated channel width at peak flood (shown in Figure 4) is highly uneven in its spatial variation along the river. This variation is gradually reduced during the flood. Widening of a section is caused by bank erosion, and reduction in width is usually caused by sandbar formation along the bank.

That changes in channel width and channel-bed elevation are closely related may be illustrated by the simulated time variation of the cross-sectional profile at the bridge crossing (Figure 7). Initially this section is on a sand ridge with borrow pits on both sides (Figures 4 and 8). Gully erosion through this sand ridge during the first flood is simulated, followed by gradual widening and lessening of the gully depth during the second flood. The maximum scour depth is predicted to occur in the initial gully. The simulated results correlate well with

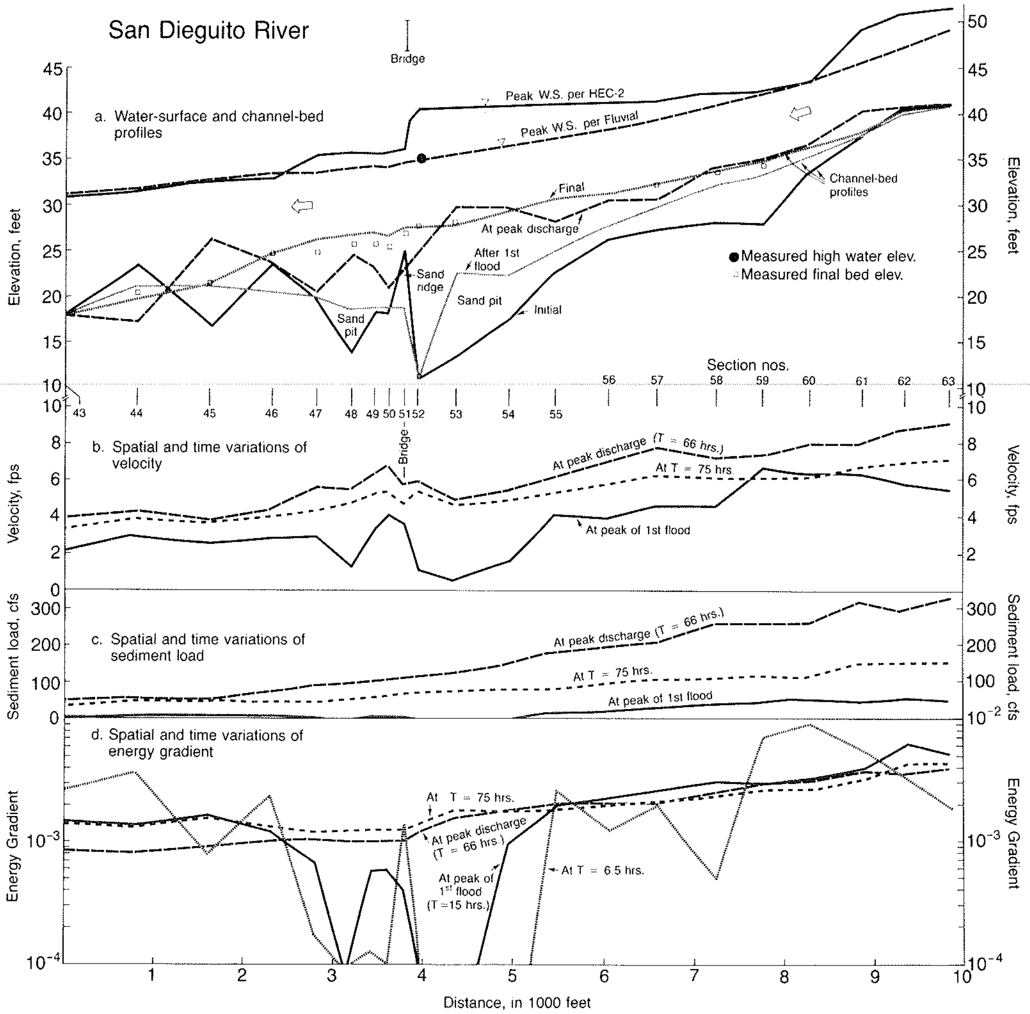

FIGURE 8 Simulated and measured results.

measurements at this section shown in Figure 7, in which the uneven final channel-bed profile as measured is related to the removal of several piers during the flood (Figure 5).

RIVER-CHANNEL CHANGES IN RELATION TO POWER EXPENDITURE

Changes in river-channel configuration are accompanied by changes in flow resistance and hence in the rate of energy (or power) expenditure. The γQS product represents the rate of energy expenditure per unit channel length. Because the spatial variation of Q is small, the spatial variation of γQS may be represented by the spatial variation of the energy gradient S shown in Figure 8. Simulated river-channel changes are associated with the gradual reduction of the spatial variation of energy gradient along the channel subject to the physical constraint of rigid banks. That the adjustment in river-channel configuration is closely related to the change in power expenditure can be illustrated by the sequential changes of cross-sectional profile at the bridge crossing as shown in Figure 7. Because it is initially on a sand ridge, the energy gradient at this section is initially much greater than those of adjacent sections. This pronounced spatial variation in energy gradient is reduced through gully formation in this section and deposition in adjacent sections. The gully, which is small in width and has a low channel-bed elevation, provides the least possible flow resistance and hence the lowest energy gradient at this section; it also reduces the backwater effect on the upstream section and thereby increases its energy gradient. At subsequent time intervals, the energy gradient at this section becomes less than those of adjacent sections. Cross-sectional changes at this section then include channel widening and aggradation in the gully. These changes are accompanied by increases in boundary resistance and energy gradient at this section, favoring the establishment of equal energy gradient along the reach. This pattern of river-channel changes, characterized by the formation of a narrow channel during channel-bed degradation and a wider channel during aggradation, is evident in nature and has been reported elsewhere (3-7, 13).

SUMMARY

General scour represents river-channel changes in response to any change imposed on the river by nature or by men. Because channel-bed evolution at bridge crossings is related to the flow and sediment-transport processes of the river reach as a system, general scour is evaluated using a mathematical model for water and sediment routing. Sample studies are presented to illustrate scour development caused by sand mining in the adjacent river channel and by flow constriction at the bridge opening. Although scour depth is measured by channel-bed elevation, evolution of bed elevation is found to be closely related to variation in channel width. Greater scour depth often occurs in a narrower channel and vice versa. For the ephemeral rivers studied, width changes are generally greater in magnitude than is scour development.

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