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Modeling of Flood-Deposited Sand Distributions in a Reach of the Colorado River Below the Little Colorado River, Grand Canyon, Arizona

By STEPHEN MARK WIELE

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CONVERSION FACTORS

Multiply	By	To obtain
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
cubic meter per second (m^3/s)	35.31	cubic foot per second
terragram (Tg)	6.852×10^7	slug

Modeling of Flood-Deposited Sand Distributions in a Reach of the Colorado River Below the Little Colorado River, Grand Canyon, Arizona

By Stephen Mark Wiele

Abstract

A release from Glen Canyon Dam during March–April 1996 was designed to test the effectiveness with which the riparian environment could be renewed with discharges greatly in excess of the normal powerplant-restricted maximum. Of primary concern was the rebuilding of sand deposits along the channel sides that are important to the flora and fauna along the river corridor and that provide the only camp sites for riverside visitors to the Grand Canyon National Park. Analysis of the depositional processes with a model of flow, sand transport, and bed evolution shows that the sand deposits formed along the channel sides early during the high flow were affected only slightly by the decline in suspended-sand concentrations over the course of the controlled flood. Modeling results suggest that the removal of a large sand deposit over several hours was not a response to declining suspended-sand concentrations. Comparisons of the controlled-flood deposits with deposits formed during a flood in January 1993 on the Little Colorado River that contributed sufficient sand to raise the suspended-sand concentrations to predam levels in the main stem show that the depositional pattern as well as the magnitude is strongly influenced by the suspended-sand concentrations.

INTRODUCTION

A controlled flood[1] was released from Glen Canyon Dam during March–April 1996 to determine the effectiveness with which the riparian environment along the Colorado River could be renewed with discharges greatly in excess of the normal powerplant-restricted maximum. Of primary concern was the rebuilding of sand deposits along the channel sides that are important to the flora and fauna along the river corridor and that provide the only camp sites for riverside visitors to the Grand Canyon National Park.

[1]The Grand Canyon Monitoring and Research Center refers to this event as a "beach/habitat-building flow" (David Garrett, Chief, Grand Canyon Monitoring and Research Center, written commun., 1997).

This report describes modeling of sand deposition and erosion in a reach of the main stem Colorado River downstream from the Little Colorado River (fig. 1). The deposition modeled for the flow of March–April 1996 is compared to deposition modeled for a flood on the Little Colorado River in 1993, which delivered sand to the main stem sufficient to elevate suspended-sand concentrations in the main stem to predam levels. Although the suspended-sand concentrations at the streamflow-gaging station on the main stem upstream from the Little Colorado River during the controlled flood were about 10 times higher than suspended-sand concentrations predicted by the sand-rating curve developed for that site, the suspended-sand concentrations were still lower than would have been typical of predam spring floods. In addition, the effect of the declining suspended-sand concentrations on

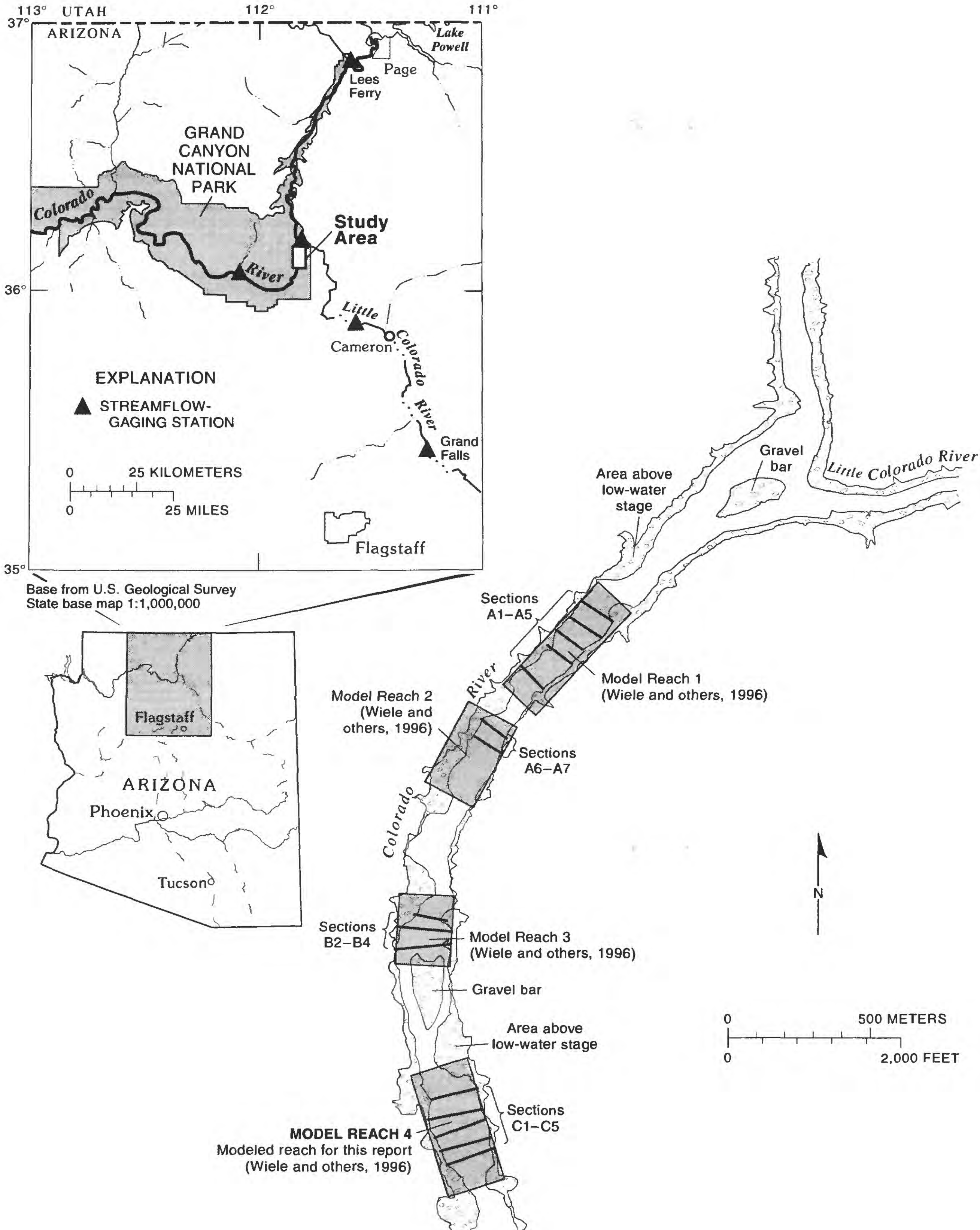


Figure 1. Study area, modeled reaches, and the cross sections used to test the model, Colorado River, Grand Canyon, Arizona.

deposits formed early in the high flow when suspended-sand concentrations were higher is examined for evidence of significant loss in initial sand-deposit volume.

A model of pool-scale flow, sand transport, and bed evolution (Wiele and others, 1996) was used to calculate changes in bed topography between measurements and to examine the effect of differences in suspended-sand concentrations. One of the advantages of modeling complicated geomorphic processes that may have several competing or complementary effects on the end result is that the geomorphic processes can be isolated with the model to test their significance in forming the final deposit. In this report, for example, the model is used to test the hypothesis that the massive erosion of a sand bar was the result of declining suspended-sand concentration during the controlled flood. This work was performed in cooperation with the Bureau of Reclamation.

FLOOD ON THE LITTLE COLORADO RIVER, JANUARY 1993

In January 1993, a large flood on the Little Colorado River contributed 4.2 Tg of sand (G.G. Fisk, hydrologic technician, U.S. Geological Survey, written commun., 1993) and increased the water discharge in the main stem (fig. 2). This flood led to large sand deposits at stages greater than the stages associated with normal powerplant capacity as well as a peak discharge that was greater than powerplant capacity. A volume of sand equivalent to that delivered by the Little Colorado River flood was deposited within about 20 km of the confluence (Wiele and others, 1996), but fresh sand deposits along the channel sides were observed for another 260 km downstream. These deposits farther downstream must have been formed from sand eroded from the channel bottom by the high water discharge. After the flood on the Little Colorado River receded, deposits in the main channel were eroded as the suspended-sand concentrations dropped to levels typical of postdam flows; however, deposits within environments that are relatively secluded compared to the main stem, such as recirculation zones and deposits above the lower stages in the main stem that followed the Little Colorado River flood, eroded at much slower rates.

CONTROLLED FLOOD, MARCH–APRIL 1996

The controlled flood consisted of a steady low flow of 226 m^3/s for 96 hours, an increase to 1,270 m^3/s over a 10-hour period where it was held steady for 167 hours, then a gradual decrease to 226 m^3/s over a 46-hour period (fig. 3). Modeling of the anticipated release before it occurred (Wiele, 1996) and modeling associated with the revision of the one-dimensional model to include higher discharges using data from the controlled flood (Wiele and Griffin, 1997) have shown that the rising limb of the wave steepened as it traveled downstream to about 250 km below the dam, where it reached an equilibrium profile. In the reach below the confluence with the Little Colorado River, the discharge increased from 350 to 1,100 m^3/s in about 3.2 hours.

Suspended-Sand Concentrations

Much of the sand from the flood of 1993 on the Little Colorado River was still present at the start of the controlled flood more than 3 years later. The high discharges during the controlled flood caused high sand loads throughout its duration and caused high rates of deposition. The suspended-sand concentrations decreased over the duration of the controlled flood (fig. 4). The sand discharge in the main stem was higher during the Little Colorado River flood (fig. 5) although the peak water discharge was lower than the peak water discharge during the controlled flood. This combination of lower water discharge and higher sand discharge led to peak suspended-sand concentrations during the flood on the Little Colorado River that were more than twice the suspended-sand concentrations during the controlled flood and were comparable to predam suspended-sand concentrations (David Topping, hydrologist, U.S. Geological Survey, oral commun., 1996).

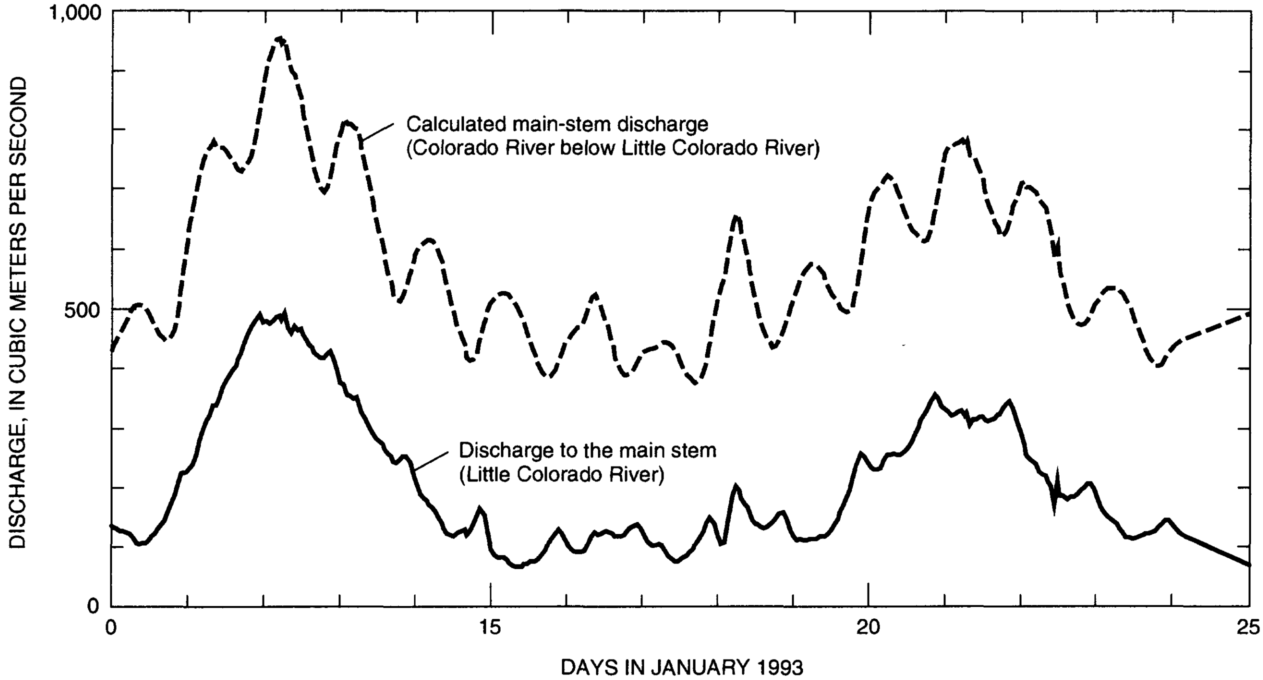


Figure 2. Discharge in the main stem of the Colorado River below the Little Colorado River, and the discharge in the Little Colorado River during the flood of January 1993.

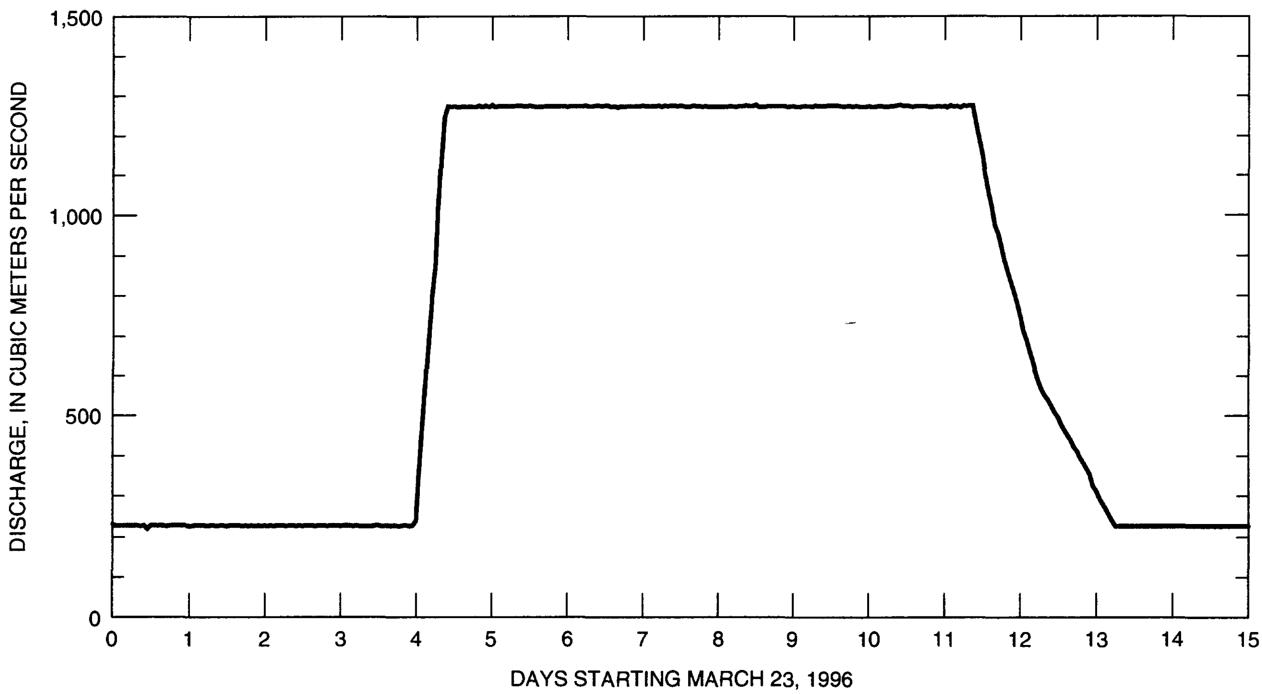


Figure 3. Discharge released from Glen Canyon Dam during the controlled flood of March–April 1996.

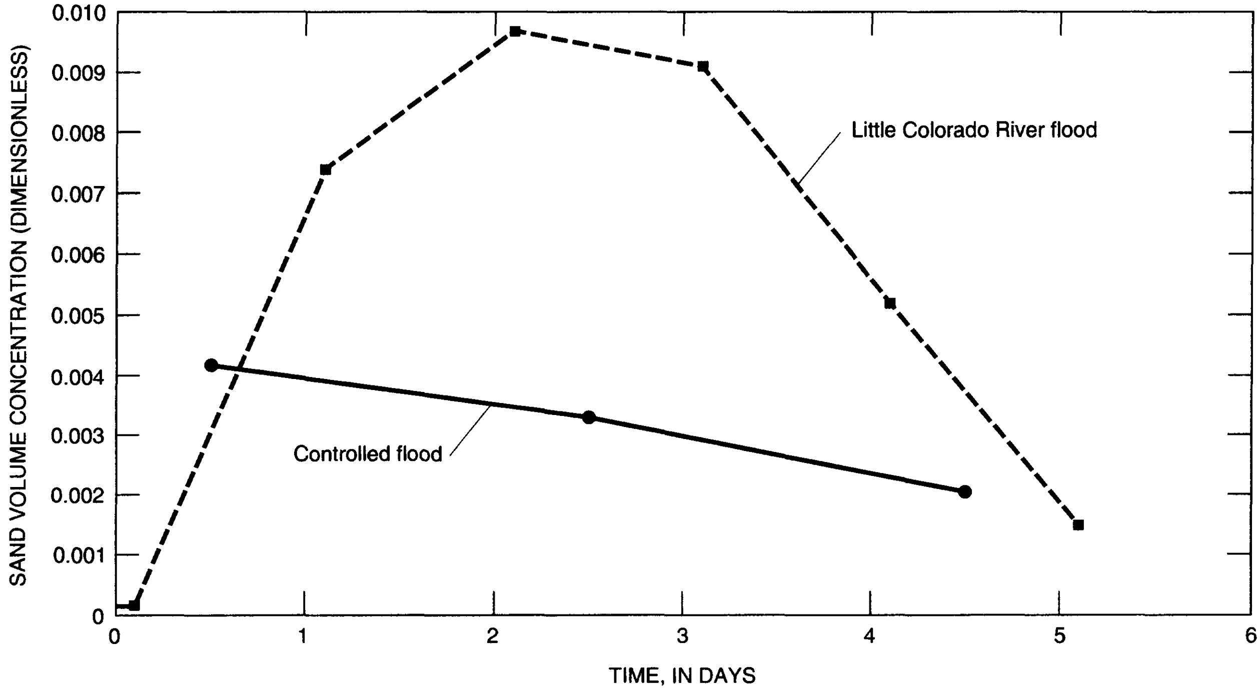


Figure 4. Suspended-sand concentrations in the Colorado River near the confluence with the Little Colorado River during the controlled flood, March-April 1996, and during the flood of 1993 on the Little Colorado River.

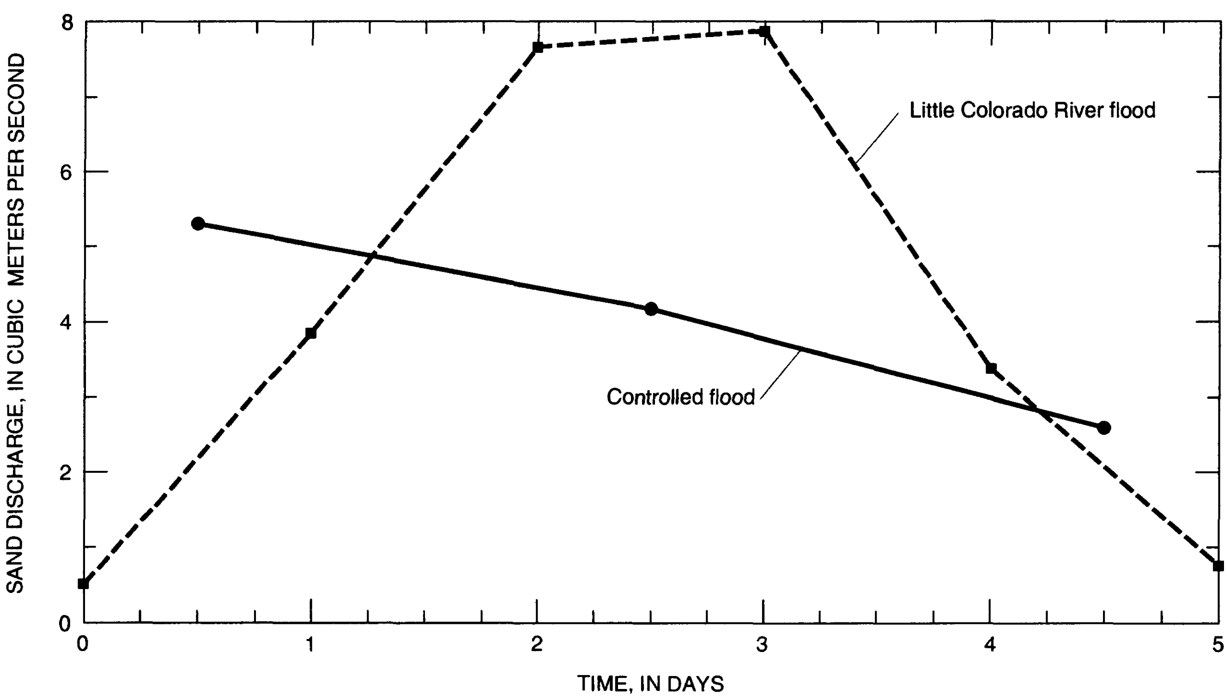


Figure 5. Sand discharge in the Colorado River near the confluence with the Little Colorado River during the controlled flood, and during the flood of 1993 on the Little Colorado River.

MODELING OF SAND DEPOSITION AND EROSION

Description of Model and Modeled Reach

The model was developed to track sand volumes and to investigate the mechanics of deposition and erosion of sand deposits in kilometer-scale reaches of the Colorado River in the Grand Canyon. The model calculates the vertically averaged two-dimensional flow field, the three-dimensional suspended-sand field, the local sand discharge, and the local sand erosion and deposition that determine the evolution of the alluvial bed over time. Channel shape, initial sand thicknesses, sand size and density, water discharge, sand discharge, water-surface elevation, average water-surface slope through the reach, and local roughness must be specified from direct measurement or estimated from auxiliary calculations. Details of the model can be found in Wiele and others (1996). One modification to the model as it was presented in Wiele and others (1996) is in the calculation of the skin friction. Skin friction is extracted from the total shear stress as a function of the deviation of the measured bed topography from the model grid using a calculation similar to a calculation of Wiberg and Smith (1991).

For the controlled flood, the sand discharge at the reach inlet was determined by using sand at the outlet of the first reach below the confluence with the Little Colorado River (fig. 1) as the boundary condition for the next reach and repeating that procedure to the upstream boundary of the modeled reach presented here. The upstream boundary condition for the sand at the first reach below the Little Colorado River confluence was taken from suspended-sand measurements made at the streamflow-gaging station above the confluence (Konieczki and others, 1997). For the flood on the Little Colorado River, the four reaches were modeled separately and used the sand influx from the Little Colorado River as the upstream boundary condition. The high suspended-sand concentrations along with the close proximity to the confluence make this a reasonable approximation for the flood on the Little Colorado River.

The modeled reach is about 2.4 km below the confluence with the Little Colorado River (fig. 1). The reach is about 350 m long and is bounded upstream and downstream by rapids that are formed by debris flows that partially constricted the channel laterally and deposited boulders in the main channel. Just below the entrance to the reach, the channel expands sharply along the left bank, and the flow forms a large recirculation zone that occupies about one-half the length of the channel. A smaller recirculation zone is on the right side. The channel also expands vertically just below the inlet, and had a depression that was about 22 m deep during the controlled flood. This depression shallows about midway through the reach to a maximum cross-stream depth of about 5 m. This morphology is characteristic of the Colorado River between the confluence of the Little Colorado River and Furnace Flats, which are about 11 km apart. This morphology is especially effective at trapping sand in recirculation zones, along margin deposits, and, if the suspended-sand concentration is high enough, in the main channel.

The model was used to calculate the time evolution of the sand deposits in four reaches during the Little Colorado River flood (Wiele and others, 1996). The model was checked against cross sections measured before and after the event and was found to match the cross sections well. For the comparison between the results of the flood on the Little Colorado River and the results of the controlled flood, the model was used for the one reach that was among the four included in the study of the effects of the flood on the Little Colorado River (fig. 1) and that also was included in daily bathymetry measured during the controlled flood by Andrews and others (1996).

Modeling Results

The increase in water and sand discharge in the main stem during the flood of the Little Colorado River led to large sand deposits below the confluence (Kaplinski and others, 1995; Wiele and others, 1996). Large deposits accumulated in the main channel as well as along the channel sides. During the controlled flood in March–April 1996, the main channel generally scoured as fresh sand deposits accumulated along the channel sides.

The reach contained more sand before the start of the controlled flood than before the Little Colorado River flood (fig. 6). More sand was stored in the main channel and along the left bank before the controlled flood; however, the overall channel shape and flow patterns were similar.

After 1 day during the flood on the Little Colorado River, the model results indicate that the main-channel depression had filled, and large bars had formed along a transition zone from high-velocity downstream flow in the main channel to the slower flow near the right bank and along the boundary between the downstream flow and the recirculating flow along the left side (fig. 7*A*). After 3 days, the left-side bar had grown nearly to the left bank and extended farther downstream, and the main channel had filled (fig. 7*B*). The total volume of sand in the reach remained nearly constant after 3 days; however, the shape of the deposits varied. The bar on the right side migrated downstream, and the bar on the left side extended farther downstream.

During the controlled flood, the model results indicate that the main-channel depression had been eroded, and sand had accumulated near the reattachment point along the left bank after 1 day (fig. 8*A*). The model results differ from the bathymetry of Andrews and others (1996) in that their measurements show additional accumulation occurred downstream from the reattachment point farther from the left bank and extended out toward the main flow. After 3 days, the main channel had eroded even more, and the bar on the left side near the reattachment point had increased slightly (fig. 8*B*).

In an alluvial river, deposition and erosion generally follow the divergence of the shear stress. A lag between shear stress and deposition is introduced where the sediment is in suspension, but in general, erosion occurs where the shear stress is increasing, and deposition occurs where shear stress is decreasing. In the study reach, however, the suspended-sand concentrations introduced at the upstream end are highly variable, and unless a major influx of sand from a tributary occurs, the river carries a load that is less than its capacity. As a result, whether sand is scoured or deposited in the main channel depends on the concentration of sand in suspension as well as on the channel shape. Following the streamlines from the inlet, the shear stress decreases where the flow expands vertically as it moves into the river segment that has the deep depression in the main channel. With sufficiently high sand loads, this decrease in shear stress would lead directly to deposition in the depression. During the flood on the Little Colorado River, which raised suspended-sand concentrations to predam levels, model results predict that the majority of the deposition early in the event was within the depression. In contrast, if suspended-sand concentrations are sufficiently low, sand residing in the depression, such as would result from deposition during previous low discharges, would be entrained and scoured from the depression despite the decrease in shear stress along streamlines. During the controlled flood, suspended-sand concentrations were low enough to cause the sand in the depression to scour.

During the flood on the Little Colorado River and during the controlled flood, significant deposition occurred along the side of the main-channel flow. In addition to the filling of the depression in the main channel, the model indicates that the high suspended-sand concentrations during the flood of the Little Colorado River led to deposition of a bar in the lateral expansion near the inlet along the left side of the main-channel flow. This bar expanded downstream and into the recirculation zone. The lower suspended-sand concentrations during the controlled flood, however, produced little deposition near the inlet. Instead, sand in suspension was carried toward the stagnation point where the separated flow reattaches to the left bank.

Response of the channel to the differences in water discharge and suspended-sand concentrations can be compared by summing the change in the cross-sectional area of the sand deposit along the channel. After 1 day, the change in sand cross-sectional area during the flood on the Little Colorado River shows an increase in the cross-sectional area of the sand deposit along the channel and no net erosion (fig. 9). The largest

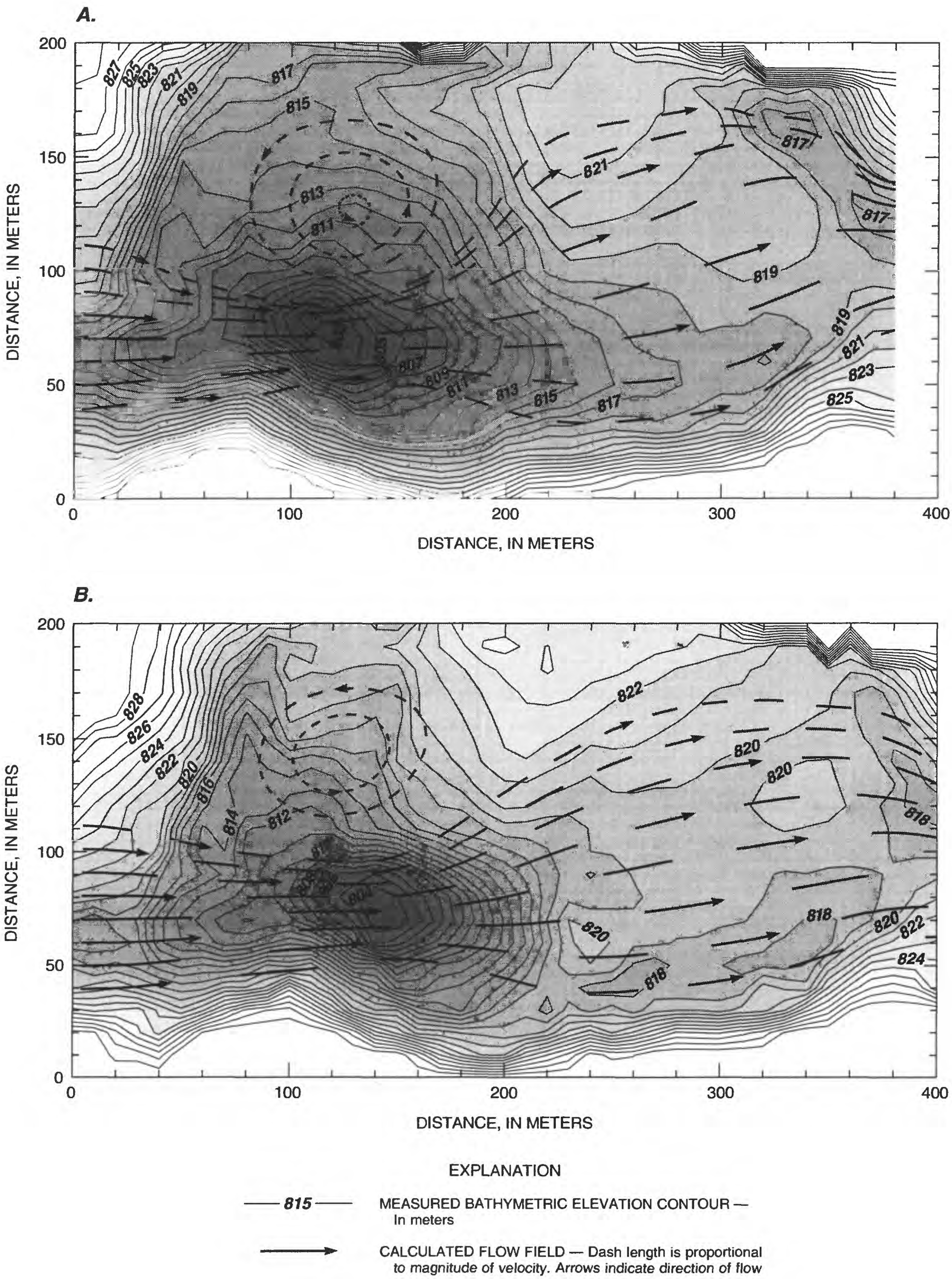
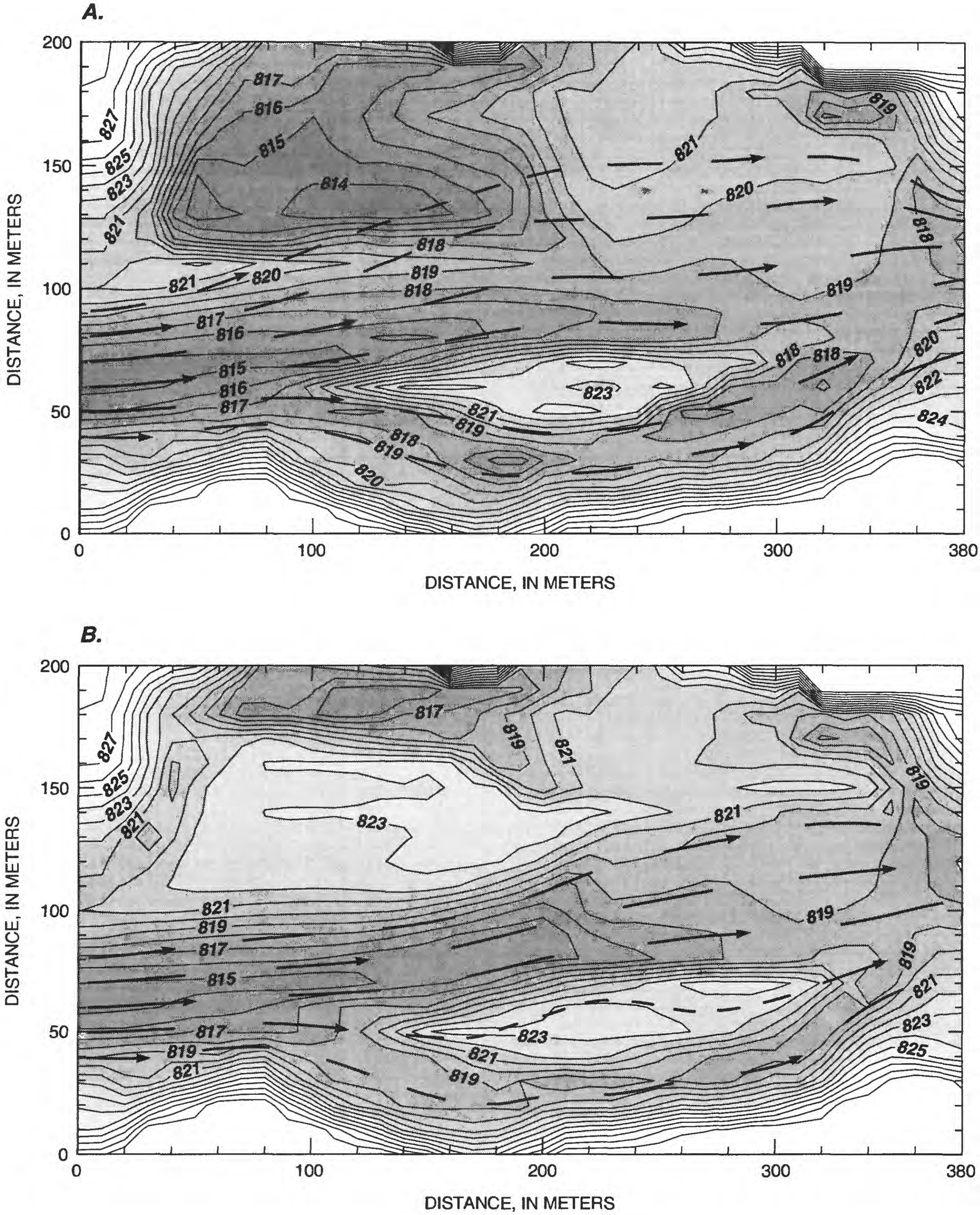


Figure 6. Bathymetry of the modeled reach. *A,* Before the flood of 1993 on the Little Colorado River. *B,* Before the controlled flood, March–April 1996.

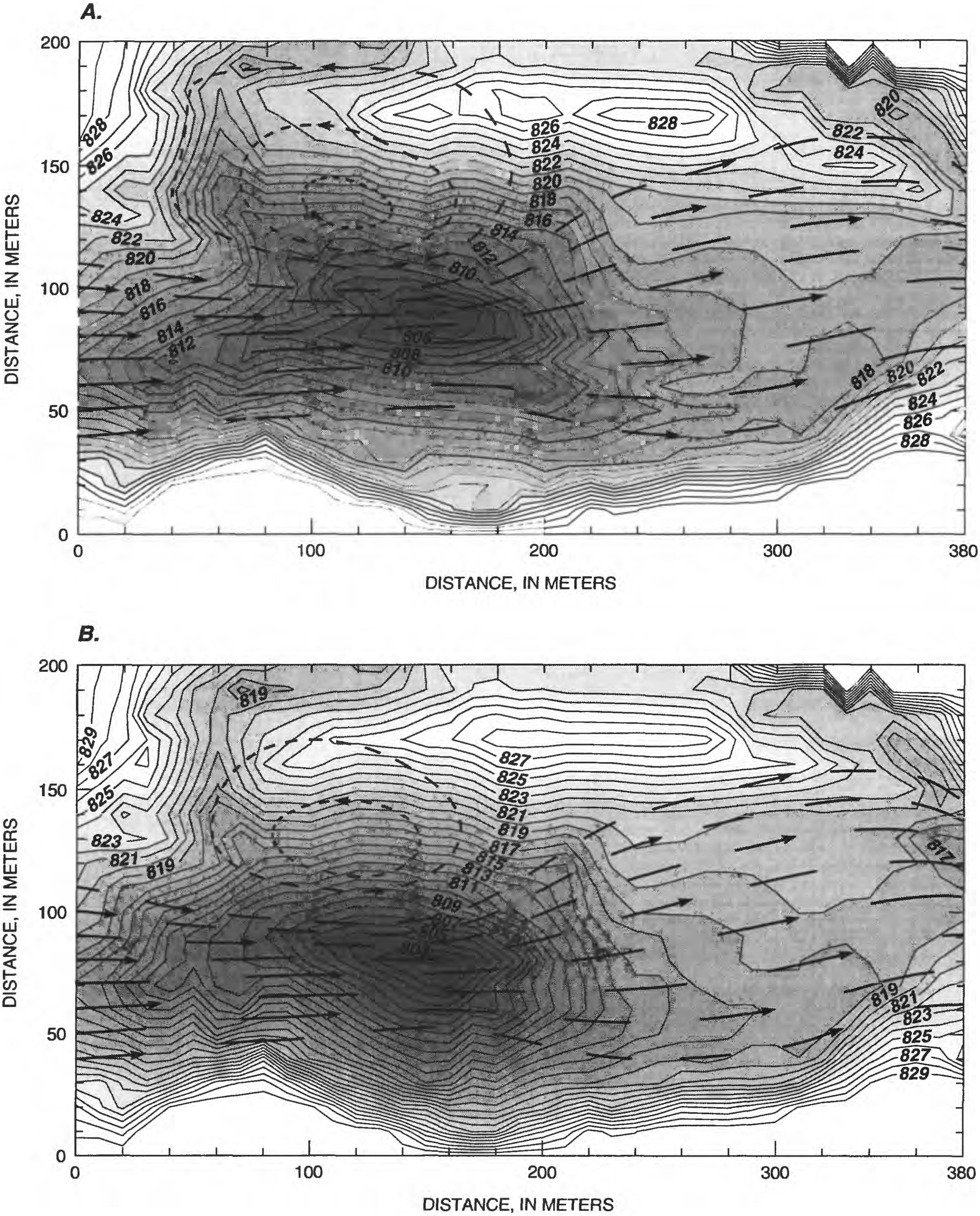


EXPLANATION

—— 815 —— MEASURED BATHYMETRIC ELEVATION CONTOUR — In meters

——→ CALCULATED FLOW FIELD — Dash length is proportional to magnitude of velocity. Arrows indicate direction of flow

Figure 7. Bathymetry of the modeled reach during the flood of 1993 on the Little Colorado River. *A,* After 1 day. *B,* After 3 days.



EXPLANATION

——815—— MEASURED BATHYMETRIC ELEVATION CONTOUR— In meters

——→ CALCULATED FLOW FIELD— Dash length is proportional to magnitude of velocity. Arrows indicate direction of flow

Figure 8. Bathymetry of the modeled reach for the controlled flood, March–April, 1996. *A,* After 1 day. *B,* After 3 days.

increase in sand cross-sectional area is about 110 m below the inlet where the deep hole in the main channel, which filled with sand, is located, and along the eddy fence on the left side of the inlet flow. The increase in sand cross-sectional area decreases downstream and corresponds to the smaller reattachment deposits and margin deposits along the left and right banks.

After 1 day during the controlled flood, the modeled and measured bathymetry show a smaller amount of deposition near the deep hole (fig. 9). Erosion rather than deposition occurred during the controlled flood in the main channel. The deposition near the inlet was along the eddy fence on the left side. The negative change in cross-sectional area of the sand at about 200 m corresponds to the loss of sand in the main channel. Downstream, the change in sand cross-sectional area increased as a result of deposition near the reattachment point. The model shows a pattern similar to that of the measured bathymetry; however, the pattern is shifted downstream about 10 percent of the length of the reach, and the model underestimated the amount of deposition farther downstream. The discrepancy between the model and the measurements is due to the additional sand in the main-channel region as shown in the measured bathymetry.

After 3 days, the deposition from the flood on the Little Colorado River had increased throughout the reach. Deposition concentrated around 150 m (fig. 10) where the bar on the left side continued to increase. In contrast, the main channel during the controlled flood continued to erode as shown by the increased magnitude in the negative change in cross-sectional area about 200 m downstream from the inlet. About 300 m downstream from the inlet where deposition was along the left bank near the reattachment point, the modeled and measured bathymetry show a small decline in the sand cross-sectional area.

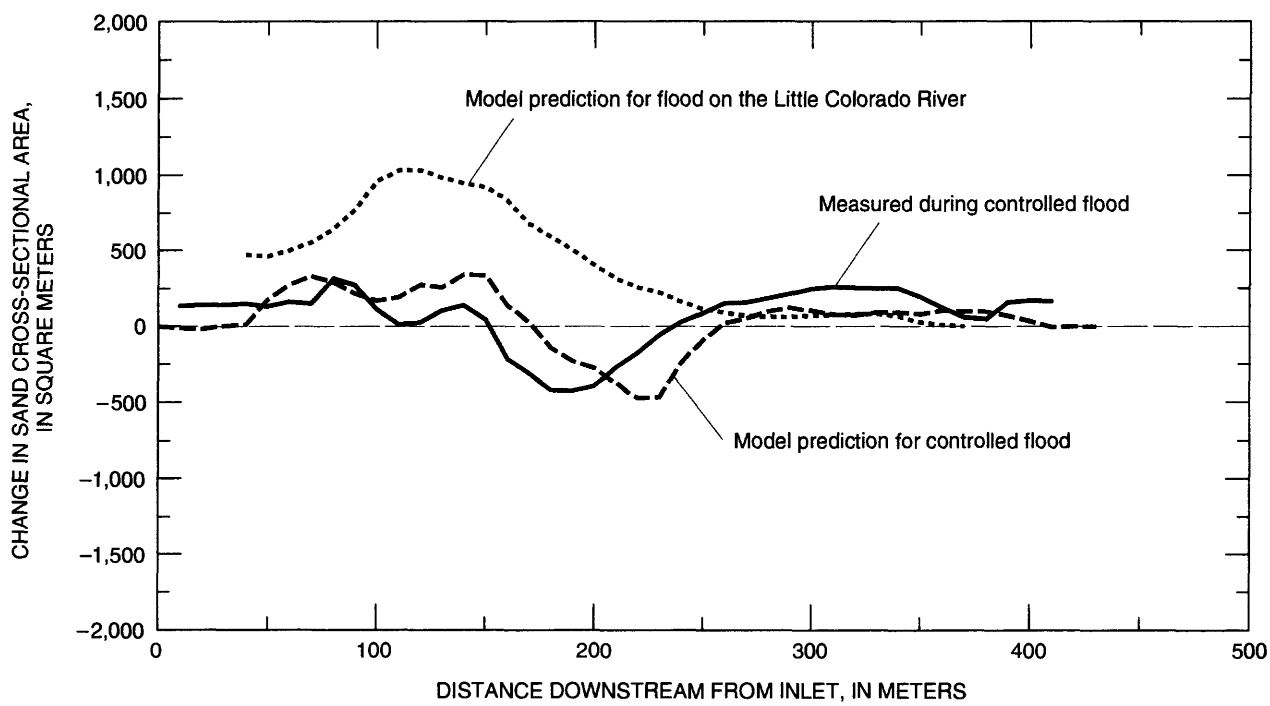


Figure 9. Changes in sand cross-sectional area after 1 day from model results during the flood in 1993 on the Little Colorado River, during the controlled flood in March–April 1996, and from measured bathymetry during the controlled flood as a function of distance from the reach inlet.

After 5 days, little increase occurred in the cross-sectional areas during the flood on the Little Colorado River (fig. 11). This pool reached its capacity to store sand after about 3 days (Wiele and others, 1996), and as a result, a volume of sand equivalent to the volume introduced at the inlet was discharged to the pools downstream.

After 5 days, the results for the controlled flood show a marked discrepancy between the modeled and measured bathymetry (fig. 11) as a result of a process that is not represented in the model. A large decrease in the cross-sectional area occurred around 200 m in the measured bathymetry between 3 and 5 days, although the model showed little change in the cross-sectional area. After 4 days, the modeled and measured bathymetry agreed well (fig. 12*A*); the model overpredicted the amount of deposition near the left bank, and underpredicted the amount of deposition slightly closer to the thalweg. After 5 days, a large difference occurs between the modeled and measured bathymetry at the same location (fig. 12*B*). The model shows the deposit from the previous day to be stable; whereas, the measured bathymetry shows a large decrease in the bed elevation along the left side. Farther downstream, where the deposit was mainly near the reattachment point, the model shows a continuing, although small decrease in the cross-sectional area; whereas, the measured bathymetry shows an increase.

The details of the mechanism that caused the large removal of sand along the left bank are unknown. The removal of that sand apparently occurred in only 2 hours (Konieczki and others, 1997). Two possibilities are a radical change in flow pattern or a response to the reduced sand concentration over time. E.D. Andrews (hydrologist, U.S. Geological Survey, oral commun., 1996) has proposed that the loss is due to mass failure. Flow patterns in a reach change over time as deposition occurs, changing the shape of the

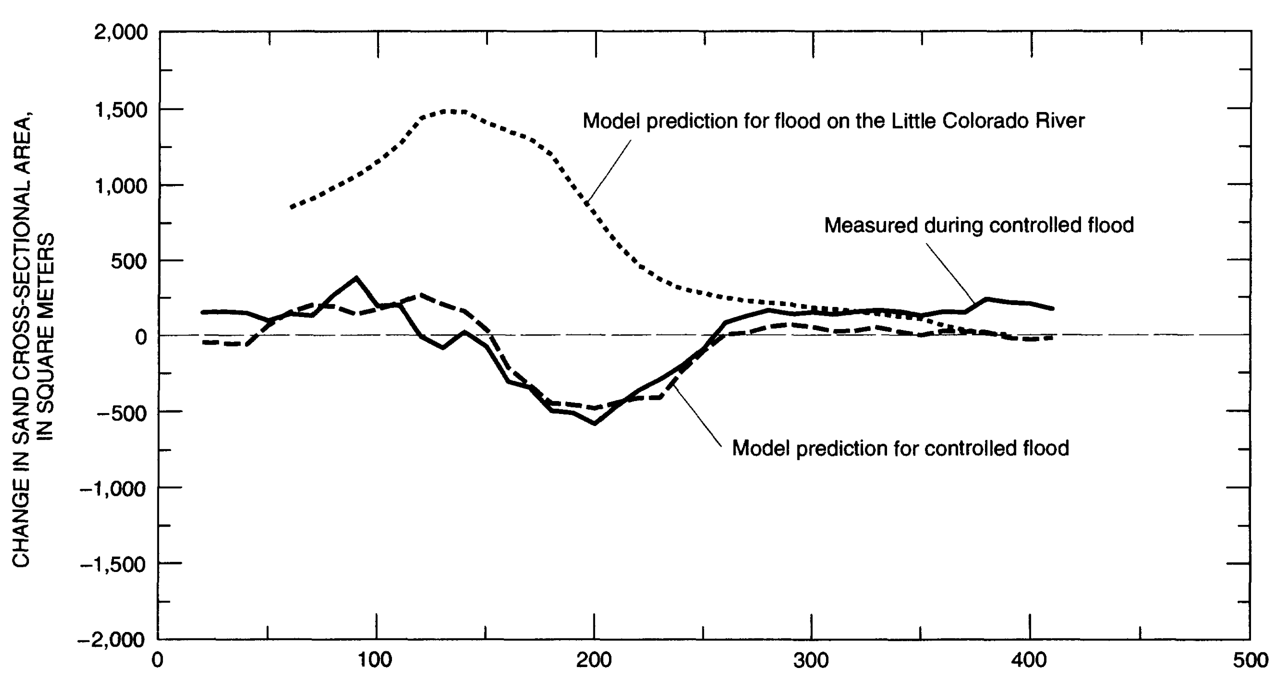


Figure 10. Changes in sand cross-sectional area after 3 days from model results during the flood in 1993 on the Little Colorado River, during the controlled flood in March–April 1996, and from measured bathymetry during the controlled flood as a function of distance from the reach inlet.

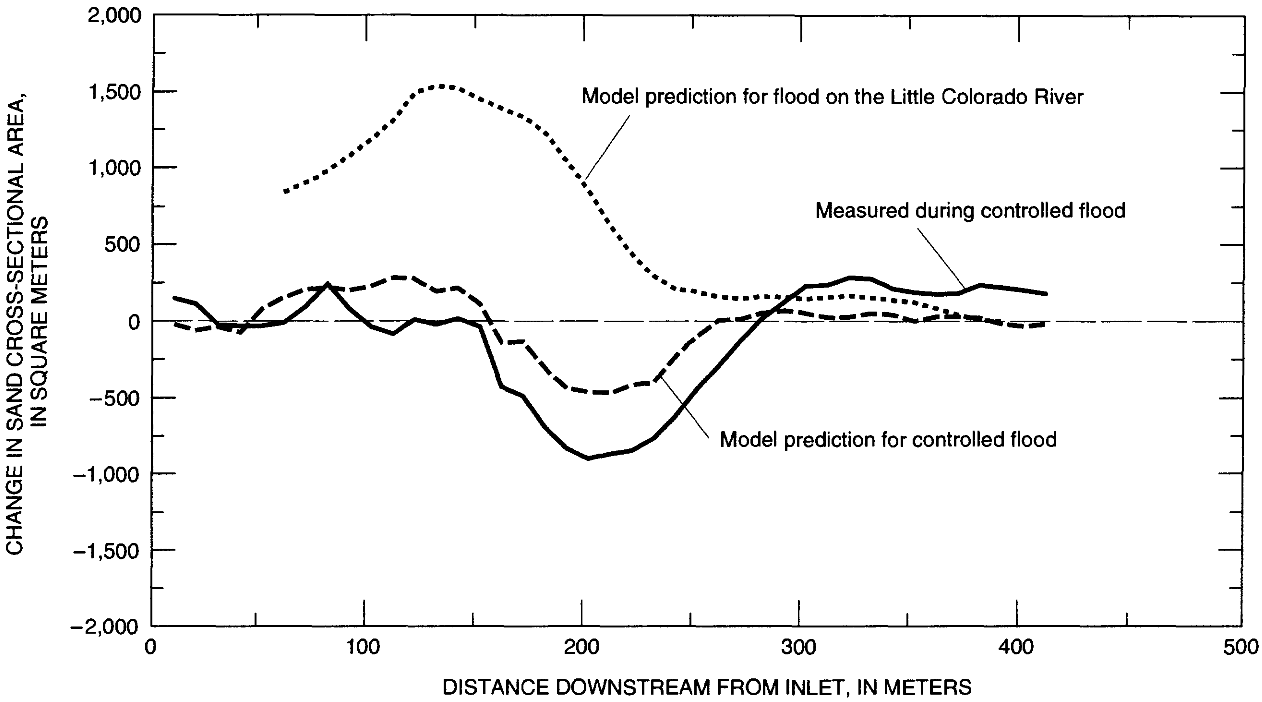


Figure 11. Changes in sand cross-sectional area after 5 days from model results during the flood in 1993 on the Little Colorado River, during the controlled flood in March–April 1996, and from measured bathymetry during the controlled flood as a function of distance from the reach inlet.

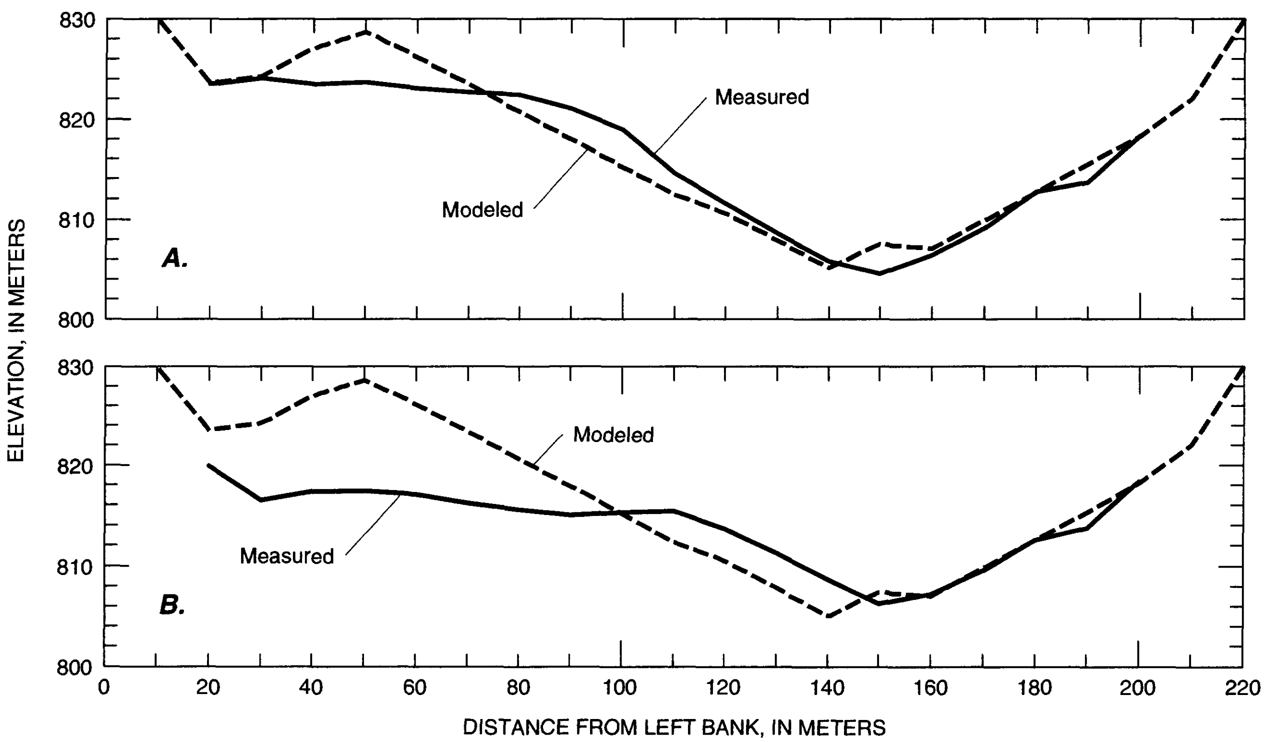


Figure 12. Measured and modeled cross sections 200 meters downstream from the reach inlet. *A,* After 4 days. *B,* After 5 days.

channel, but in this case, the flow is in quasi-equilibrium with the bed shape. Random fluctuations in the location of the reattachment point in flume studies have been observed by Schmidt and others (1993) and Rubin and others (1990). These fluctuations in a real river would occur on the time scale of minutes to hours; a sudden and sustained shift after several days of depositional development is unlikely. There is a random component to flow patterns, such as from turbulence or the fluctuations in the location of the reattachment point, but for a given bed configuration and upstream boundary conditions, the flow pattern averaged over a short time period is fixed by the governing physics of the flow. These random fluctuations would instead tend to spread the deposit near the reattachment point and modify its shape but not cause a sudden direct scour of the deposit. The modeling shows that the reduction in suspended-sand concentration affected the deposits formed early during the controlled flood; however, the erosion was minor. Reduction in suspended-sand concentration alone could not have resulted in the removal of so much sand so quickly.

These deposits were probably removed as a result of a mass failure. This process is consistent with the removal of the sand over a short time and does not require a radical change in flow pattern. Small fluctuations in flow, such as fluctuations in the location of the reattachment point, could play a role in triggering such a failure. Cluer (1997) has proposed that local erosion caused by increases in flow velocity near the base of bars could trigger slumping.

Rapid removals of sand such as this one may have occurred during the flood on the Little Colorado River; however, there are no measurements to document the removal. Cluer (1995) observed similar sudden losses of sand from deposits during normal dam operations using daily photographs and found that the deposits were replenished within weeks to months. Sudden losses of sand during the flood on the Little Colorado River probably would be replaced even more rapidly as a result of the high concentration of sand in suspension, which would leave a final deposit that showed no evidence of such losses. In the absence of surveys made during an event, the only evidence of such losses would be found if the conclusion of the event coincided with a recent loss that allowed no opportunity for redeposition.

CONCLUSIONS

Changes in suspended-sand concentration over the course of a controlled release, such as during the controlled flood, potentially can affect deposits formed early during the release when suspended-sand concentrations are higher. Modeling results for this reach indicate that the reduction in suspended-sand concentration did cause a reduction in the size of deposits formed under conditions more favorable for beach restoration. The effect, however, was small and occurred at a much slower rate than the rate at which the deposits formed.

The modeling results presented here support the hypothesis that sand residing on the bottom of the channel can be redistributed effectively to the channel sides with dam releases greater than powerplant capacity. The depositional processes, however, do not appear to duplicate the processes as they occurred before the closure of Glen Canyon Dam. High suspended-sand concentrations during the flood on the Little Colorado River led to rapid and massive deposition in the main channel and a slower continuous buildup of bars along the channel sides over about 3 days. During the controlled flood, however, the lower suspended-sand concentrations led to erosion in the main channel and deposition near the reattachment point. Sand carried from the inlet along streamlines toward the reattachment point was deposited because of the high magnitude of the negative divergence of the shear stress along these streamlines.

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