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MEASUREMENTS OF SAND THICKNESSES IN GRAND CANYON, ARIZONA, AND A CONCEPTUAL MODEL FOR CHARACTERIZING CHANGES IN SAND-BAR VOLUME THROUGH TIME AND SPACE

by

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ABSTRACT

In order to manage the sediment resources in Grand Canyon National Park it is essential to determine not only the sediment budget (inflow and outflow), but also to quantify the volume of sand contained within the system. If the river contains a large reservoir of sand (relative to the mean annual sediment deficit or surplus), then the bars in the river can be expected to be less sensitive to the sediment input of any particular year or sequence of several years. This study is a first attempt at quantifying the volume of sediment within the system and evaluating the relative amounts stored within the subaqueous channel and within subaerially exposed bars.

Three techniques were employed to measure sand thicknesses in bars along the Colorado River in Grand Canyon: depth of penetration of a vibrating aluminum rod (vibra-probe), seismic refraction surveys on subaerially exposed bars, and examination of cross-channel seismic reflection lines. The results suggest that the mean thickness of sand in much of the canyon is between a few tens of centimeters and a few meters.

A conceptual model is presented to characterize changes in sand volume through time and with distance downstream. Although sand-transport calculations made by Andrews (1991) suggest that net aggradation is occurring from the Little Colorado River (mile 61) downstream, field observations suggest that bars are eroding as far downstream as mile 120 (Webb and others, 1991). The conceptual model presented here is used to reconcile this paradox of observed bar degradation in a region that is calculated to be undergoing net aggradation. If the observations and calculations are correct, then the Colorado River in Grand Canyon may be characterized as (1) an upstream reach (miles 0 to 61) in which the reach and the subaerially exposed bars are losing sediment; (2) a middle reach (miles 61 to approximately 120) which is experiencing net aggradation while subaerial parts of the bars are losing sediment to the subaqueous channel; and (3) a downstream reach in which both the subaerially exposed bars and the subaqueous channel are gaining sediment. Alternatively, the observations may not be representative of the system's behavior, or the calculations may be incorrect.

INTRODUCTION

When Glen Canyon Dam was completed in 1963, flow down the Colorado River in Grand Canyon National Park was radically altered. Before the dam was built, river discharge exhibited large annual variations and small daily variations. Since the river was dammed, sediment transport into Grand Canyon was reduced, annual flow fluctuations were drastically reduced, and daily fluctuations were instituted. Bars in Grand Canyon National Park have been adjusting topographically in response to these changes.

Because these sand bars are an important biological habitat and an important recreational resource, it may become desirable to manage releases from Glen Canyon Dam so as to maximize construction of the bars. In order to evaluate the effects of bar-building flows on the river system, it is necessary to quantify both the sediment budget (inflow from tributaries and outflow down the river) and the reservoir of sediment stored within the system.

It is important to determine sediment reservoir in order to evaluate observed or calculated excesses or deficits in the annual sediment budget. If the volume of sand in storage is large relative to the annual sediment supply from tributaries, then the effects of a few years of reduced sediment supply will be unimportant, and dam operators will have greater flexibility in producing flows that build bars. If the volume of sand in storage is small, however, then the amount of sediment available for beach-building flows may vary from year to year, providing additional constraints on operational regimes.

The purpose of this report is to summarize results of three kinds of sediment-thickness measurements in bars along the Colorado River in Grand Canyon. The results were

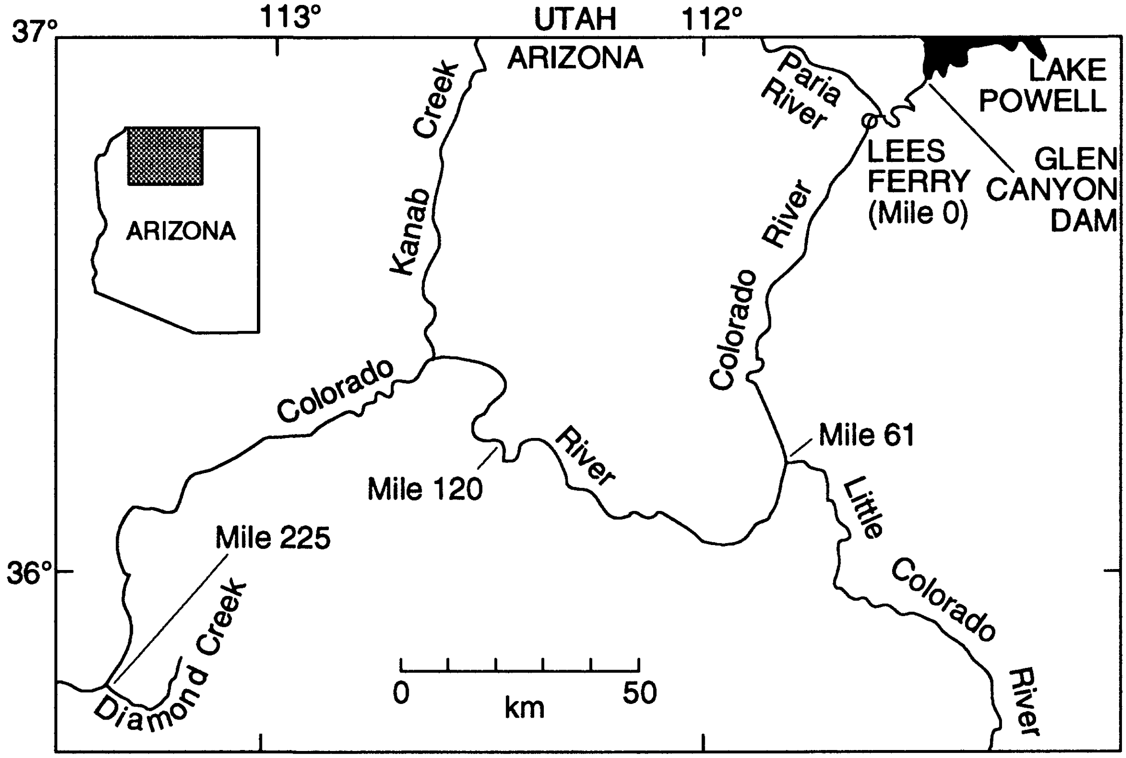

Figure 1. Map of Colorado River downstream from Glen Canyon Dam, Arizona.

developed for the Environmental Impact Statement on operational alternatives for Glen Canyon Dam. This work was one component of Phase II of the Glen Canyon Environmental Studies.

METHODS

Sand thicknesses in the canyon were investigated using three techniques: measuring depth of penetration of a vibrating aluminum rod (vibra-probe), seismic refraction surveys on subaerially exposed bars, and examination of previously collected seismic reflection lines across the river channel. The seismic reflection lines were collected by U.S. Geological Survey Water Resources Division in 1984.

RESULTS AND DISCUSSION

Vibra-probing was used to measure thicknesses of sand deposits at more than 200 locations on 15 bars in Grand Canyon between Lees Ferry and Diamond Creek (Fig. 1). Measured depths range from 0.13 to 13.1 meters (Fig. 2). The main limitation of this technique is that it can not always succeed in penetrating depths that approach or exceed 10 m. Where the sediment cover is thinner, the rod vibrates down until contacting bedrock, boulders, or consolidated sediment.

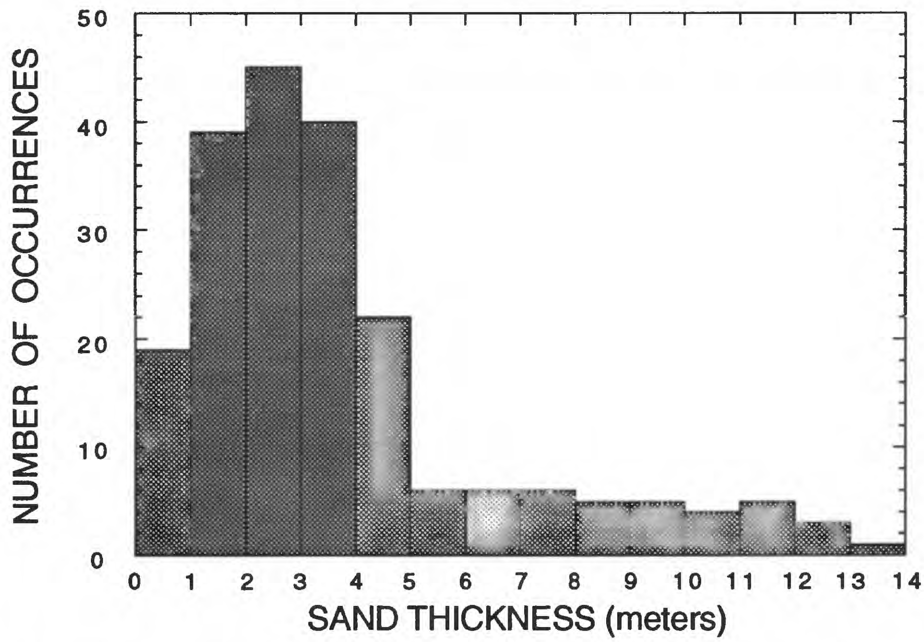

Figure 2. Histogram showing sand thicknesses measured by vibra-probing. More than 200 thickness measurements were made through 15 reattachment bars, separation bars, and channel-margin deposits. Mean sand thickness through these bars is 4 m.

The mean thickness of unconsolidated sediment in bars along the Colorado River was found to be 4 m. The vibra-probe sites were not selected randomly, however, and include some relatively large bars that were selected for other sedimentologic studies. Inclusion of these bars may tend to bias the results toward a high value.

Despite 200 vibra-probe measurements on 15 bars, only a tiny percentage of the canyon has been surveyed. The bars investigated represent only a few percent of the bars in the canyon, and data presented by Schmidt and Graf (1990, table 7) demonstrate that such bars constitute only a small part of the river corridor (2 to 14 percent).

Seismic refraction was tested as a technique for measuring sand thicknesses but was found to be incapable of distinguishing talus from sand. The technique succeeded in measuring bedrock depths beneath the endpoints of 15 profile lines across 5 bars. Bedrock depths range to as much as 45 m (Fig. 3). These results, combined with the vibra-probe results, indicate that the bars are underlain by tens of meters of talus and a few meters of sand. Results of the refraction surveys may be of interest for morphological studies but do not help define sand volumes.

Seismic reflection lines were also examined to investigate sand volumes. The 200 lines include some profiles across relatively thick sediment bodies, such as the bar illustrated in Figure 4. In general, however the reflection lines suggest that a significant portion of the river bed has little or no sand cover. The sediment cover is commonly so thin as to be less than the limit of resolution of the seismic system (estimated to be tens of centimeters to possibly as much as a few meters). More recent observations with underwater television document that much of the river bed is devoid of sand.

The volume of sand underlying the exposed parts of bars can be estimated by multiplying the 4-m mean sand thickness determined from vibra-probing by the sand-bar surface-area reported by Schmidt and Graf (1990) for selected reaches of the river. This volume of sand beneath the area of exposed bars is equivalent to a uniform thickness of approximately 0.3 m spread over the entire channel. If this calculated volume of sand

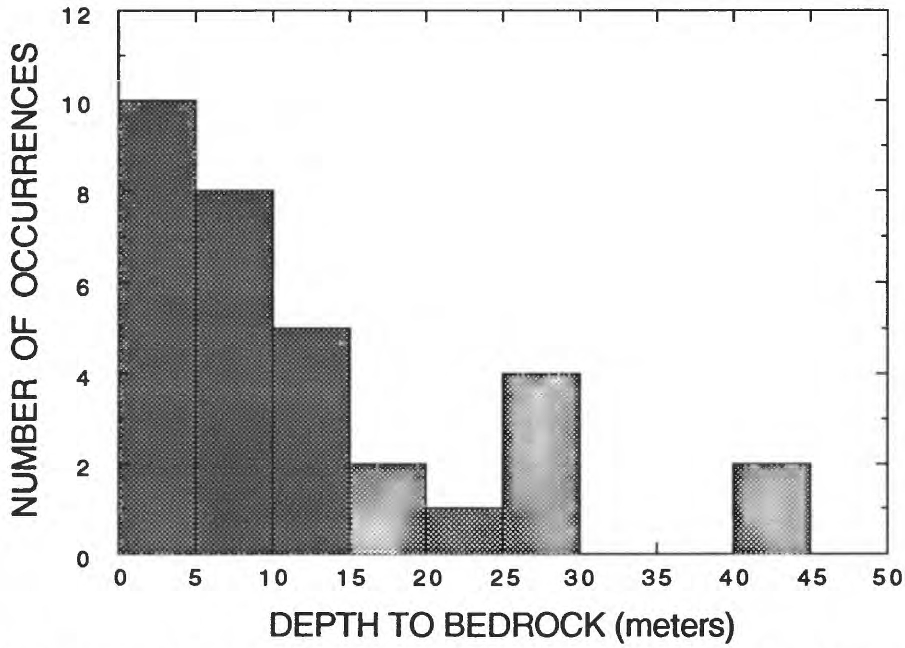

Figure 3. Histogram showing depths to bedrock measured by seismic refraction. Bedrock depths were measured at each end of 15 profiles beneath 5 separation and reattachment bars.

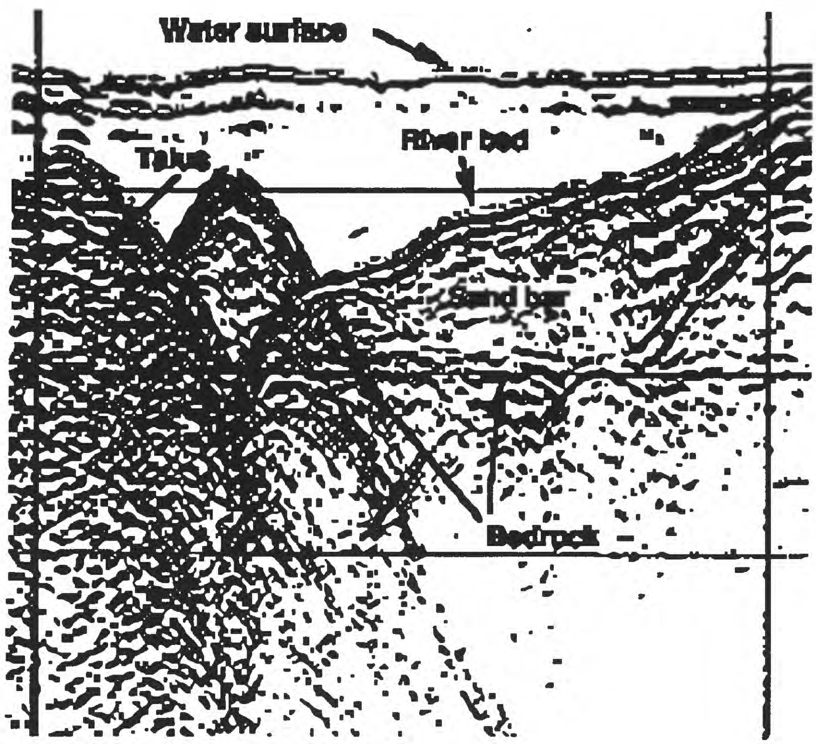

Figure 4. Cross-channel seismic reflection profile. The right side of the profile shows a relatively thick sand deposit that overlies bedrock; the left side of the profile shows talus with little or no sediment cover. Channel width is approximately 100 m; vertical distance between scale lines is approximately 8 m.

represented the entire volume of sand in the system (the channel contained no other sand), then the mean thickness for the system would be a few tens of centimeters. This value represents the minimum sand thickness for the system, as it does not include a contribution from the subaqueous part of the channel.

An estimated upper limit for sand thickness is more difficult to calculate, because less is known about sand thickness in the subaqueous channel. It is unlikely, however, that the mean thickness of sand in subaqueous parts of the channel exceeds the thickness of sand within the bars, which would place the upper limit of sand thickness at 4 m. Considering the widespread areas of thin sand coverage evident in the reflection profiles and the abundance of areas that are entirely devoid of sand in underwater television surveys, the upper limit of sand thickness could be expected to be less. Thus, the mean thickness of sand for the system is estimated to be at least a few tens of centimeters and not more than a few meters. Using an estimated thickness of 1 m and a channel width of 100 m, the reach between Lees Ferry and the Little Colorado (miles 0 to 61) is estimated to contain roughly 10^7 m^3 of sand.

CONCEPTUAL MODEL OF BAR-VOLUME CHANGE

In order to understand changes in sand-bar volume through time and with distance downstream, it is essential to distinguish between two distinct effects of the dam. First, the regulated flow regime may cause a transfer of sand between bars and the channel; this effect can cause a change in bar volume through time but would not be expected to cause a change that varies systematically with distance downstream. Second, the dam alters the sediment budget by reducing the rate (and spatial gradient) of sand transport through the canyon and by eliminating mainstem sediment supply from upstream. This effect could be expected to vary with distance downstream.

These two effects—and their possible combinations—are illustrated in Figure 5A. The vertical columns illustrate three hypothetical exchanges between bars and the channel: net transfer of sand from bars to channel, no change, and net transfer from channels to bars. The horizontal rows illustrate hypothetical changes to the volume of sand in storage. In all three cases illustrated by horizontal row, the volume of sand in storage decreases through time immediately downstream from the dam, but tributary sediment input and the reduced transport rate of the post-dam operating regime cause the volume of sand in storage to increase with distance downstream. In this simple model, transient effects are not considered; site-specific deposition at individual bars also is not considered.

The two kinds of effects that are illustrated in Figure 5A cause different changes to the volume of sand stored in bars. Exchange between bars and the channel is essentially constant with distance downstream, whereas the altered sand budget causes aggradation to increase systematically downstream.

The hypothetical examples illustrated in Figure 5 can be used to reconcile paradoxical behavior of bars in the canyon. By comparing sand bars photographed in 1890 and rephotographed in 1990, Webb and others (1991) found that bars that are inundated at moderately high flows (between 30,000 and 60,000 ft^3/sec) tended to erode at locations upstream from river mile 120. In contrast, sand-transport calculations made by Andrews (1991) suggest that net deposition should occur as far upstream as the Little Colorado River (mile 61). How can net deposition occur in the same region where bars exhibit net erosion? Figure 5A illustrates that this response is not necessarily contradictory. A decrease in bar size can be caused by a net transfer of sand from bars to the channel (left vertical column), while net deposition occurs simultaneously as a result of the altered sand budget (bottom horizontal row). The combined effects of the two processes can cause erosion of upstream bars, aggradation of downstream bars, and net deposition as far

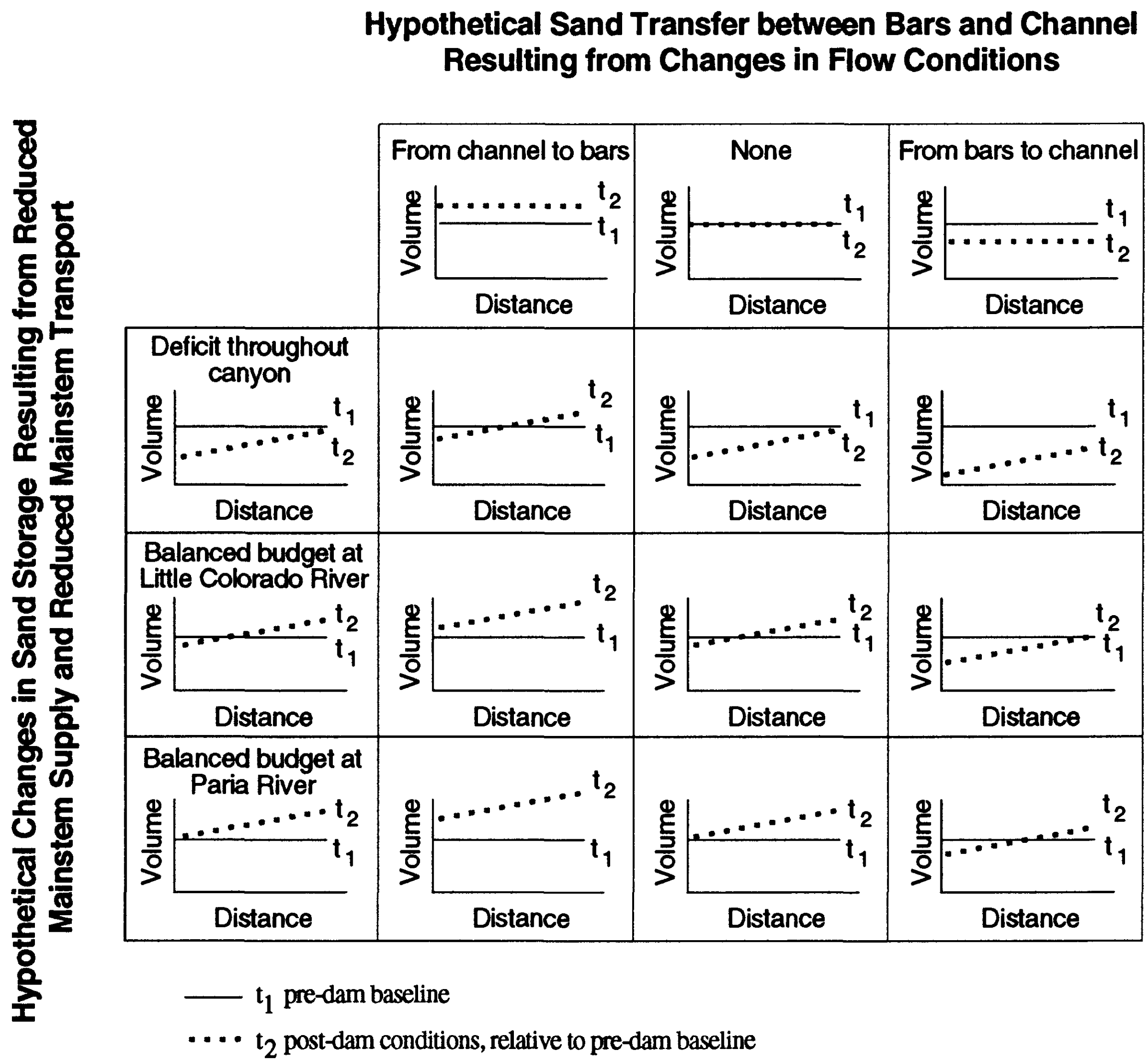

Figure 5A. Conceptual model illustrating the differing downstream effects on bar topography caused by three hypothetical changes in sand budget and three hypothetical transfers of sand between bars and the channel. The three changes in sand storage are shown in horizontal rows; the three bar-to-channel transfers of sand are shown in vertical columns. A plot is shown to illustrate each of the nine combinations of the two effects. All plots show a baseline representing pre-dam (1890) bar volume per unit length of river and post-dam (1990) volume. Both volumes are normalized relative to the pre-dam volume, so that the pre-dam conditions are constant with distance downstream. Effects due purely to dynamic transfer between bars and channel are presumed to be relatively constant with distance, whereas changes in sand storage should become systematically more positive downstream (because of addition of sand by tributaries).

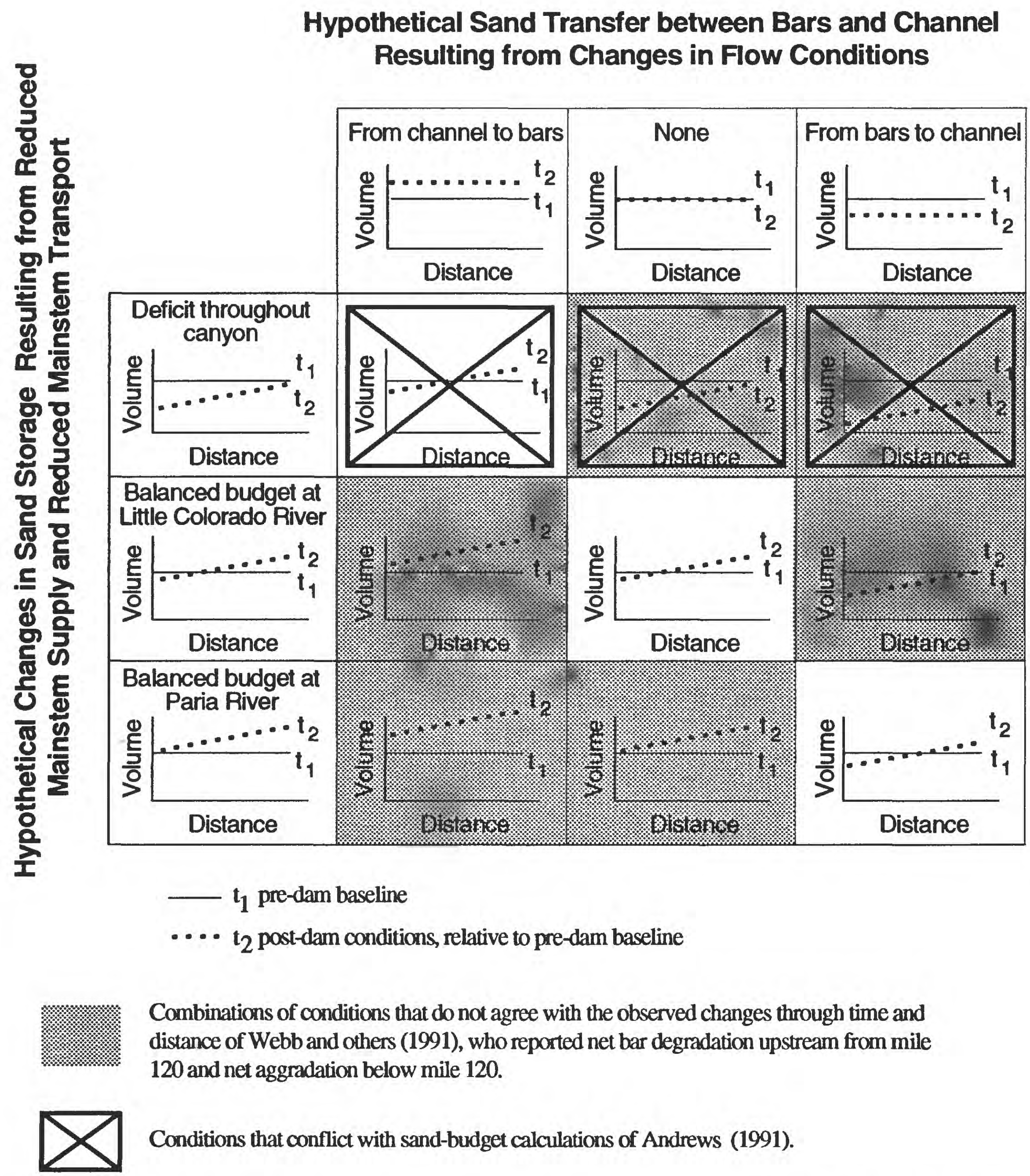

Figure 5B. Schematic diagram characterizing bar behavior in the Colorado River in Grand Canyon.

upstream as the Paria River. Aggradation of bars downstream of river mile 120 was also reported by Webb and others (1991).

The hypothesis that sand abundance increases downstream is also compatible with observations of Beus and others (1991). They reported that short-term changes in bar volume (both positive and negative) increase downstream. This suggests that the abundance of sand increases downstream.

By combining the observations of Webb and others (1991) with the sand-transport calculations of Andrews (1991), it is possible to constrain the combination of conditions that occur in the canyon (Fig. 5B). The field observations narrow the possible conditions to those in which the balance between upstream erosion of bars and downstream aggradation occurs in the vicinity of river mile 120. The sand-transport calculations suggest a net sediment surplus downstream from mile 61 (Little Colorado River). If the observations and calculations are correct, then the Colorado River in Grand Canyon may be characterized as (1) an upstream reach (miles 0 to 61?) in which both the subaerially exposed bars and the bar/channel system are losing sediment; (2) a middle reach (miles 61? to approximately 120) in which subaerial parts of the bars are degrading while the subaqueous channel is undergoing net aggradation; and (3) a downstream reach in which both the subaerially exposed bars and the subaqueous channel are gaining sediment. Alternatively, the observations may not be representative of the system's behavior, or the calculations may be incorrect.

Figure 5B also illustrates the difficulty of reversing the erosion of bars in upstream reaches. If the goal is to modify the flows so as to transfer sand from the channel back to higher elevations on the bars (i.e., move to the left from the conditions plotted at the lower right corner of Figure 5B), the difficulty is to accomplish this change without causing a sediment deficit (moving upward in Figure 5B).

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