GEOMORPHIC STABILITY OF SANDBAR 43.1L ON THE COLORADO RIVER IN THE GRAND CANYON IN RESPONSE TO GROUND WATER SEEPAGE DURING FLUCTUATING FLOW RELEASES FROM GLEN CANYON DAM

William Werrell

Richard Inglis Jr.

and Larry Martin

Technical Report NPS/NRWRD/NRTR-92/10

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July 1993

United States Department of the Interior
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ABSTRACT

An investigation of sandbar erosion caused by ground water seepage was conducted by the National Park Service (NPS) in support of the Glen Canyon Environmental Studies (GCES) program. The GCES program, funded by the Bureau of Reclamation, is evaluating the effects of daily water release patterns from Glen Canyon Dam on downstream resources in Glen Canyon National Recreation Area (NRA) and Grand Canyon National Park (NP). This investigation focused on evaluating the effects of shallow water seepage on the erosion of sandbars along the Colorado River in this area.

Ground water movement is the result of recharge and discharge (seepage) from the river banks during daily river stage fluctuations. This study was conducted during two time periods under different flow release regimes from the dam. During April 3 - 9, 1991, (7 days) dam releases ranged from approximately 100 to 425 cubic meters per second (m^3/s) resulting in river stage fluctuations of about 1.9 meters (m). During August 8 - 26, 1991, (19 days) flow releases from the dam ranged from about 280 to 510 m^3/s, and river stage fluctuated about 1.2 m.

River stage and ground water elevations were monitored continuously during each period. Daily measurements of land surface elevations were recorded along transects on the beach face between high and low river levels. Elevation data were collected with a Surface Profile Gage that was designed for this study and built by the authors. The gage provides topographic data at 58 points over a distance of 4.5 m. In addition, an experiment was conducted with drain pipes set horizontally into the face of the sandbar to enhance ground water drainage from a small area of the sandbar. Photographic and video documentation was produced during both periods to further demonstrate the role of ground water seepage on sandbar erosion.

Erosion and deposition processes occur daily in response to changing hydrologic and hydraulic conditions. The net effect of these opposing processes varies with changing river flow characteristics. When the river stage falls below the water table in the sandbar, ground water discharges from the face of the sandbar as a seep or spring line. Seepage erosion occurs as water flowing down the sandbar to the river's edge concentrates and forms rills, scouring loose sand from the sandbar in the process. Sandbar aggradation could be caused by soil creep or sand deposition by near-shore eddy action.

In April, the net effect of these opposing processes was a decrease in mean elevations of transects. Sandbar erosion of 2 to 12 millimeters (mm)/transect occurred during the April study period of seven days. In August, the net effect was an increase in mean elevations. Sandbar aggradation of 3 to 9 mm/transect occurred during the August study period of 19 days.

ACKNOWLEDGEMENTS

This study was conducted by a team from the NPS Water Operations Branch (WOB), Water Resources Division (WRD), under the direction of Bill Jackson. Data collection assistance was provided by John Sloat, Beth Glasbrenner and Mike Kearsley as unpaid volunteers. We also wish to thank Brian Cluer (NPS), Larry Stevens (NPS), Mike Carpenter U.S. Geological Survey (USGS), and Rob Carruth (USGS) who were also conducting investigations for GCES at the study site during our work. Their direct assistance and shared thoughts were invaluable in support of our work.

INTRODUCTION

The Colorado River riparian zone and its associated resources in the Grand Canyon are influenced by the operation of Glen Canyon Dam. The dam was constructed for several reasons, but primarily for flood control and water storage for Arizona, California and Nevada, as well as hydroelectric generation. The hydroelectric capability is designed to provide peak power generation during daily peak electrical demands. Consequently, the release of water from the dam fluctuates with power demand, and a daily surge of water continues downstream through the entire length of the Grand Canyon. Water levels in the river have fluctuated in narrow parts of the canyon as much as 4 meters in one day. A more typical fluctuation is from 1 to 3 meters. Interrelated processes occurring between the river and its riparian areas are affected by the fluctuation.

This report describes the relationship of bank stored ground water to sandbar erosion occurring during fluctuating Colorado River flows. The Colorado River below Glen Canyon Dam is within both Glen Canyon NRA and Grand Canyon NP. NPS concerns include the preservation of sandbars along the Colorado River. These sandbars have high natural resources value and are used as camping sites by park visitors floating down the river.

The terms "sandbars, alluvial sand deposits, selected alluvial deposits, and sediment deposits", have been used to describe what are colloquially called "beaches". In this report, the term sandbar will be used to be consistent with recent reports of other investigators.

The purpose of this report is to evaluate and demonstrate the role of ground water on sandbar erosion observed at Sandbar 43.1L during daily fluctuations of the Colorado River. The objectives are: 1) to confirm that ground water is a contributing factor to erosion; 2) to quantify sandbar erosion rates directly associated with ground water seepage from the sandbar; and 3) present a hypothesis of ground water related processes contributing to sandbar erosion.

PROBLEM STATEMENT

Observation of sandbars during the daily Colorado River stage fluctuations revealed that during times of falling stage, a zone of saturated sand formed on the face of the sandbar adjacent to the water's edge. This saturated zone moves down the face of the sandbar as the river stage and water table falls. As the stage approached minimum level, the zone gradually widened to about 2 m, remaining adjacent to the river's edge. Rills formed in the saturated zone, moving sand grains down the face of the sandbar.

The responses of the water table in the sandbar to the fluctuating river stage were thought to be the driving mechanism of seepage erosion processes. During the rising river stage, river water infiltrates the sandbar causing the water table to rise in the area adjacent to the face of the sandbar. Shortly after the river stage begins to fall, ground water will flow toward the river, exiting from the sandbar as a spring or seep line, forming a seepage face. Water flowing down the face of the sandbar to the river's edge concentrates and forms rills, scouring the upper layer of sand in the process. As the river stage begins to rise, the seepage face is submerged and river water begins to recharge the sandbar. Thus the cycle is complete. The rate of stage decline, the length of time stage remains at a minimum, and the amplitude of the river stage fluctuation are thought to be important variables in determining the rate of erosion of the sandbar.

The objectives of this investigation are to quantify erosion rates and relate the variation in erosion rates to fluctuations of river stage and the water table in the sandbar. The investigation had four major components:

1. Ground elevation transects in the zone of fluctuations on the face of the sandbar.

2. Continuous monitoring of river stage and the water table in the sandbar.

3. Demonstration of the direct relationship of ground water seepage to rill formation during falling river stage by placing horizontal drains in the beach face to promote faster drainage of ground water during periods of falling river stage.

4. Video-tape documentation of the erosion processes related to the river stage, water-table elevation, and the onset of ground water seepage from the sandbar.

PREVIOUS INVESTIGATIONS

Past and present studies of sandbar morphology and sedimentology of the Colorado River can be divided into three periods. These are works published prior to the GCES, publications from GCES Phase I, and GCES Phase II investigations that are currently under way. A brief discussion of each follows.

The classic description of the geomorphology of the Grand Canyon was written by Leopold (1969). Early work on sandbar deposits consisted mainly of aerial and ground photography (Laursen and Silverston 1976; Turner and Karpiscak 1980) and topographic surveys of deposits begun in 1974 (Howard 1975; Beus et al. 1985; Ferrari 1987).

GCES Phase I studies included:

1. Collection and analysis of flow and sediment transport data at gaging stations (Graf 1986; Pemberton and Randle 1986).

2. Analysis of historical flow and sediment records, channel morphology, and their relationship to Colorado River dynamics at gaging stations (Burkham 1986).

3. Mapping of channel-bed materials (Wilson 1986).

4. Development and application of a sediment-transport model in the main channel (Orvis and Randle 1986; Pemberton and Randle 1986).

5. Evaluation of sediment contributions from ungaged tributaries by debris flows (Webb and others 1987).

6. Classification and description of alluvial sand deposits (Schmidt and Graf 1988).

The results of these studies are summarized in the GCES Final Report (USDI 1988).

Present research related to this investigation are being conducted as part of two of the ten major components of the GCES Phase II studies (USDI 1990). The first, sediment transport and beach (sandbar) studies, has four sub-components:

1. Paleoflood studies.

2. Beach evolution studies which include sand inventory, depositional history of the sediment deposits, eddy dynamics, slope stability, and debris flow effects.

3. Sediment transport studies which include flow model development, solute transport models, debris flow models, and eolian inputs.

4. Beach and sediment deposit characteristics which include historical data assessment, empirical studies, and modeling studies.

The second major component of the Phase II studies is the hydrology study which includes two sub-components:

1. Gaging of streamflow levels which includes mainstream and tributaries.

2. Evaluation of Glen Canyon Dam releases which includes historic review of Glen Canyon Dam releases and review of GCES research flows.

PHYSICAL SETTING

Study Site Selection

The sandbar at River Mile 43.1L was selected as the site for the study. The name 43.1L indicates that the sandbar is located 43.1 river miles (69.3 kilometers [km]) downstream from Lees Ferry and on the left bank of the river. Lees Ferry is 24.9 km downstream from Glen Canyon Dam. Thus the study site is 94.2 km below the dam (Figure 1). This sandbar was selected for study for the following reasons:

1. The sandbar had been selected by other investigators as one of three validation sites (sandbars at river mile -6.5R, 43.1L, and 172.3L) for GCES research. This selection was based on:

   a) geographic distribution within the reach of the Colorado River between Glen Canyon Dam and Lake Mead,

   b) sufficient sandbar size to sustain erosion and remain as a sandbar for the duration of studies,

   c) not intensively used by park visitors. Expensive scientific equipment could be left unattended at the site without being subject to theft or vandalism, and

   d) geomorphic, sedimentary, and stratigraphic variation among study sites to allow investigation of processes at different types of sandbars.

2. Other research projects at the site would provide supplementary information, (e.g. topographic surveys, stratigraphy, and aerial photography). The other projects included:

   a) Long-term vegetative studies.

   b) Repeated aerial photography program.

   c) Photographic documentation of the sandbar over the last 10 years.

   d) Sandbar ground water study (USGS).

   e) Modeling of erosion from the face of the sandbar by ground water seepage (University of Arizona).

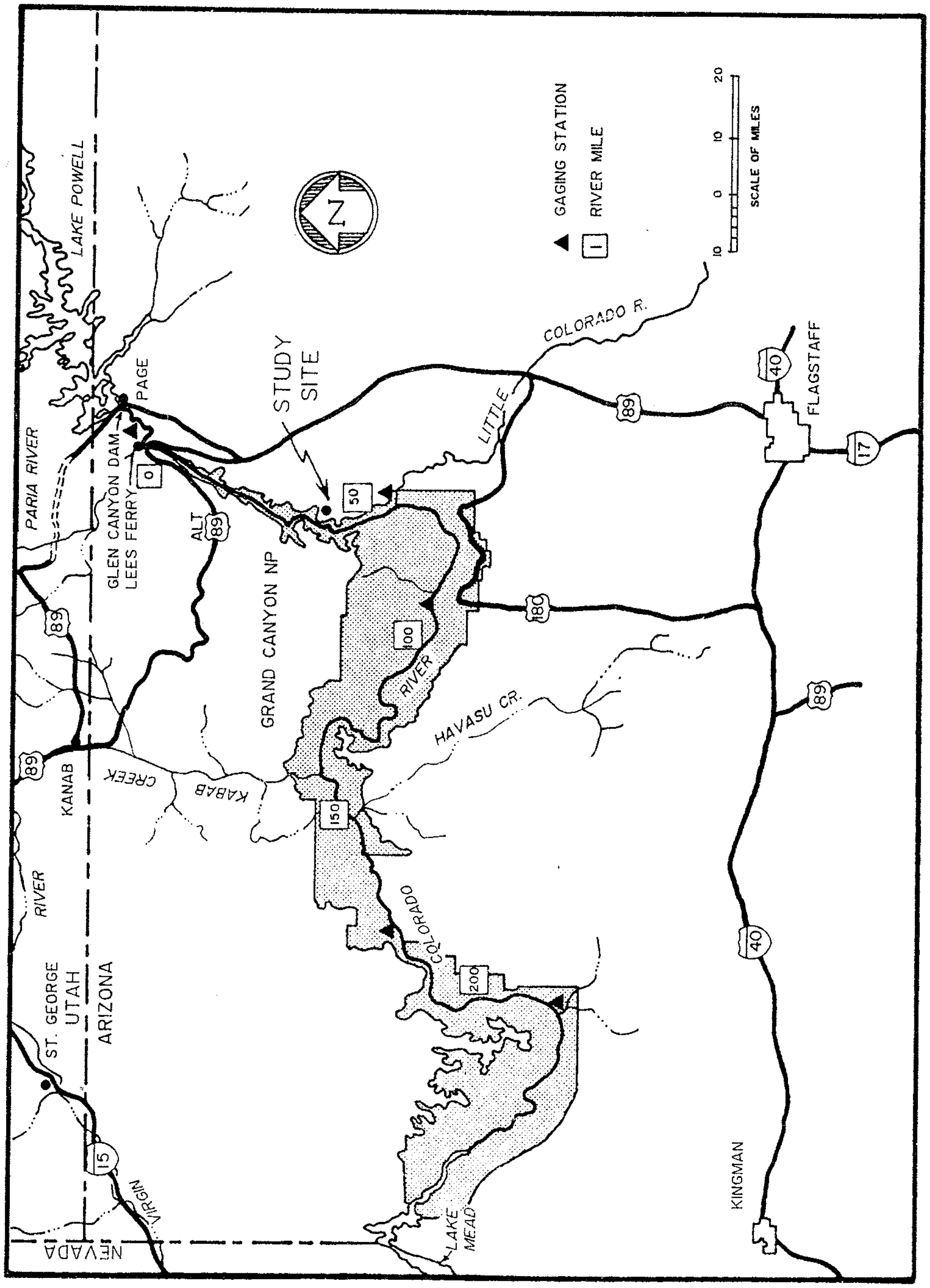


FIGURE 1. Location map.

f) Daily photographs of the site to document morphological changes (NPS-GRCA).

3. Features of Sandbar 43.1L favorable to this study were:

   a) The steepness of the face of the sandbar was deemed sufficient to study seepage effectively (i.e., very gently sloping sandbars would have large areas of saturated sands exposed at low river stage), making data collection physically difficult and reducing data accuracy.

   b) Studies by the USGS indicated that the sand deposits at the site were fairly homogeneous. This would reduce complications in analyzing processes of ground water response to fluctuating river stage.

   c) The sandbar at River Mile 43.1L is close to Glen Canyon Dam. Effects of river stage fluctuations would be more apparent here than further downstream where natural peak attenuation could reduce the range of fluctuations.

   d) Location upstream of the Little Colorado River. The sediment load in this reach is less than the load downstream of the Little Colorado River. Sandbars in this reach are expected to be more susceptible to depletion than bars further downstream due to the reduced sediment load of water released through Glen Canyon Dam.

Sandbar 43.1L Characteristics

The study area for this investigation was a sandbar located on the left side of the Colorado River at River Mile 43.1 in the Grand Canyon. The sandbar is roughly crescent shaped, approximately 120 m long by about 30 m wide, at its widest point (Figure 2). It is located just upstream from a moderate-sized rapid of the Colorado River. The rapid is at a river constriction resultant of a debris fan from a small, unnamed tributary. The debris fan contains sediments ranging in size from silts to boulders. The sandbar is composed of fairly uniform fine to medium sand and is classified as an upper pool deposit (Schmidt and Graf 1988). Sandbar 43.1L was enlarged during the high water period of 1983-84 and is largely covered by reworked sand from that flood.

At the study site, the Colorado River flows from west to east, and Sandbar 43.1L is located on the north side of the river. A return channel is present on the sandbar. It begins at the downstream end of the sandbar, adjacent to the debris flow located about 10 meters from shore, then it extends in an arc to the west, adjacent to the talus/bedrock of the canyon wall for the majority of the sandbar length, before joining the Colorado River at the west end of the sandbar. Return channel drainage

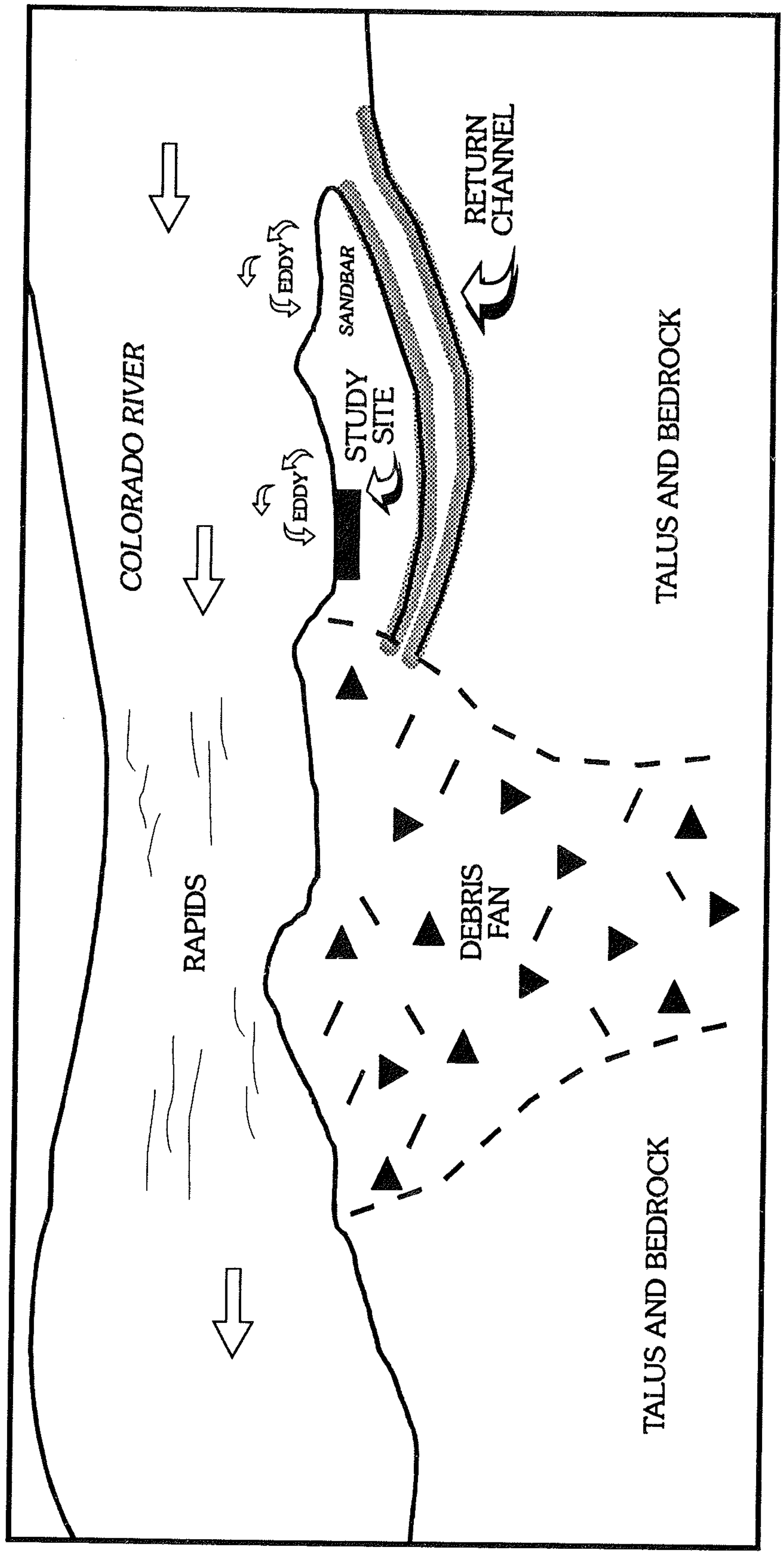


FIGURE 2. Major geomorphic features at Sandbar 43.1L and location of study site.

is east to west. This return channel contains water only during flood flows, thus a generic description of a reattachment bar is applicable (Schmidt and Graf 1988). However, the sandbar is an upper pool deposit with a weak recirculation eddy under normal flow operations.

The main current of the Colorado River as determined by surface flow directions is separated from the sandbar face by two eddies. Each eddy is adjacent to the sandbar and is elongated, parallel to the shore. One eddy is offshore for approximately the downstream half of the sandbar, and the other eddy is correspondingly present for the upstream half. The eddies were present at all observed river stages, and both have counterclockwise circulation directions. Upstream flow currents adjacent to the shore ranged from near zero to about 0.6 meters per second (m/s). Eddy circulation extends to about 10 m from shore. At the contact point between the two eddy cells, the sandbar is more gently sloped and projects into the river about 2 - 3 m. In August 1991, the eddy shapes were observed at low and high river stages. There was no longitudinal shift from low to high flow, only lateral compression or expansion of the eddies. Because they move little, the point in the center of the bar is coincident with the stagnation point between the two eddies. (B. Cluer 1991, personal communication). A panoramic view of the study site is shown in Photo 1.

METHODS

The investigation was conducted during two study periods, April 3 - 9 and August 8 - 26, 1991, to allow investigation during different Glen Canyon Dam flow release regimes. Flow regimes for the two study periods had different ramping rates, ranges, and mean daily discharges. The relative location of monitoring wells and transects for the two study periods are shown in Figure 3.

A study site was identified in the zone of active erosions on the face of the sandbar during each study period. Study plots, each containing several transects were established within the site. The study sites and a buffer area around the sites were marked with flagging to prevent people from accidentally walking through the sites.

Transects were established by driving lengths of rebar into the sandbar at a predetermined distance apart, 4.5 m (14.8 feet [ft]). This distance corresponded to that required to support the Surface Profile Gage. The gage was designed and constructed to allow accurate measurement of erosion or deposition of the site without trampling or other anthropogenic disturbance of the transect (Photos 2 and 3). A description of the Surface Profile Gage is included as Appendix 2. The rebar remained in place throughout the study period, serving to both support the Surface Profile Gage and to insure that repeated measurements were taken exactly along the same line. The Surface Profile Gage was positioned on the rebar, and 58 vertical

PHOTO 1. Panoramic view of Sandbar 43.1L, looking south. River flow is from right to left.

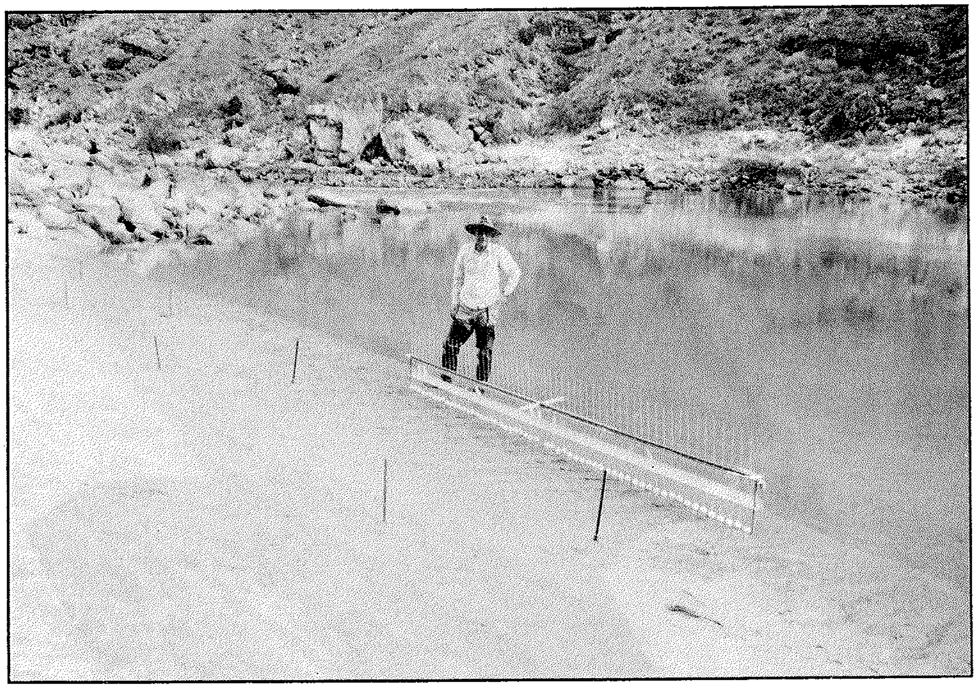


PHOTO 2. Employment of the Surface Profile Gage in April 1991.

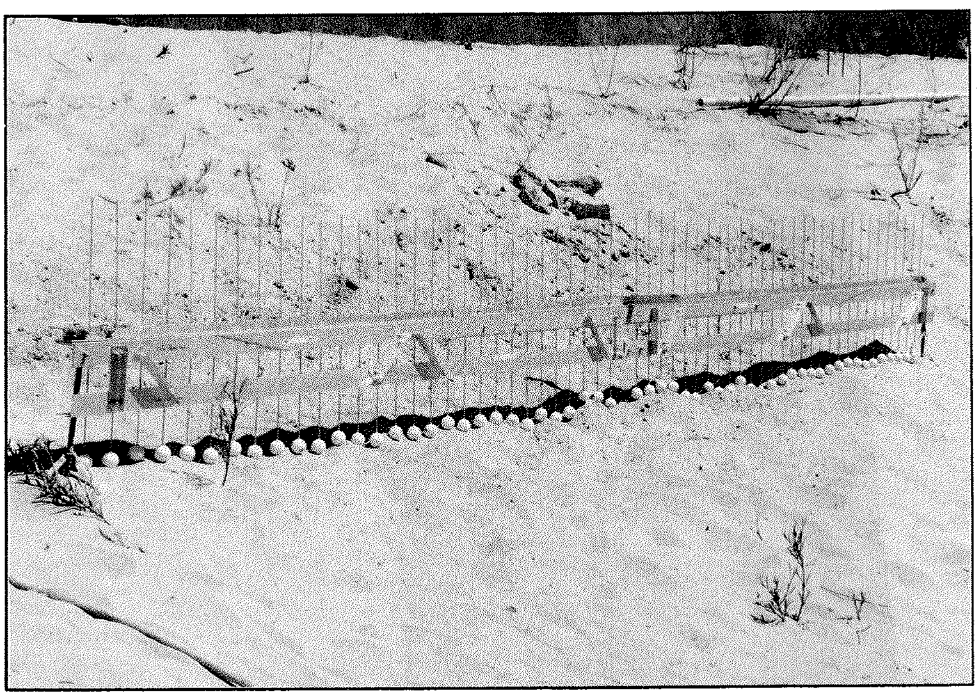


PHOTO 3. Demonstration of the capability of the Surface Profile Gage.

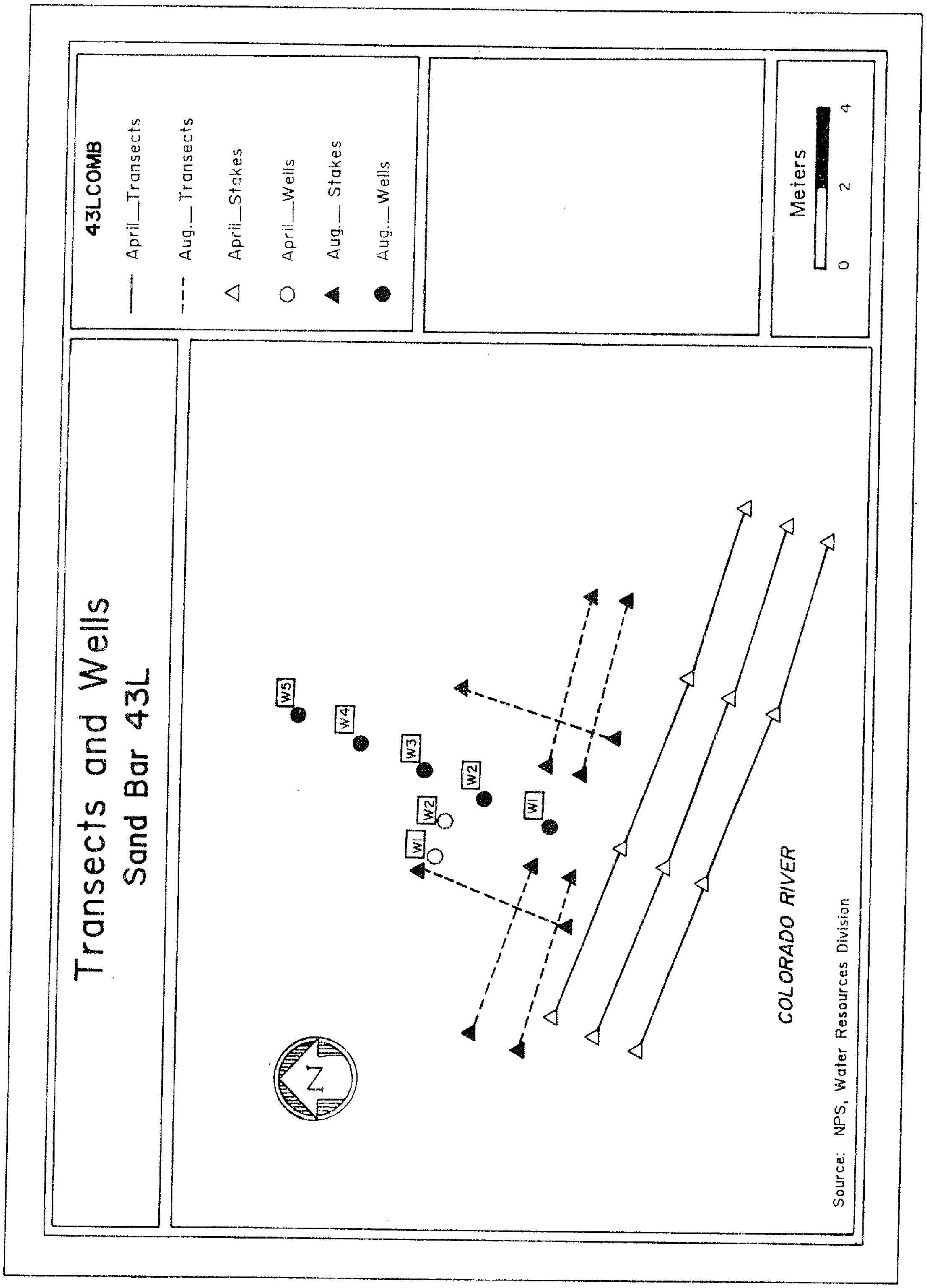


FIGURE 3. Relative locations of monitoring wells and transects for the two study periods.

measuring rods with ping-pong balls attached to the lower end, were allowed to drop to the ground surface. The ping-pong balls prevented the rods from penetrating the sand surface. The vertical rods were clamped in position and the gage was removed to measure and record the extended distance of each rod. The mean rod length for each transect was computed to indicate mean values of erosion or deposition over the entire length of the transect. Mean elevations were computed using values for balls numbering 6 - 54, from the center part of each transect. Balls numbering 1 - 5 and 55 - 59, located at each end of the transect, were not used in computing means in order to omit data which might have been subject to footprint disturbance near the edges of the transect (i.e., to insure that only data from undisturbed areas were used in computing mean elevations). Repeated measurements allowed determination of ground surface elevation changes. Measurements were converted to elevations relative to an arbitrary local datum.

Transect measurements were made daily following the decline of the river stage. However, measurements were not made on every transect on every day of the study. At times, some transects were still submerged during the lowest river stage, thus preventing access to the ground surface. On other days, river fluctuation did not submerge some transects and no erosion processes (i.e., formation of a seepage face or rilling) were visibly observed. If minor erosion had occurred on days of no measurement, it would be reflected in the measurement of the following day.

Shallow monitoring wells were installed in the sandbar in the vicinity of the study plots to monitor water level response to fluctuating river stage. Water levels were monitored with pressure transducers and recorded at ten minute intervals with a digital recorder. River stage was monitored using a pressure transducer attached to a rock and lowered to the bed of the river in the vicinity of the study site.

The elevation of the top of the plot transect stakes (rebar) was surveyed three times during the April study period, and five times during the August study period. The surveys were made to determine if any stake elevation changes were occurring. Systematic and obvious survey errors were corrected. Elevations of the stakes from each survey were plotted and no upward or downward trends were detected. Relative surveyed elevations of the stakes varied as little as ± 1.0 mm and as much as ± 3.0 mm. It is the authors' opinion that this variability is a result of measurement errors and limitations of the surveying equipment. Visual field observations had indicated the rebar stakes were stationary during study periods. Our analysis of survey data also indicates no rebar elevation changes for the short study duration. Topographic surveys of the entire sandbar were made by other investigators as part of the GCES studies. Those surveys provided data for mapping contours and geomorphic features.

Methods and Analyses for Determining Rebar Elevations

Because changes in the beach face measured by the Soil Profile Gage were quite small during the relatively short study periods, and because all Soil Profile Gage measurements are relative to the rebar stakes set during each study period, it was necessary to determine what changes in rebar elevation were occurring. Therefore, during the study periods all stakes were surveyed for elevation relative to a benchmark established by GCES for topographic surveys. Three surveys were conducted during the April study period and five were conducted during the August study period. Surveying instruments used were a Lietz SDR 3A Electronic Total Station with an accuracy of 15 seconds of arc, and a Topcon At-F2 Automatic Level with an accuracy of 0.3 seconds of vertical arc. Using the longest typical shot of 29 m and the vertical arc of the least accurate instrument (15 seconds), the largest vertical error was computed as 0.002 m.

The following analysis was conducted for the August study period. Initial plots of the surveyed elevations of all 12 stakes showed unexpected variation. Under ideal conditions, it was hoped that the surveys would reveal a set of surveyed elevations (for each of the 12 stakes) that would deviate from the initial surveyed elevation for each stake by no more than the accuracy of the surveying equipment ($\pm$0.002 m). This analysis would effectively guarantee that the rebar stakes had remained stable/stationary during the study period. However, the surveyed elevations for individual stakes were not consistent and, in fact, elevations varied by as much as .06 m.

In further analysis, we disregarded five deviant measurements taken on August 15th, 20th, and 26th (i.e., attributed to human error), and saw that the remaining surveyed elevations vary in a set pattern with time (Figure 4). This is definitely not the random or haphazard distribution one would expect to observe if random settling or rising of individual stakes had occurred (or with indiscriminate human surveying errors). It is also not a consistent increase or decrease in elevation that one could easily attribute to the continual rising or settling of individual stakes over time. Instead, it is apparent that "systematic patterned" errors are somehow incorporated into the elevation measurements. These patterned deviations are consistent with surveying errors that can credibly be attributed to, or explained by, imperfections or biases generated in the establishment of the baseline elevation for each individual survey. These baseline elevation errors are suspected to be associated with the initial height or instrument determination for the individual surveys conducted by different crews using different instrumentation.

In order to remove this bias or systematic error from the data set, we selected one date, August 9, 1991, as a frame of reference, and "normalized" all other elevation measurements relative to this survey. In doing so, we obtained a data set of relative relationships between stakes, allowing analysis of movement of individual stakes in

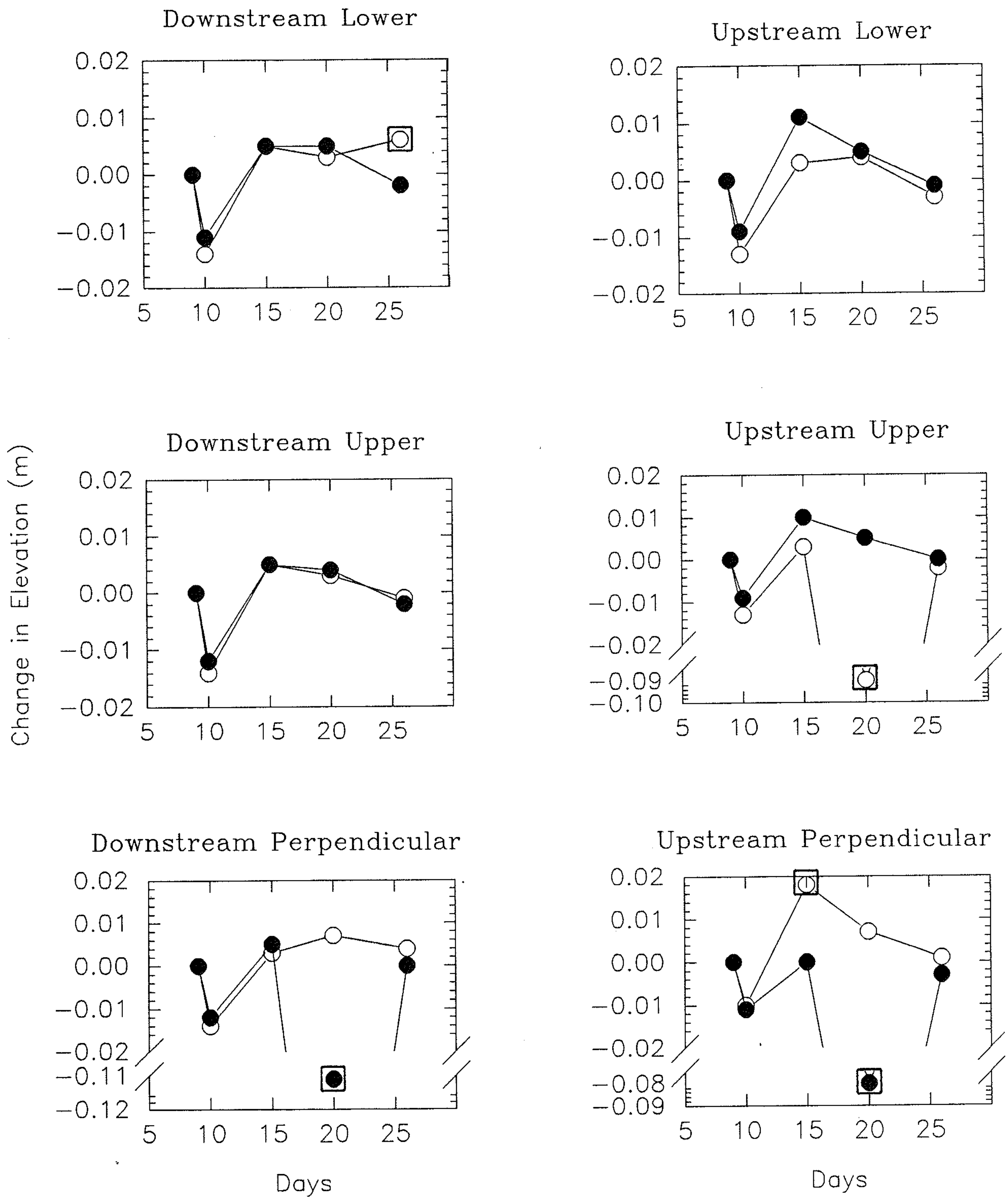


FIGURE 4. Rebar stake elevations, August study period. Boxes indicate data discarded from analysis as attributed to human error. Changes in rebar elevation are determined by comparing subsequent surveyed elevations to the original survey elevation. "Low" indicates transects of lowest elevation. Refer to Figure 11 for transect configuration.

relationship of one to another. The largest range of deviation of any one stake is 0.004 m, and average change is 0.001 m. Therefore, we feel confident in concluding that the 12 rebar stakes provided a stable/stationary platform for taking Soil Profile Gage measurements for the duration of the study period. And as a result, we are now reasonably confident that our measurements reflect actual sandbar elevation changes and not a shifting of the rebar.

A review of the April survey data was made. Using all data from the three surveys, the maximum variance in elevation was only 0.004 m (Figure 5).

As a final consideration, the results of the study provide an inference to stake stability. The Soil Profile Gage operation provides the distance to the ground surface from the top of the Soil Profile Gage. Thus, a case of uniformly sinking stakes would lead to the appearance of sandbar aggradation if no corrections were applied. Likewise, if stakes by some means were lifted or forced upward from the sandbar, erosion would be indicated. The fact that Soil Profile Gage measurements indicated erosion in April and aggradation in August (any physical conditions on the sandbar, inducing stake elevation changes, would be expected to be the same during each study) further supports our premise of stable stake elevations.

APRIL STUDY PERIOD

Design and Instrumentation

The April study period consisted of 7 days (April 3 - 9, 1991). Study plots were located on the face of the sandbar, within the area affected by stage fluctuations of the Colorado River. Three study plots with three transects each (for a total of nine transects) were located in the zone of active erosion as indicated by the presence of rills. The transects were located parallel to the river's edge with a low, middle and high transect spaced about 1.2 m apart (Figure 6). The low transects were located about 0.3 m from the river's edge at lowest stage (90 m^3/s) and the high transects were approximately midway between the daily high stage (approximately 425 m^3/s) and the lowest stage. Plot 1 was in a downstream position and Plot 3 was upstream relative to the other plots. The three study plots were adjacent to one another, the upstream end of Plot 1 coincided with the downstream end of Plot 2, and the upstream end of Plot 2 coincided with the downstream end of Plot 3.

A demonstration to evaluate ground water flow near the face of the sandbar entailed placing drains in the zone of fluctuations to promote faster drainage of ground water from within a plot. The demonstration consisted of different treatments on each of three study plots: 1) a control area with no disturbance (Plot 1);
2) horizontal placement of blank (non-perforated) pipe to provide an assessment of

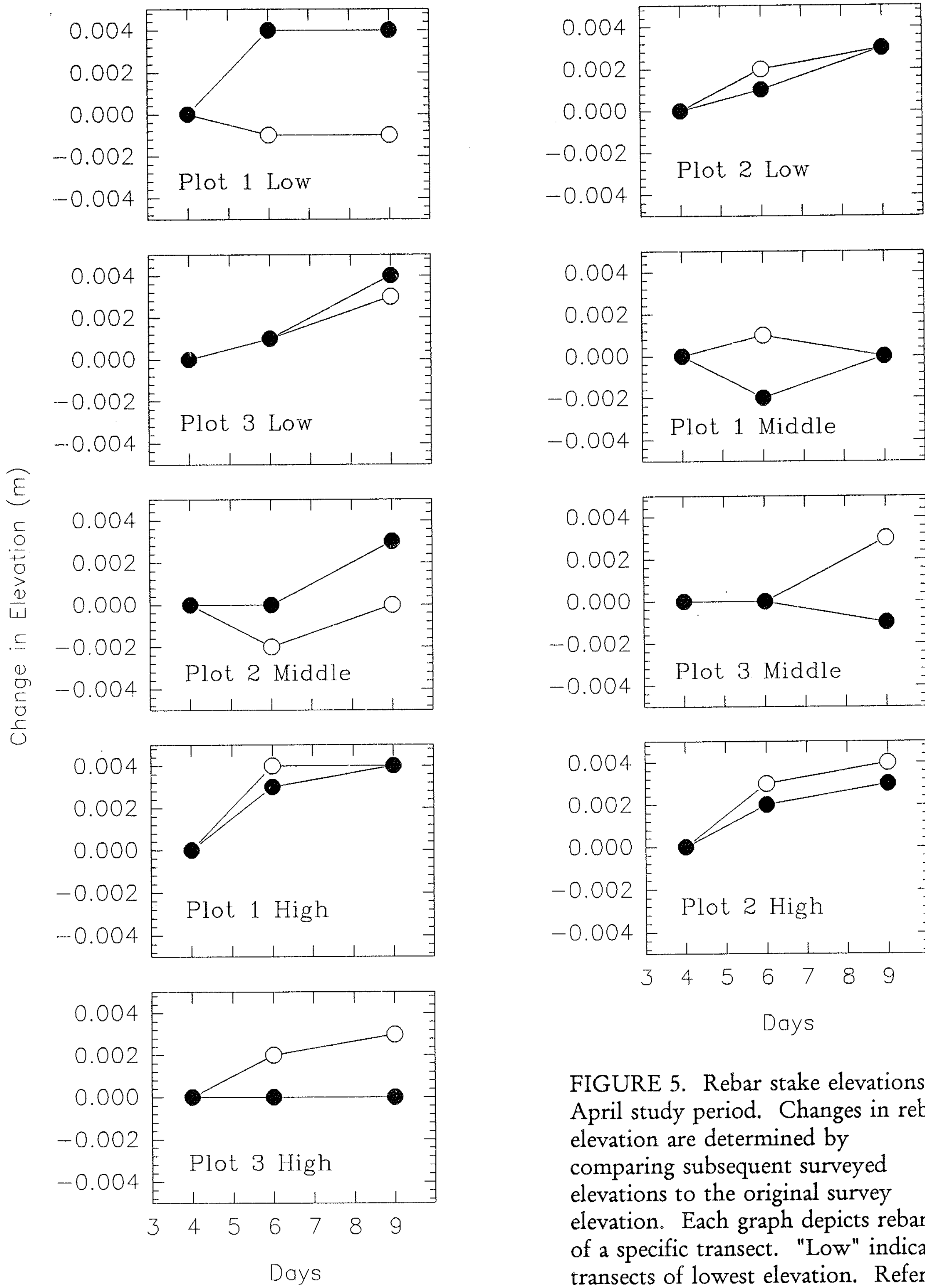


FIGURE 5. Rebar stake elevations, April study period. Changes in rebar elevation are determined by comparing subsequent surveyed elevations to the original survey elevation. Each graph depicts rebars of a specific transect. "Low" indicates transects of lowest elevation. Refer to Figure 6 for transect configuration.

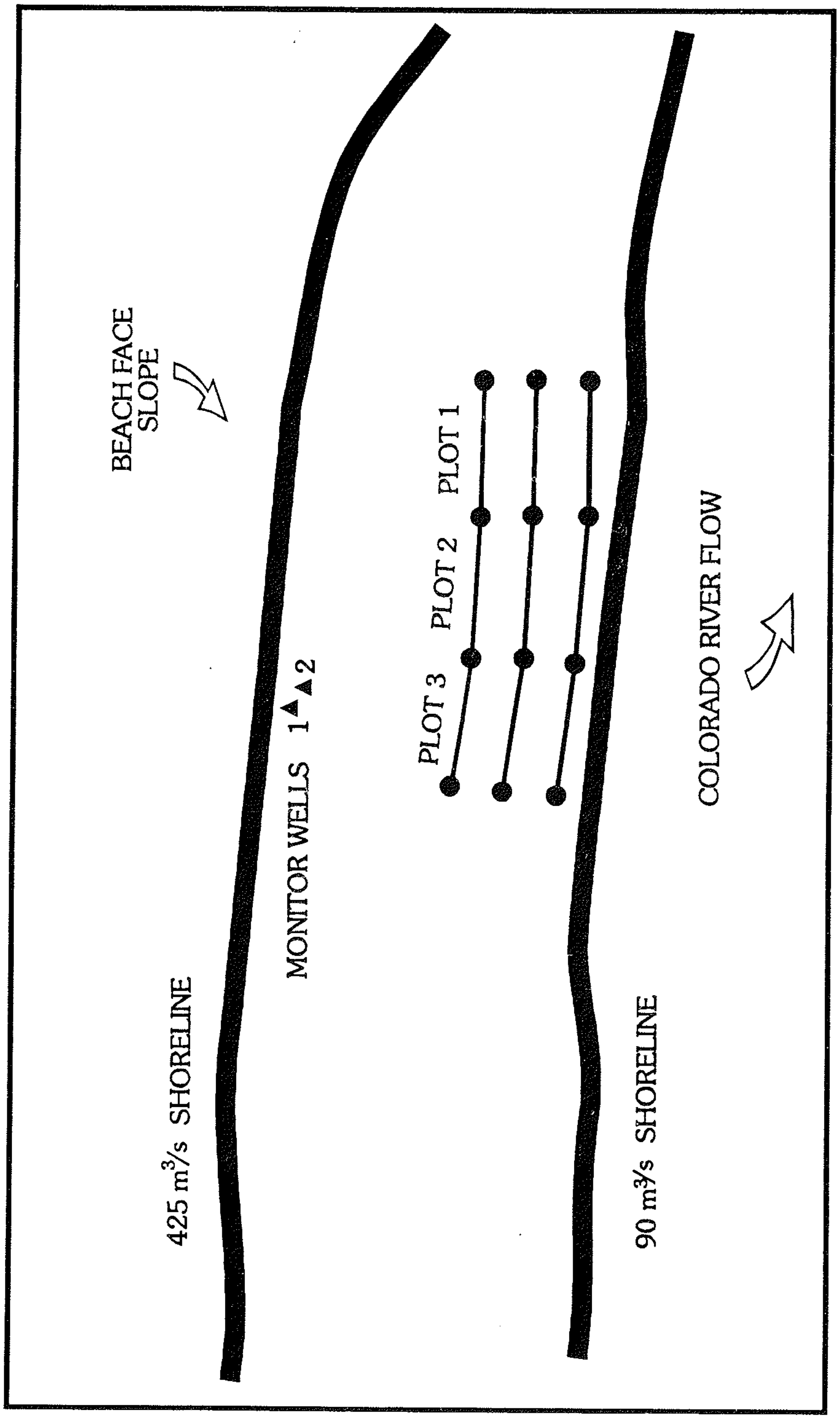


FIGURE 6. Layout of study plots, April 1991.

disturbance associated with installation (Plot 2); and 3) placement of perforated horizontal drain pipe (Plot 3). The perforated drain treatment was designed to induce faster ground water drainage near the face of the sandbar and thus prevent erosion.

Two shallow wells were constructed to monitor the water table in the sandbar. The monitoring wells were located about 0.3 m above the daily high water mark and up slope from the study plots. The monitoring wells were made of PVC pipe. Well 1 was 5 centimeters (cm) (2 inches [in]) in diameter and about 1.5 m deep. Well 2 was 2.5 cm (1 in) in diameter and about 3 m deep. Different construction techniques were used for installing the monitoring wells: the shallower monitoring well was installed by auguring to the water table and then driving in the casing; the deeper monitoring well was jetted while driving the case. Water level response in the two wells indicate that construction techniques did not affect the response of well water levels in the monitoring wells to water table fluctuations. Water levels in both monitoring wells were monitored using pressure transducers and digital recorders.

Colorado River Flow Characteristics

During this study period the operation of Glen Canyon Dam and thus, the flow release pattern was a continuation of normal dam operations (i.e., operation to generate peak electrical power within the constraints of legal mandates). Dam release discharges ranged from 90 to 445 m^3/s. River stage varied approximately 1.9 m from low to high stage.

Data Analysis

River stage and water table fluctuations with associated lag times and daily differences of fluctuation for the study period are shown in Figure 7. Well 1 was shallow and went dry each day at low river stage. Only data from Well 2 are shown on Figure 7. Minimum river stage ranged from about 96.3 to 96.45 m during the study, corresponding to minimum flow releases from the dam of 90 to 120 m^3/s. Maximum river stage varied by more than a meter, from 97.0 to 98.2 m, in response to differences in the maximum discharge from the dam and the length of time that the maximum discharge was maintained. Large discharges for a short duration are attenuated downstream to produce a maximum stage less than a smaller discharge of greater duration. For example, release of 450 m^3/s from the dam for a short duration on April 9th produced a lower (0.2 m) stage at the study site than did discharge of 430 m^3/s for a longer duration on April 5th. The longer peak duration of April 5th caused a water table height closer to peak river stage than short duration peaks of April 7th and 9th. The longer duration of elevated river flows allows increased time for ground water movement into the sandbar and a corresponding increase in well water levels.

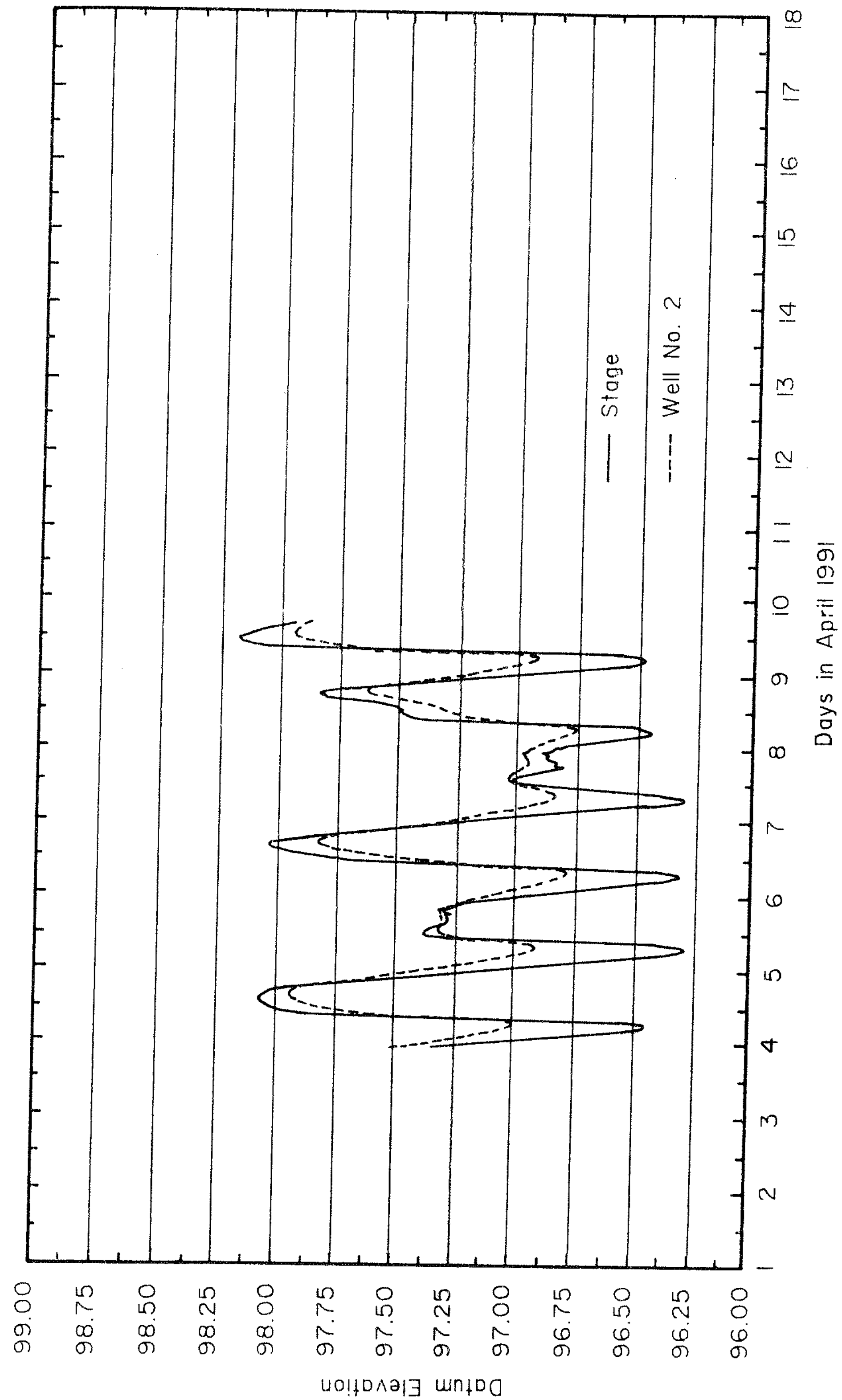


FIGURE 7. April hydrographs - River stage and monitoring Well No. 2.

Figure 8 shows the daily mean elevation changes at Plot 1. Both the high and low transects show very little change (less than 3 mm) during the study period. The mean elevation of the middle transect decreased approximately 12 mm during the study period. The greatest losses occurred following the largest stage fluctuations early in the study period. Lower peak flows on April 6th and 8th allowed drainage of ground water from the sandbar for longer time periods. This resulted in lowering the water table in the sandbar, leading to lesser amounts of erosion for April 9th and 10th, even after larger stage fluctuations resumed.

Mean elevation changes for the transects in Plot 2 are shown in Figure 9. The high transect had less than 1 mm elevation change during the study period. The middle transect in Plot 2 showed a gradual decrease in mean elevation of 9 mm from April 3rd to April 6th. The low transect had less than 1 mm elevation change through April 6th. Immediately after the April 6th measurements, blank PVC pipe was buried in the study plot to simulate the disturbance caused by placing horizontal drains in Plot 3 (see next section). Following installation of the blank pipe, the mean elevation of the transect increased slightly due to the disturbance of excavating through the transect. Wave-induced erosion near the end of these blank pipes caused a decrease in the mean elevation of the low transect on April 7th and 9th. The study period did not continue long enough following installation of the blank PVC pipe for measurable elevation changes to occur. Rills were observed to reform in the sand overlying the blank pipe following river stage fluctuations during the remainder of the study period.

Mean elevation changes for the transects in Plot 3 are shown in Figure 10. The high transect had less than 1 mm elevation change prior to installation of the horizontal drains on April 6th. Mean elevation of this transect was higher (9 mm) on April 7th and 9th. Nearby foot traffic and/or soil creep may have disturbed this transect during this time period. The middle and low transects showed a gradual elevation decrease of about 6 mm from the start of the study on April 3rd until the horizontal drains were installed on April 6th. Following installation of the drains, the middle transect showed a slight elevation increase on April 7th and 9th due to disturbance from excavation for drain installation. The mean elevation of the low transect decreased due to erosion caused by water flowing from the horizontal drains. The study period did not continue long enough following installation of the drains to determine if the horizontal drains would prevent erosion from taking place. Rills were not observed to reform over the horizontal drains during the remainder of the study period.

The amount of erosion at each transect was partially determined by the relative position of the transect on the sandbar. For example, those transects that were located higher up on the sandbar were only marginally within the active erosion for several days during the study, and totally above the zone of fluctuation for several other days. Measurable erosion did not occur on these transects on those days

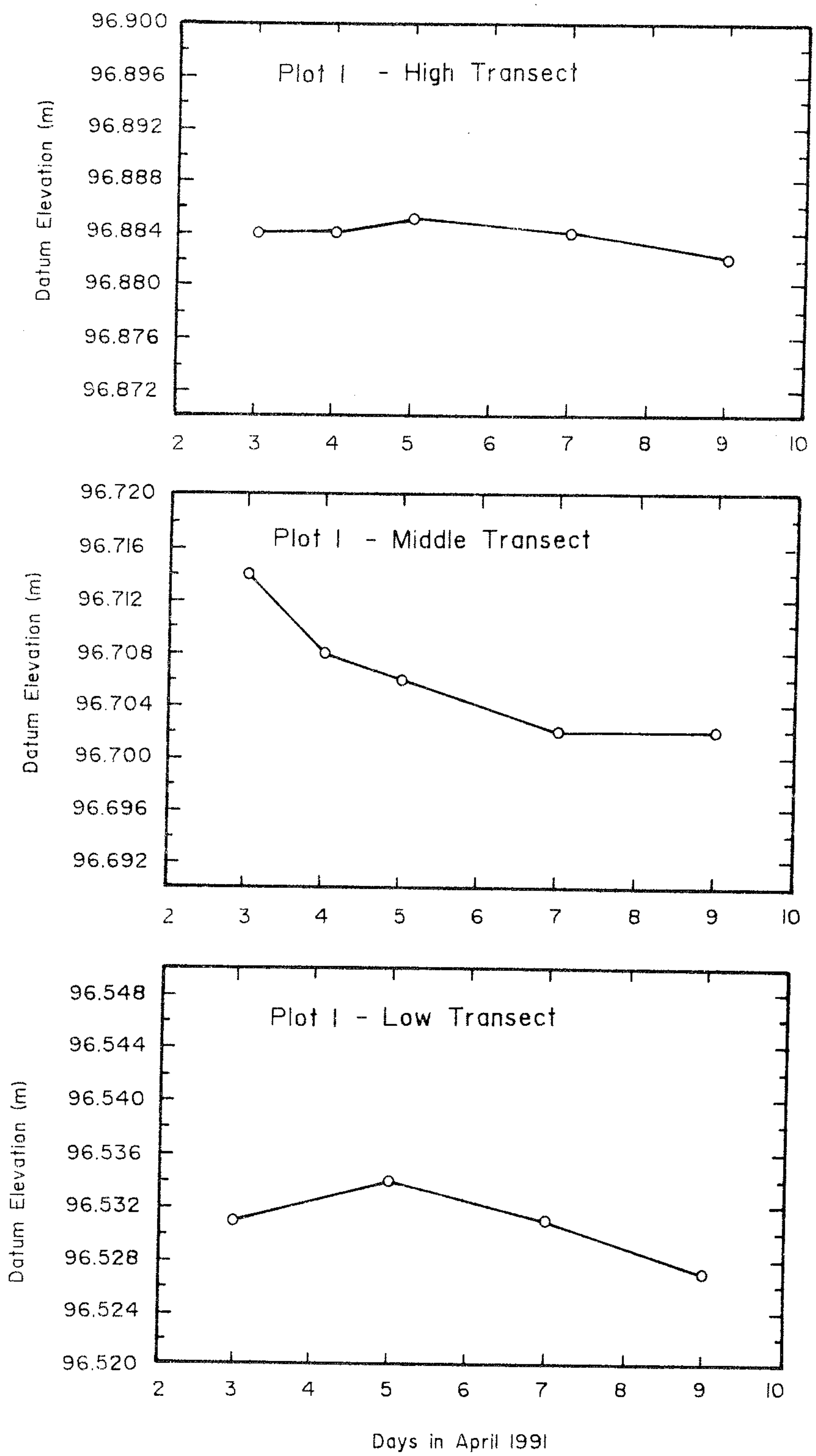


FIGURE 8. Mean elevation of transects in Plot 1, April 1991.

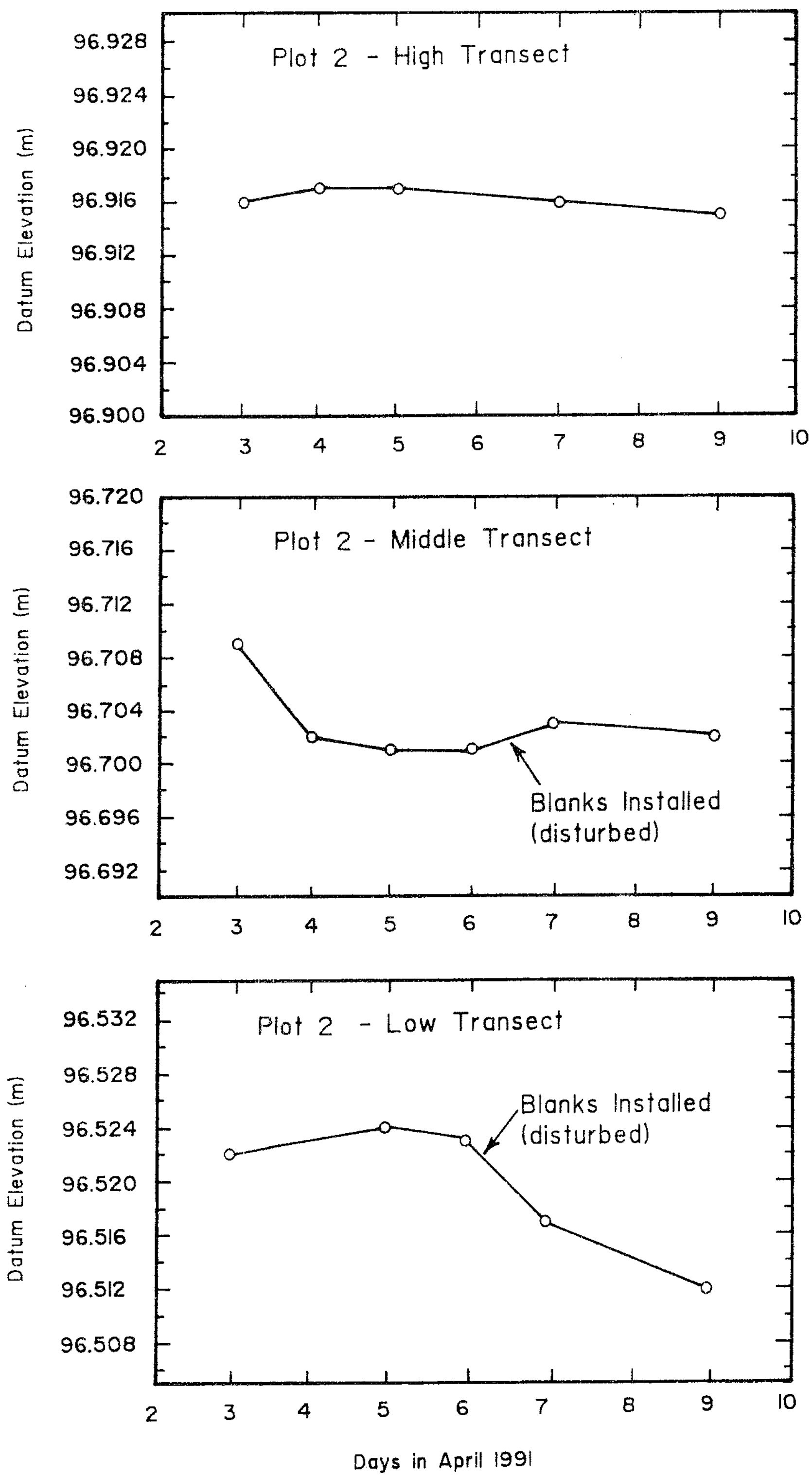


FIGURE 9. Mean elevation of transects in Plot 2, April 1991.

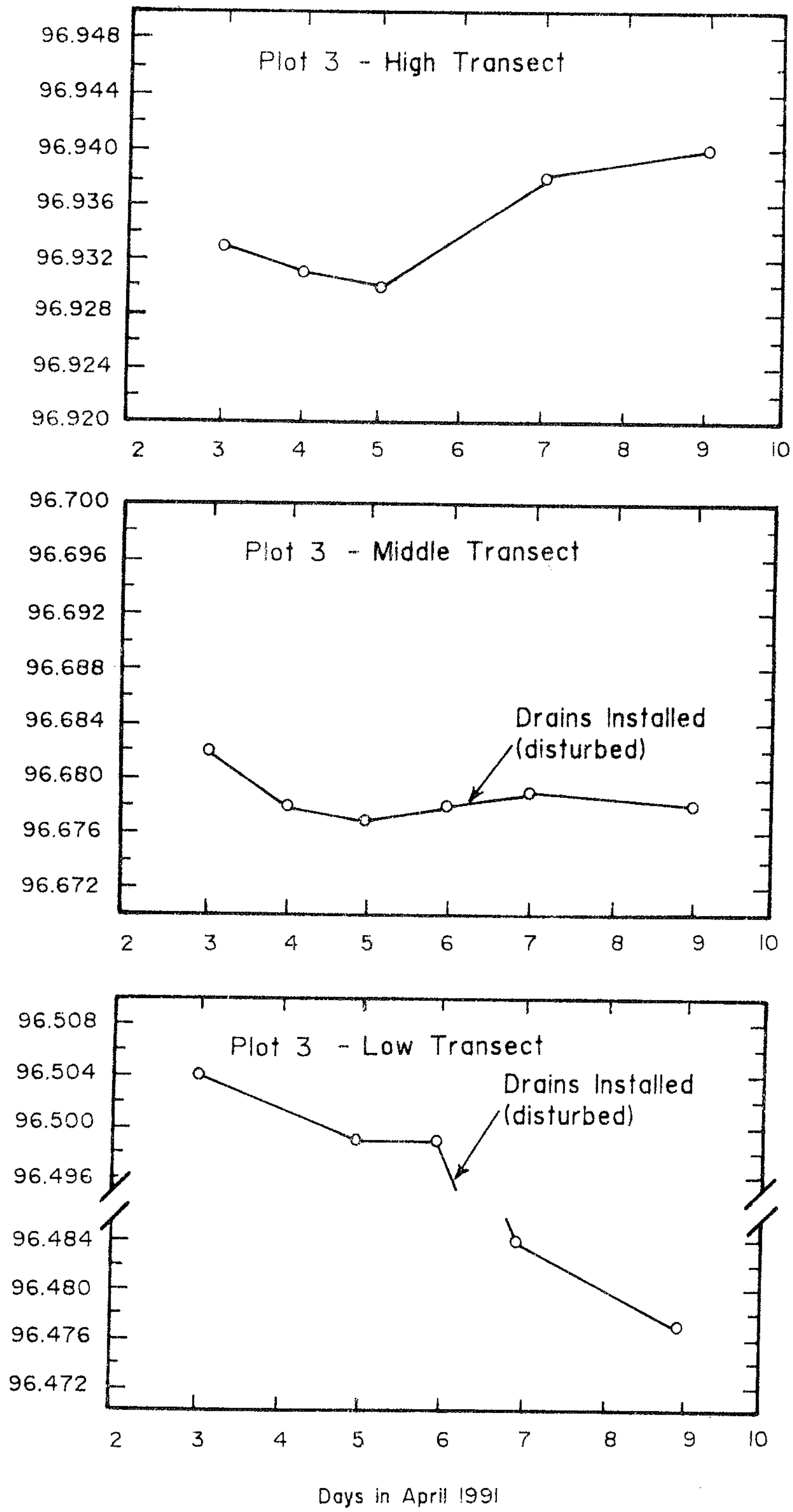


FIGURE 10. Mean elevation of transects in Plot 3, April 1991.

having small river stage fluctuations because there was no opportunity for a seepage face to develop. Transects located lowest on the sandbar, near the river's edge at low stage, showed either no change or a slight increase in elevation either from sand grains eroding down the face of the sandbar and being deposited near these transects, or from sediment deposition by near-shore eddy action at high river stage. Transects located midway in the zone of active erosion showed the most erosion. These transects were within the zone of active erosion during most days of the study and were exposed to active rills for longer periods each day than the other transects. Seepage faces developed at these locations every day in response to the rapid fall of the river stage.

Horizontal Drains

As a demonstration of the relationship between ground water stored in the sandbar and the development of a seepage face, horizontal drains were installed in one of the study plots (Plot 3), late on April 6th. The drains were installed to induce faster ground water drainage from a section of the sandbar during the falling limb of the river fluctuation. Lengths of blank (non-perforated) PVC pipe were placed in an adjacent study plot (Plot 2) as a control to observe the impacts resulting from the excavation for the placement of the drains. The third study plot (Plot 1) was used as an experimental control to monitor erosion on an undisturbed plot during the 7-day (April 3 - 9) study period. Plot 2 impacts were limited to the excavation and burying of the pipe. Plot 3 impacts included the installation of the drains for the drainage of the sandbar. Details of the design and installation of this demonstration include the following:

1. The pipes/drains measured approximately 1.8 m (6.6 ft) in length.

2. The drains installed were factory slotted with 0.020 inch cuts.

3. The buried end of the pipes/drains were capped.

4. Pipes/drains were buried approximately 0.5 m deep.

5. Pipes/drains were spaced approximately 0.5 m apart

6. The pipes/drains extended from about the middle transect to the low transect in the 2 plots.

7. The drains were sloped toward the river to insure drainage.

8. Pipe/drain installation was performed by shovel trenching and burial.

The middle and low transect data for Plots 2 and 3 acquired after April 6th shows impacts of the excavation associated with this demonstration. On each subsequent day following installation, the slotted drains in Plot 3 were observed to flow at an estimated rate of 0.25 liters/second (l/s) per drain (Photo 4). These observations were only possible during the brief time of minimum river stage due to the position of the end of the drains. Sand overlying the drains was observed to be distinctly drier than corresponding areas of the other plots as shown in Photo 5. Rills did not form (i.e., no running water was seen) on the face of the sandbar overlying the drains. Also, ground elevation measurements indicate no elevation change during the remainder of the study at the middle transect. The low transect was affected by the presence of the drain openings and no conclusions are drawn from these data.

By contrast, Plot 2 which contained the blank PVC pipe exhibited rill formation by flowing water. Analysis of ground elevation data indicated subsequent erosion in the low transect. Although data analysis of the middle transect does not indicate subsequent erosion during the remaining 4 days of the study, it is believed that some erosion processes were on-going, due to the observance of rill formation.

Wind Blown Sand

Potential erosion effects caused by wind blown sand were investigated by establishing a study site with one transect on the western portion of the sandbar above the area normally affected by river stage fluctuations. This site was selected because:

1. it lacked nearby vegetation which might block wind effects,
2. it was out of the path of normal foot traffic and thus was not likely to be disturbed, and
3. the relatively flat topography would reduce the potential for slumping.

The site also was flagged to maintain its pristine integrity.

The transect was first measured on April 3rd. The ping-pong balls created a very faint depression in the sand which could be observed by looking at the transect with the sun in the background. This visual observation was made for the next 3 days and appeared unchanged. The following night winds were noted in the early morning hours. A visual check of the transect the following day showed that the ping-pong ball depressions were nearly obliterated. Measurements with the Surface Profile Gage on April 8th showed that elevations across the transect had not changed from the first measurements made on April 3rd.

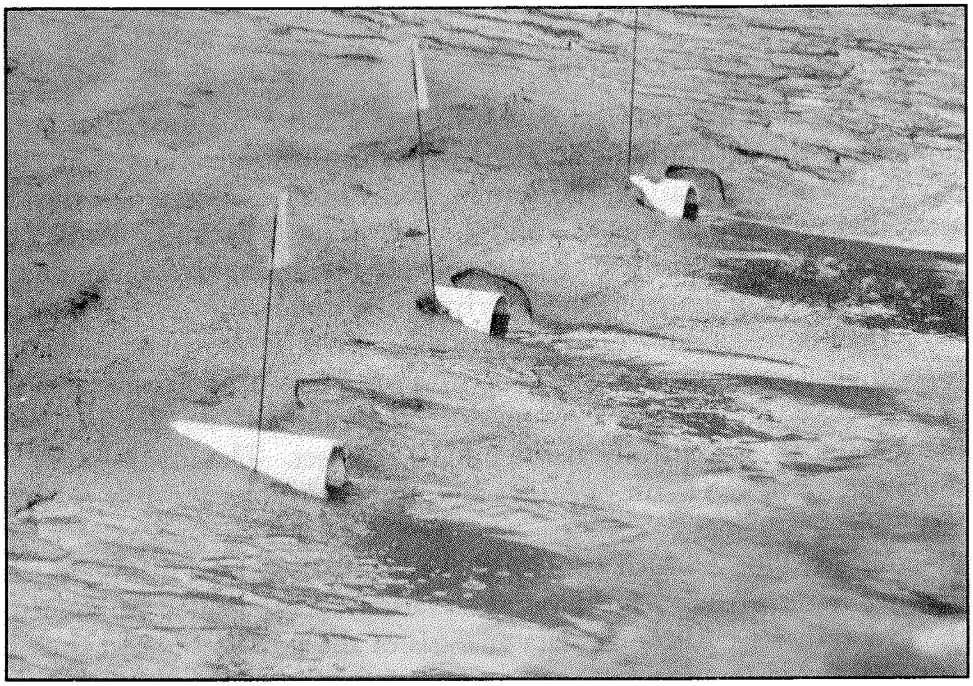


PHOTO 4. Downstream end of perforated lateral drains showing flow of intercepted ground water at low stage of the Colorado River.

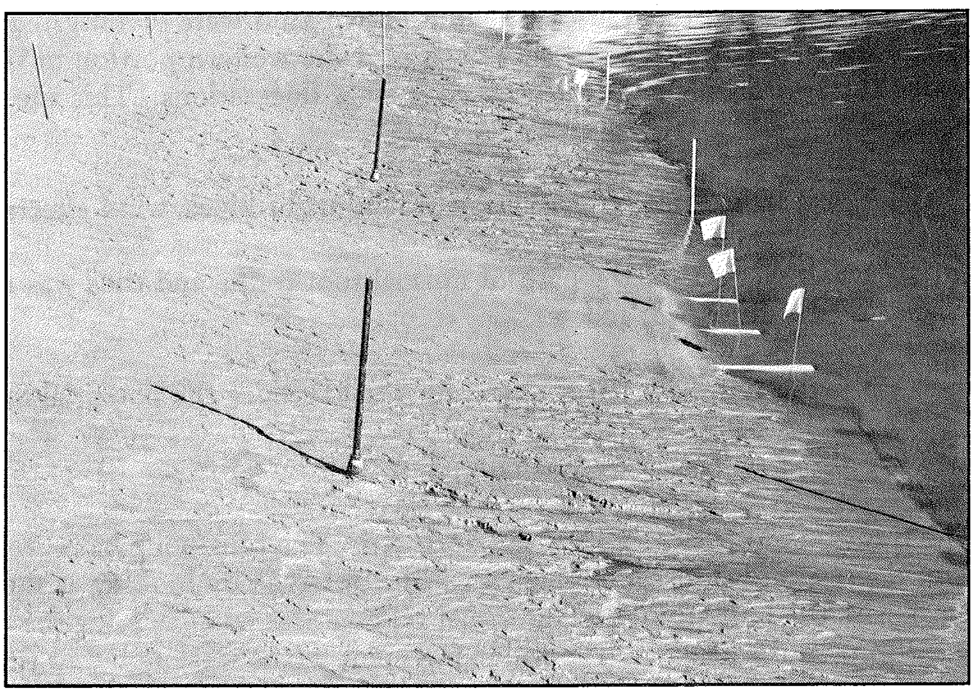


PHOTO 5. Plot 3 with perforated lateral drains as seen at the center of the photo. Note relatively dry sand without rivulets overlying the drains. Plot 2 with blank pipe is seen in the upper center of the photo. Wet sand and rivulets are seen overlying these pipes.

Photos of lateral drains taken April 7, 1991, approximately 24 hours after installation.

Video Documentation

A video recording camera was used to document physical processes on the face of the sandbar during the falling stage of river fluctuation. The video documents the processes of seepage, rill formation, and movement of sand grains. Record of the date and time of the video recording allowed comparison to river stage and water table elevations for the same time period. Factors affecting the erosion processes were thus identified.

Observations of numerous, small channels on the face of the sandbar seemed to remain intact from the previous day as the river stage first started to fall. As the river stage continued to fall, these small channels were seen to extend farther down the face of the sandbar under water. When the river stage fell to expose the channels, rills formed in the channels. As the river stage continued to fall, a seepage face developed and flow was observed to increase down the face of the sandbar. With substantial river stage decrease, the uppermost portion of the channels became dry. In subsequent days, the small channels were observed daily while still being under water. Their continued presence indicates that river currents were not a major erosion or deposition factor during the study. The elevation of the top of the small channels is believed to approximately coincide with the water table in the sandbar when the river is at low stage. A formal video tape presentation of this study, including field documentation of observed physical processes, will be released soon.

AUGUST STUDY PERIOD

Design and Instrumentation

The August study period consisted of 19 days (August 8 - 26, 1991). Ground elevations were measured daily for 8 days, from August 8th through August 15th. The sandbar was unoccupied for 4 days, and measurements were resumed on August 20th, and continued through August 26th (7 days). River stage and water table elevations were monitored continuously with digital recorders.

Two study plots, with three transects each, were located on the face of the sandbar, within the area affected by river stage fluctuations. The August study site was in approximately the same location as the April study site. The study plots were located in the zone of active erosion as indicated by the presence of rills. In each study plot, two transects were parallel to the river's edge with a lower and upper transect spaced approximately 1.2 m apart (Figure 11). The lower transects were located about 0.3 m from the rivers edge at lowest stage (280 m^3/s) and the upper transects were approximately midway between the daily high stage (approximately

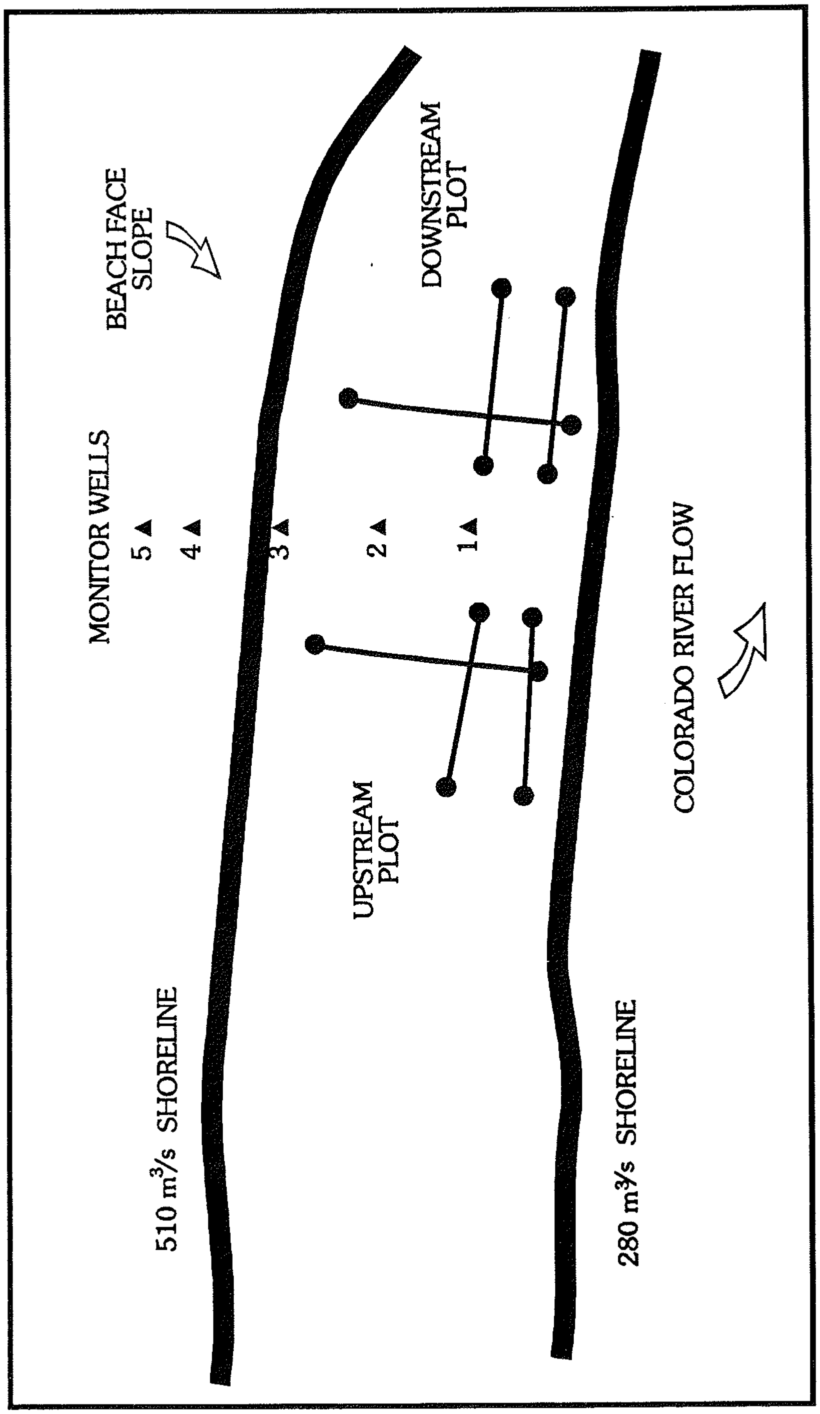


FIGURE 11. Layout of study plots, August 1991.

510 m^3/s) and the lowest stage. The third transect in each study plot was perpendicular to the river. The two study plots were identified as upstream and downstream, according to their position relative to river flow.

Five ground water monitoring wells were installed along a line perpendicular to the river, approximately 1.5 m apart. In comparison to the April study, the increased number of monitoring wells and their positioning at lower elevations were modifications made to enhance delineation of the water table in proximity to the transects. The wells were located between the study plots. The wells were installed by auguring to the water table and then jetting while driving a PVC casing, 5 cm (2 in) in diameter, to a depth of approximately 1.5 m below the water table. Slotted casing with a well point on the end provided hydraulic connection with the ground water in each monitoring well. Water levels in Wells 1 - 4 were monitored at 10 minute intervals using pressure transducers in combination with a digital recorder. Data for Well 5 was acquired by manual measurements using a chalked steel tape.

Colorado River Flow Characteristics

During the August study period, the flow of the Colorado River was regulated by Glen Canyon Dam releases in accordance with the restrictions of the *Interim Flows*, implemented on August 1, 1991 under the direction of the Secretary of Interior. River flow varied from about 280 m^3/s to about 510 m^3/s during this period. Colorado River stage was monitored by a pressure transducer in combination with the same digital recorder used for measuring water levels in the monitoring wells. River stage fluctuated about 1.2 m from low to high stage.

Data Analysis

River stage and water table fluctuations with associated lag times and daily differences in fluctuation for the study period are shown in Figure 12. Minimum river stage ranged from about 97.4 to 97.7 m during the study, corresponding to minimum flow releases from the dam of 290 to 305 m^3/s. Maximum river stage varied from about 98.6 to 98.9 m, corresponding to dam flow releases of 515 to 545 m^3/s. The exception to these ranges occurred during the night of August 18 - 19, 1991, in response to smaller dam flow releases during the preceding weekend; maximum stage and discharge were 98.2 m and 415 m^3/s, respectively. The pressure transducer used to monitor river stage showed some drift during this period, accounting for the apparent increasing trend of the river stage shown on Figure 10. Land surface measurements were made across the transects at each of the plots using the Surface Profile Gage following the daily fall of the river stage. The same methodology was used as during the April study period.

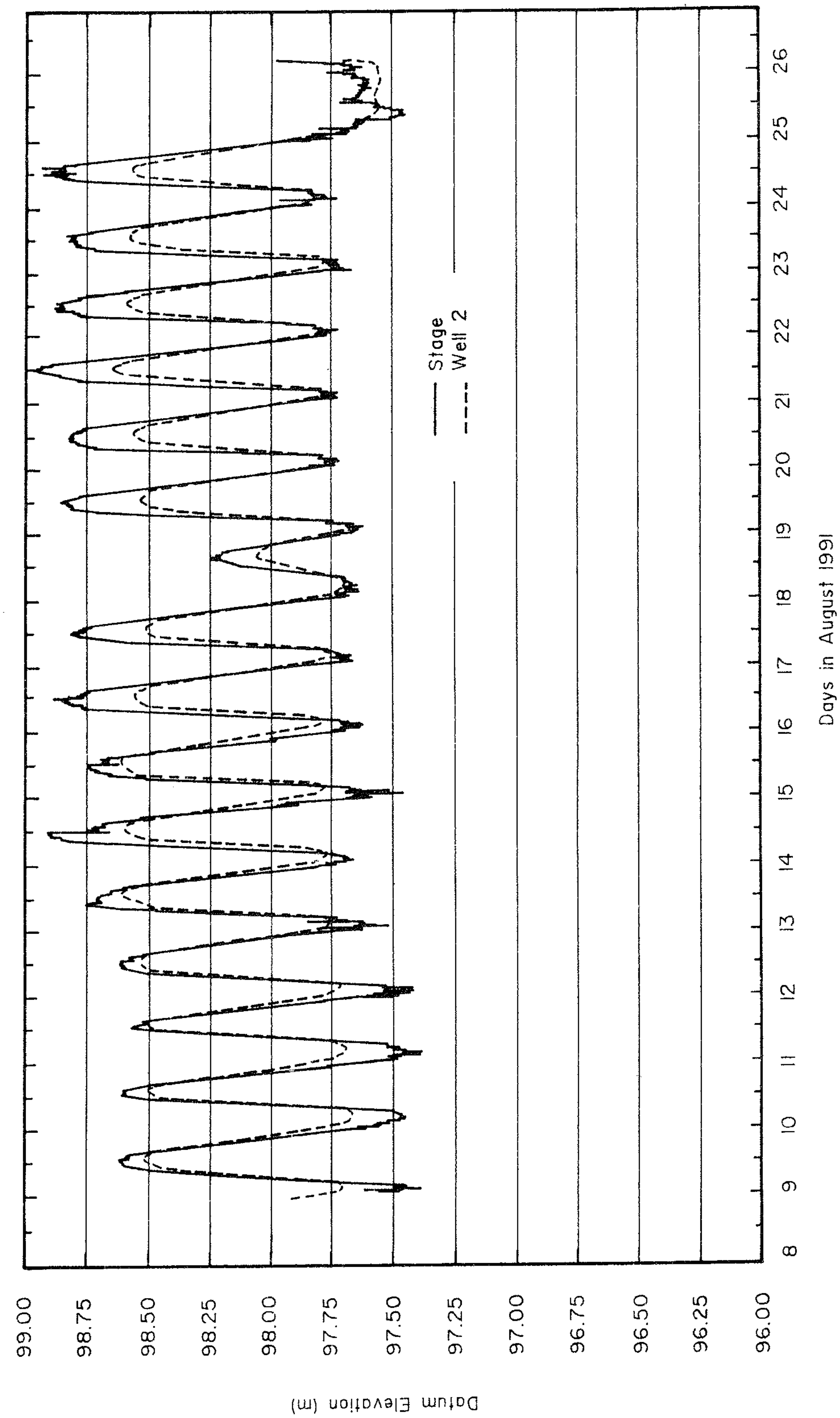


FIGURE 12. August hydrographs - river stage and monitoring wells.

Figures 13, 14, and 15 show the mean elevation changes for each of the transects during this study period. All of the transects had a net gain in mean elevation. Mean elevation gain ranged from 4 - 9 mm/transect. Individual ball elevations varied. Both increases and decreases occurred in response to variations in the amount of erosion and deposition occurring on a daily basis and with the meandering of rill channels. However, since the net effect was an increase in mean elevation for all of the transects, it can be deduced that the dam flow releases during this period did not result in net erosion of the sandbar.

Analysis of data for the upper transects, Figure 13 reveals similar characteristics to the pattern of elevation change during the August study period. The average elevation changes show similar breaks in the trend of aggradation. Mean elevation of the upper transects had been increasing for the first 8 days of the study. Measurements were not made for the next 4 days. When measurements resumed, the mean elevation decreased for 2 days at both transects before resuming an increasing trend. The slightly higher river stage on August 21st may have passed a threshold where seepage erosion became dominant over aggradation processes, or higher stage may have caused a slight shift in the circulation patterns of the eddy cells. A shift or modification of the eddy vortex and eddy fence in relation to the main river current may locally affect the supply of sand available for accumulation on the study plots.

A similar reversal from aggradation to erosion may be seen in the lower transect averages (Figure 14) on August 13th. Close examination of river stage and water levels in monitoring wells confirm that a higher peak stage occurred on the 13th compared to the previous days. Again, it is believed that erosion processes became dominant or changes in eddy currents resulted from the small difference in stage. Explaining such small changes in aggradation or erosion on the face of the sandbar would require greater sensitivity and quantification of eddy dynamics and sediment transport processes. River stage was coincident with the elevation of the upstream lower transect for some time period on August 23 - 24, 1991. During this time, a small wave-cut terrace formed, resulting in a relatively large elevation change at this transect from August 23rd to 24th.

Irregularities in the river stage fluctuation pattern occurred on August 19th in response to lower weekend electrical demands at Glen Canyon Dam. Unfortunately, transect elevations were not measured due to absence of observers from the study site. Subsequent measurements 2 days after the weekend flow did not reveal significant deviation from the general trend of aggradation.

Perpendicular transects (Figure 15) were utilized in the August study period to detect zones of erosion or deposition at different elevations on the face of the sandbar. We hoped to learn if the parallel transects on the lower part of the face of the sandbar truly represented the quantity of aggradation or erosion taking place on

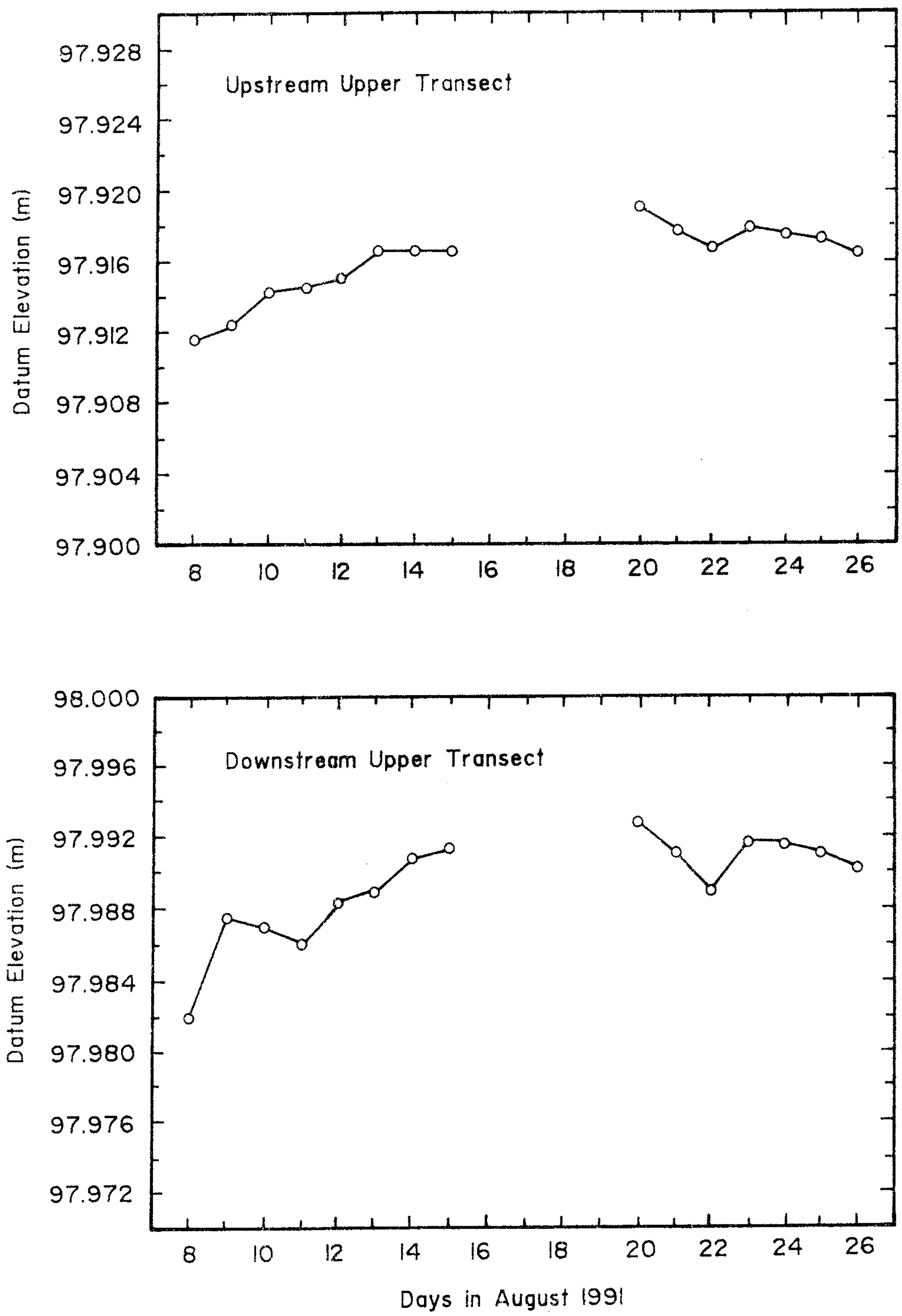
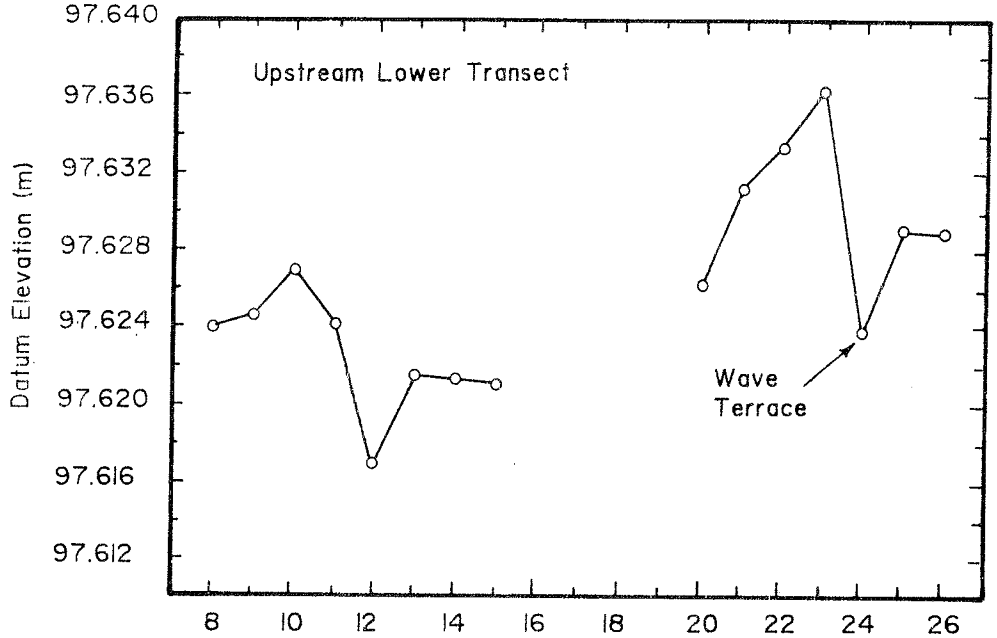


FIGURE 13. Mean elevation of upper transects, August 1991.



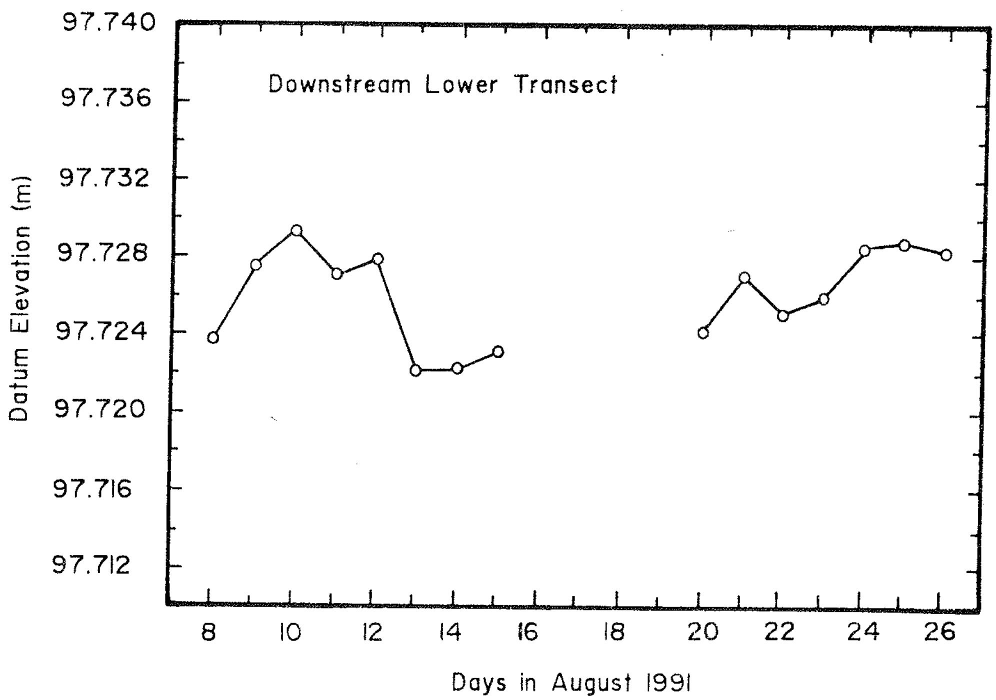


FIGURE 14. Mean elevation of lower transects, August 1991.

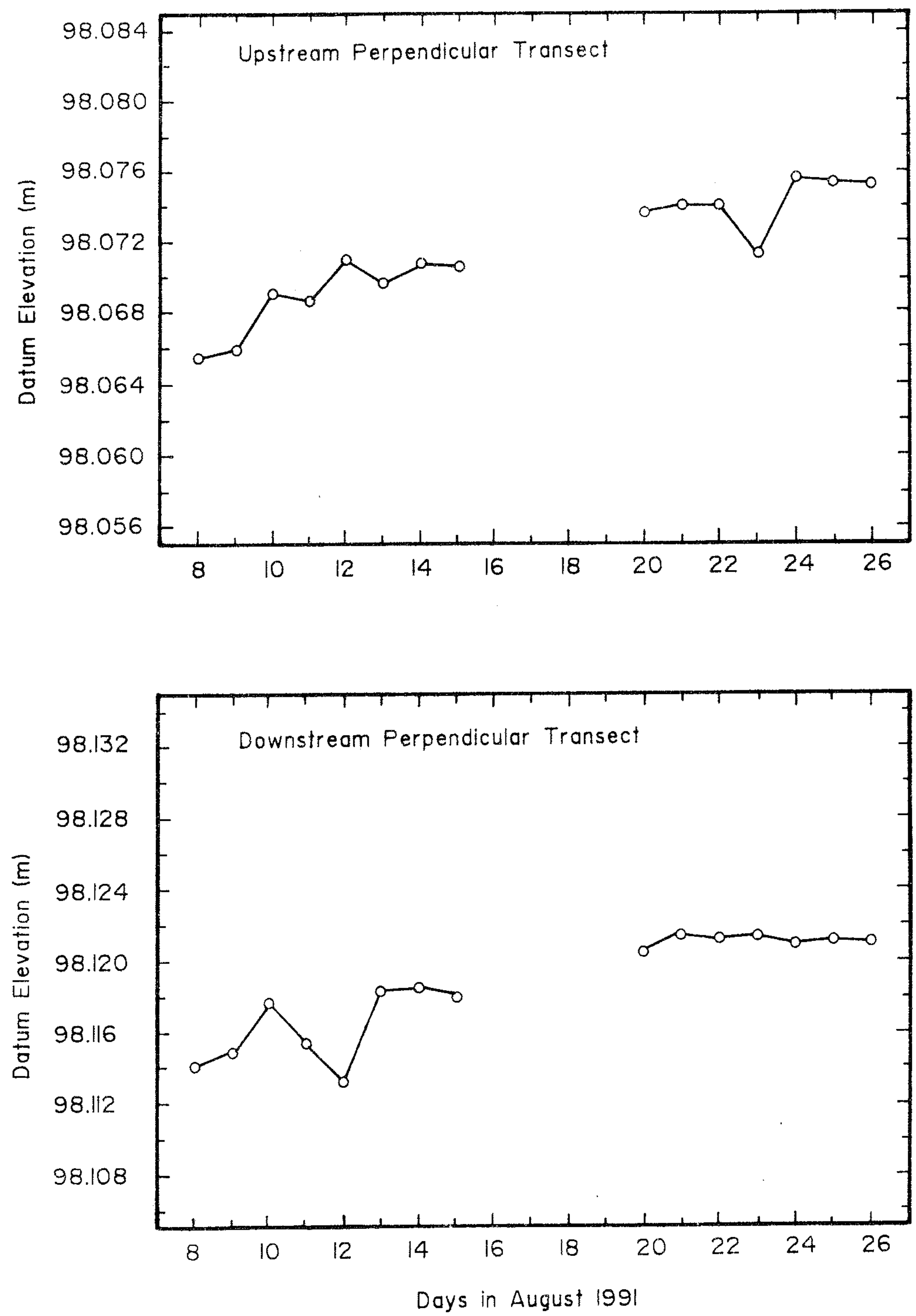


FIGURE 15. Mean elevation of perpendicular transects, August 1991.

the entire face of the sandbar. Generally, aggradation was uniformly distributed throughout the perpendicular transects. However, a narrow region indicated by a finer texture of sand on the surface of the sandbar was detected by the Surface Profile Gage and is seen in the photos. It is believed that this different texture of sand was a recent deposit on the sandbar and was gradually being eroded. A small ledge (estimated height of 10 mm) was slowly retreating up the face of the sandbar. The narrow region of sloughing was not measured by the parallel transects.

Rill formation and movement of sand grains down the face of the sandbar were observed during both the April and August study periods. However, the mean elevation was observed to increase in the August study period, whereas the mean elevation had decreased in April. This apparent contradiction is believed to be the result of two or more, opposing processes:

1. Seepage erosion occurs only during periods of low Colorado River stage. In August, the range of river stage fluctuations was less than in April and therefore, the amount of erosion from the beach face would be expected to be less.

2. Aggradation processes that could have been occurring include sand deposition by near-shore eddies and creep or slumping of sand moving down the face of the beach.

3. Other processes that could have resulted in apparent aggradation include vertical rebar settling or surveying errors in determining the elevation of the top of the rebar.

Each of these processes may occur daily, but at different rates depending on flow characteristics of the river for that day.

DISCUSSION

Rills and small channels form on the face of the sandbar in response to ground water seeping from the sandbar at low river stage. Rill channels were also observed below the surface of the Colorado River during the daily recession of river stage, indicating that the channels had remained essentially intact during high river stage (there was relatively minor deposition or reworking of the sandbar face). Changes in rill and channel form and location were observed at low river stage while water was flowing down the face of the sandbar. Lateral channel shifting and erosion or deposition processes occurred continuously. These small rill and channel changes are reflected in the measurements made with the Surface Profile Gage. Individual ball elevations show large (several millimeters) changes, both increases and decreases, on a daily basis as a result of lateral migration of the channels. The daily variance of individual ball elevations makes analysis of individual ball elevations difficult, on a daily basis. Thus, the arithmetic mean of ball elevations for an entire transect was used to evaluate elevation changes.

The basic processes observed and conclusions drawn during this investigation were:

1. The water table underlying the sandbars in the Grand Canyon fluctuates in response to river stage fluctuations. Water table fluctuation is greatest near the river and dampens with increasing distance from the river.

2. When the river stage falls at a rate that is faster than the water table can drain by gravity through the face of the sandbar, a saturated zone (seepage face) forms on the face of the sandbar. The height of this saturated face is dependent on the rate of river stage decline and factors controlling the gravity drainage of water from the sandbar.

3. Water seeping from the saturated face of the sandbar forms rills which move sand particles down the face of the sandbar to be deposited in areas with lower gradients or at the river's edge.

4. If the water table near the face of the sandbar can be artificially drained to keep pace with a falling river stage (i.e., no saturated zone formed), erosion will be prevented or at least lessened.

5. When the river stage decline is equal to or less than the rate at which ground water naturally drains from the sandbar, a seepage face will not form.

In a big sandbar, such as the one at River Mile 43.1L, a large volume of ground water is stored in the sediments. The mean water table elevation in the sandbar is controlled by the elevation of the mean daily river stage, taking into account the pattern of river stage fluctuations. Erosion occurs when the river stage falls significantly below the mean water table in the sandbar and a saturated seepage face forms as ground water flows toward the river in response to the gradient differential. Ground water emits from, and flows down the seepage face, forming rills and eroding sand grains down to the river's edge.

The video film produced in this study was compared to river stage and water table fluctuations to determine the sequence of events leading to seepage erosion from daily fluctuations of river stage. The following discussion explains our interpretation of the various phases of the ground water induced seepage erosion process as illustrated in the accompanying figures (16a - 16f). The position of each figure relative to the daily stage fluctuation of the Colorado River is shown as a dot on the hydrograph adjacent to each figure.

Figure 16a -- Lowest River Stage

The river is maintained at a low stage for several hours in response to minimal discharges from the dam during times of low demand for electricity. The water table in the sandbar is higher than the river stage due to recharge at high river stage the previous day. The river stage has been at a low level for a long enough time for ground water near the face of the sandbar to drain, lowering the water table. The size of the saturated seepage face depends on the volume of water draining from the sandbar, and on the duration of the lowest river stage. The height of the seepage face will decrease as the volume of stored ground water continues to drain, and the gradient decreases as the river stage begins to rise.

Figure 16b -- Rising River Stage

As the river stage rises, the seepage face is soon drowned out by rising river water, and the area near the face of the sandbar that had been drained becomes saturated again very rapidly. The river stage continues to rise above the average level of the water table in the sandbar. This causes a rise in the water table (recharging the aquifer) with its high point coincident with the river stage and tapering back to an average height of the water table, at some distance from the river.

Figure 16c -- Highest River Stage

The water table in the sandbar continues to be recharged from the river. The water table near the face of the sandbar is coincident with the river stage. This increase in the water table level will extend some distance into the sandbar depending on the amount of time the river is maintained at high stage and the permeability of the sediments.

Figure 16d -- Falling River Stage, Phase I

As the river stage begins to fall, gradients are reversed and ground water that was re-charged to the sandbar begins to flow back into the river. Initially, this volume of water is small because the top of the recharge ridge does not extend far into the sandbar. The water can drain through the face of the sandbar at a rate such that the water table in the sandbar declines nearly as fast as the river stage. A seepage face normally does not form, and rill erosion does not occur high on the beach face within the zone of fluctuations.

Figure 16e -- Falling River Stage, Phase II

The river stage has dropped to a level below which the ground water can no longer drain fast enough to keep up with the declining river stage, due to the large volume of ground water now influenced. A spring line forms parallel to and above the river's edge, and seepage occurs through the face of the sandbar below the spring line. The water concentrates in rills and flows down the face of the sandbar eroding sand grains in the process. The height of the seepage face is increasing with time.

Figure 16f -- Falling River Stage, Phase III

The river stage is near its lowest level. Ground water continues to drain from the face of the sandbar. The zone of active erosion (flowing rills) is still visible on the face of the sandbar. The seepage face has migrated down the face of the sandbar as the river stage receded. The river stage will change only slightly in the next few hours. The height of the seepage face will gradually decrease as ground water drains from the sandbar.

FACTORS AFFECTING SEEPAGE EROSION

Based on the preceding discussions, erosion by ground water seepage through the face of a sandbar will primarily be a function of operational factors at the Glen Canyon Dam; range of stage fluctuations, ramping rate, and length of time the river stage is held at high or low stages. Stage range is the change between high and low river stage on a daily basis. Ramping rate is the rate at which stage changes. Whatever the stage range and ramping rates are, the river stage fluctuates cyclically on a daily basis. These operational factors are somewhat interrelated and combine to determine whether the net effect of river fluctuations is erosion or deposition.

Stage range is probably the more important of the two factors in affecting ground water seepage and related sandbar erosion at large sandbars (i.e., sandbars in which ground water storage is large, as compared to the rate of seepage, and a near "static" water table can be maintained at the back of the beach over a daily river stage cycle). If the river stage has a large range, then the river stage will fall further below the average ground water level in the sandbar (the average ground water level would be approximately the same as the mean daily river stage if not for the changes in daily fluctuations). The seepage face that forms will have a greater length (height) and duration and will therefore cause more erosion when the range of river stage fluctuations is large.

Large ramping rates induce the formation of a seepage face by rapid river stage fall after the river stage drops below the average water table level in the sandbar. However, the seepage face will not form if the ramping rate is reduced after the river stage has dropped to approximately the mean ground water level. In this case, the range of fluctuations will be reduced because there is a limit as to how much stage change can occur on a daily basis, with a reduced rate of change.

Another factor affecting seepage erosion from the face of the sandbar is the volume of water stored in the sandbar. The volume of stored water is directly related to the width of the sandbar. Narrow sandbars will have a smaller volume of ground

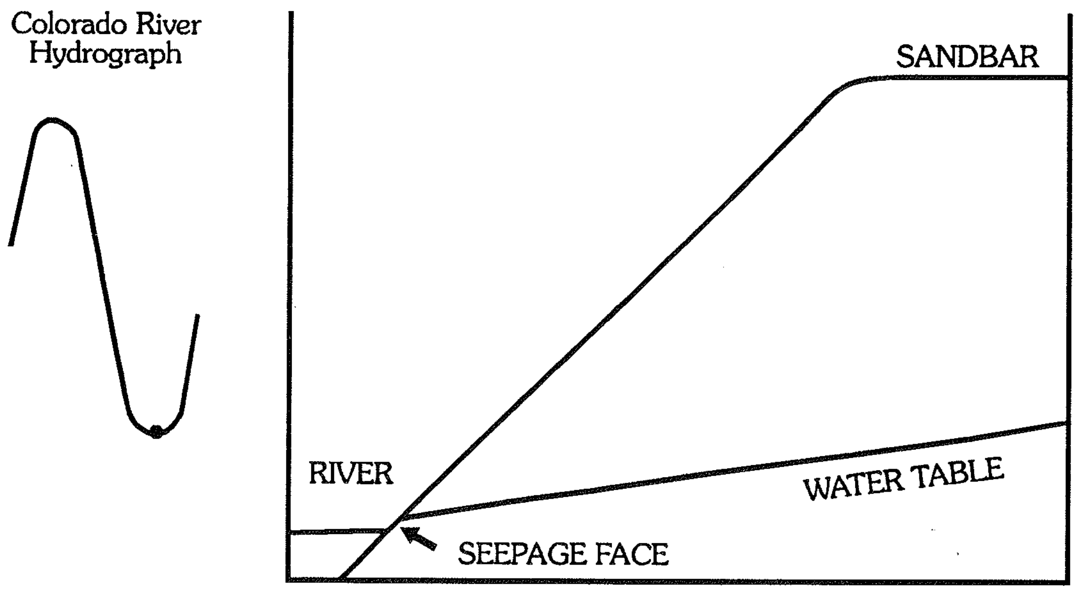


FIGURE 16a. Lowest river stage.

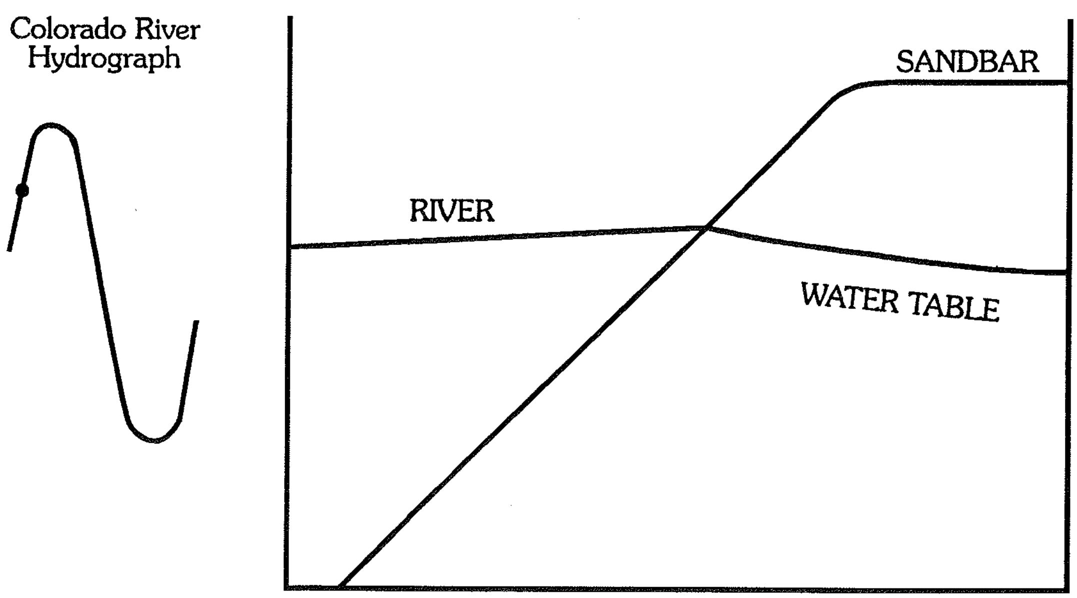


FIGURE 16b. Rising river stage.

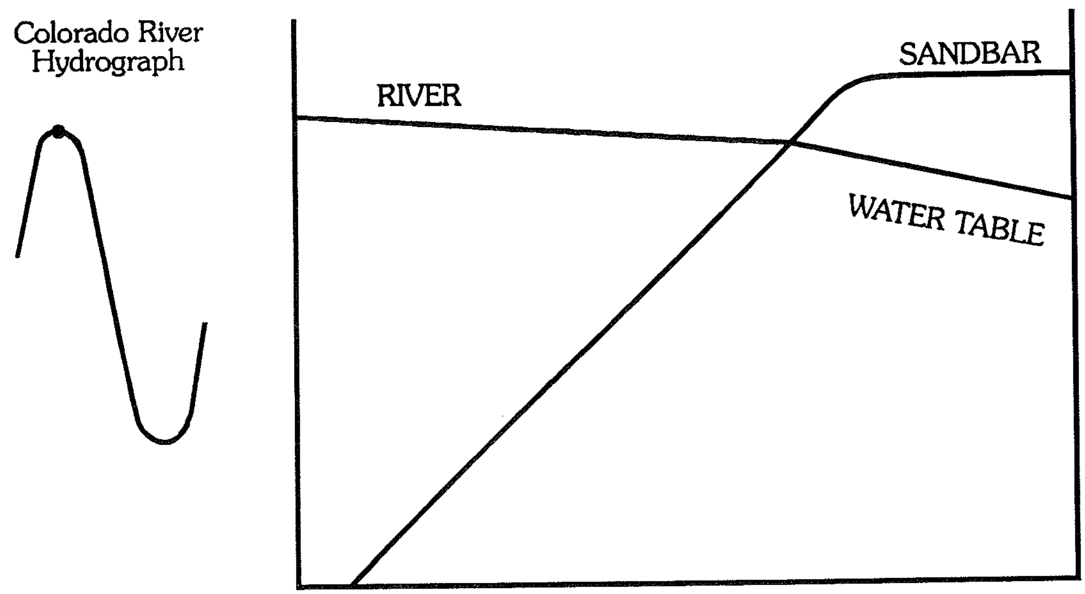


FIGURE 16c. Highest river stage.

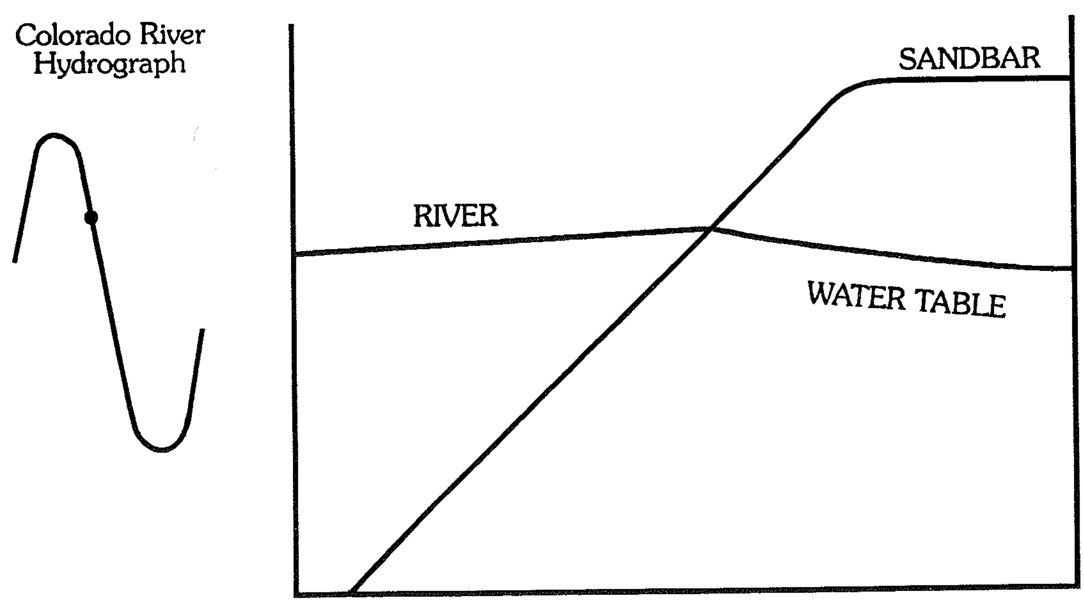


FIGURE 16d. Falling river stage, Phase I.

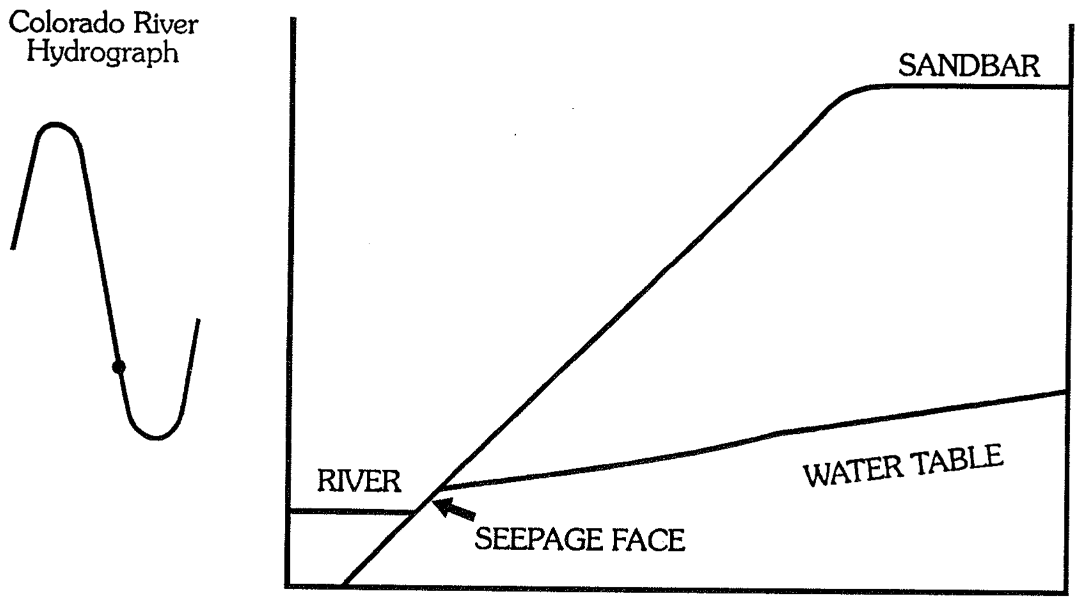


FIGURE 16e. Falling river stage, Phase II.

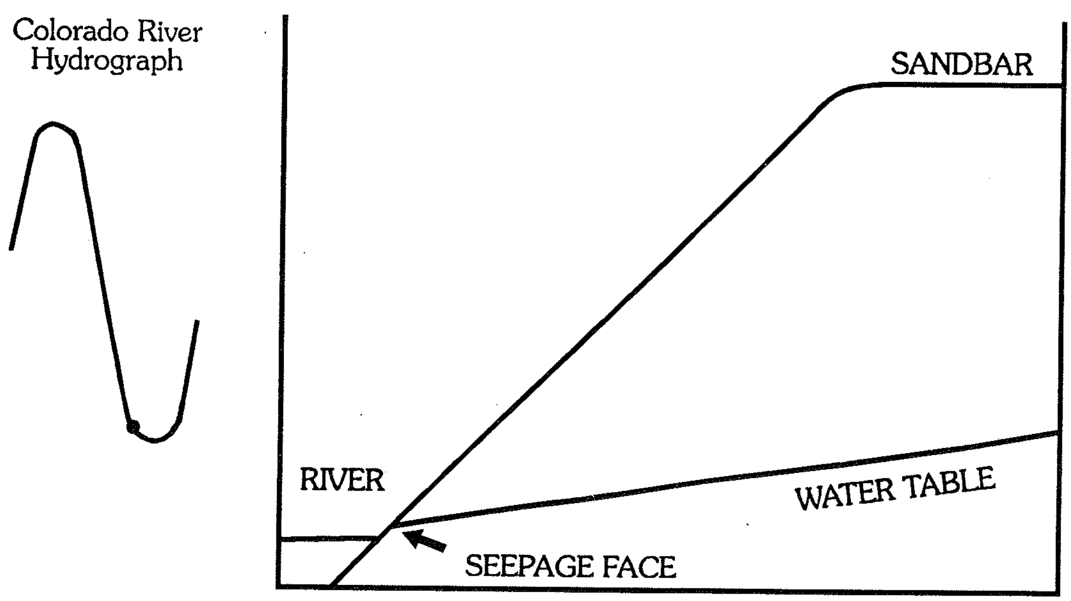


FIGURE 16f. Falling river stage, Phase III.

water in storage. When the river stage falls below the static ground water level, this smaller volume of ground water can drain from the sandbar relatively quickly. Faster drainage time (reduced lag time between river stage and water table decline) reduces the height of a seepage face and length of time during which erosion from ground water seepage occurs. In contrast, wide sandbars will have a larger amount of ground water in storage. Seepage through the face of the sandbar will occur, as previously described, when the river stage is lowered below the average ground water level. This seepage must continue for a longer period of time to drain the larger volume of water stored in the sandbar. Erosion via rill formation will occur for a longer period of time and from a higher seepage face.

Other factors affecting the amount of erosion from ground water seepage on the sandbar face:

1. Slope and length of the sandbar face.

2. Sediment grain size and distribution.

3. Sediment cohesion, which is dependent on particle size, particle shape, and to a lesser extent on sediment and water chemistry.

4. Geomorphic position above the main river channel.

Horizontal drains installed in one of the study plots verify the role of ground water in seepage erosion. The drains induced more rapid drainage of ground water from near the face of the sandbar, thereby limiting formation of a seepage face. There was a noticeable difference in the appearance of the face of the sandbar in the vicinity of the drains after installation. Ground water near the face of the sandbar drained very quickly through the perforated pipe after the river receded. The area above the drains became unsaturated very quickly. Rills did not reform in the immediate area, indicating that ground water was no longer seeping from the sandbar. Adjacent areas on the sandbar, including the study plots where blank pipes were installed, still appeared saturated and rills reappeared.

CONCLUSIONS

Erosion and deposition processes occur daily in response to changing hydrologic and hydraulic conditions. The net effect of these opposing processes varies with changing river flow characteristics. Sandbar 43.1L erosion caused by ground water seepage was documented in the April study period, during which the daily range of the Colorado River stage fluctuation was relatively large and the mean stage of the river was low. Net aggradation on the sandbar was documented in the August study period. Several processes could be responsible for the net aggradation. One possibility is that because the daily range of the Colorado River stage fluctuations was less than in April, erosion by ground water seepage was reduced. Also, the mean river stage was higher in August. The higher mean stage may have resulted in slightly different eddy characteristics. Changes in eddy-flow patterns may locally affect the sediment supply available for accumulation on the sandbar. Another possible explanation is creep or other mass wasting. Because several processes have been identified as possibly affecting sandbar erosion and sediment deposition, future investigations of this type should attempt to isolate effects from each of these processes.

River stage fluctuations occur daily as a result of variable flow releases from the Glen Canyon Dam for power generation. When the river stage is lowered rapidly, the rate at which the sandbar drains will not permit the water table to decline as fast nor remain coincident with river stage. The water table in the sandbar is temporarily higher than the river stage. This condition can be described as a difference in potentiometric head between the water table and river stage and will result in ground water movement towards the river. Ground water will drain from the sandbar at a rate limited by the aquifer properties of the sandbar and the head difference between the water table and the river. When sandbar discharge (seepage) is of such quantity that the upper limit of the discharge zone (interface between the water table and the sandbar) is higher than the river stage, water will flow down the face of the sandbar forming rills and transporting sand grains down the slope to the river's edge. This process was documented in the April study period. The amount of sandbar seepage (and therefore erosion) decreases when the range of river stage fluctuations is reduced. Reduced stage range and less prominent formation of rills in the August study period is an example of these conditions.

This study has focused only on the role of ground water seepage on sandbar erosion. Erosion by ground water seepage is only one of many geomorphic process affecting sandbars in the Grand Canyon. Systemwide sediment budget, main channel sediment transport, mass wasting, creep, eddy dynamics and related sediment storage in eddy basins are other aspects being studied which affect sandbar stability. Interaction by research scientists will be necessary to determine dominant components of sandbar stability affected by river stage fluctuations.

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APPENDIX 1

GLOSSARY

Aggradation[1] - The building-up of the Earth's surface by sediment deposition. A synonym of accretion, as in development of a sandbar.

Drains - Perforated pipe buried in the face of the sandbar and used to intercept and convey ground water to an outlet.

Eddy[1] - A circular movement of water that is generally in a different direction from that of the main current. It is a temporary current, usually formed at a point where the main current passes some obstruction, or between two adjacent currents flowing in opposite directions, or at the edge of a permanent current.

Erosion[1] - The general process or the group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another, by natural processes, which include weathering, solution, corrosion, and transportation, but usually exclude mass wasting. The mechanical destruction of the land and the removal of material (such as soil) by running water (including rainfall), waves and currents, moving ice, or wind.

Range - The difference between high and low flow releases from Glen Canyon Dam as measured on a daily basis.

Ramping Rate - The rate of change of flow releases from Glen Canyon Dam.

Return Channel - A feature of sandbars formed by a large eddy or recirculation zone usually found on the upstream portion of the sandbar where a counter current formed a depression in the deposit by means of scour. The remnant land form is categorized as a return channel by Schmidt and Graf (1989).

Rill Erosion[1] - The development of numerous, small, closely-spaced channels resulting from the uneven removal of surface soil by running water that is concentrated in rivulets of sufficient discharge and velocity to generate cutting power.

Sandbar[1] - A ridge-like accumulation of sand, gravel, or other alluvial material formed in the channel, along the banks, or at the mouth, of a stream where a decrease in velocity induces deposition.

Sandbar Face - The surface of a sediment deposit (sandbar) adjacent to and sloping toward the river. Synonym is beach face.

Seepage Line[1] - The uppermost level at which flowing water emerges along a seepage face; an outcrop of the water table.

Seepage Face[1] - A belt along a slope, such as the bank of a stream along which water emerges at atmospheric pressure and flows down the slope.

Stage - The elevation of a river water surface relative to a datum.

Surface Profile Gage - A device to determine accurate elevation of 58 points along a transect without disturbing the ground surface (i.e., erosion bridge).

Transects - A line or profile of scientific interest on the ground surface that is delineated by the position of stakes 15 feet apart. Measurements made along the transect are used to document vertical changes in topography. A transect and surrounding area is identified by flagging and protected from trampling by human footprints or other intrusive activities.

Transect Stake - A five or ten foot length of metal rod (1/2-inch re-enforcement bar) driven into the sandbar to support the Surface Profile Gage and delineate the end point of a transect.

Zone of Active Erosion - A section of the sandbar susceptible to seepage from bank stored ground water usually indicated by the presence of rilling.

Zone of Fluctuations - A zone on the face of a sandbar that is influenced by the fluctuation of river stage. The area of a sandbar between the range of high and low water levels.

[1]Source: *Glossary of Geology*, 1980 Second Edition, edited by Robert Bates and Julia Jackson, American Geological Institute, Falls Church, VA.

APPENDIX 2

DESIGN AND OPERATION OF THE SURFACE PROFILE GAGE

An instrument to quantify erosion and deposition on the sandbars in the Grand Canyon needed to be portable, accurate and adapted to specific conditions encountered at remote sites. From a practical standpoint, access to the sandbar is limited to rafting down the Colorado River from Lees Ferry. Thus, a measuring device needs to be durable, portable, and capable of providing very accurate measurements.

Design

The Surface Profile Gage was designed and constructed by the authors. This instrument measures the elevation of a ground profile at 3-in intervals over a distance of 15 ft without individuals having to traverse the area to be measured. A total of 58 data points were acquired over the profile.

Preliminary tests were conducted to determine the least penetration of pliable surfaces by falling rods. Several materials including brass and plastic tubes, aluminum arrow shafts, and fiberglass rods were examined for weight, stiffness and length. One-eighth-inch wooden dowels had the best combination of material strength and least weight. Various designs were tested to reduce the sharpness of the end of the dowel. Styrofoam cubes, plastic disks, and ping-pong balls were tested on a loose surface of fine sand collected from a sandbar along the Colorado River. Measurements were compared from each assembly to determine the least deformation of the sand surface. Spheres have the advantage of smooth edges as opposed to the sharp edges found on flat disks or cubes, which tended not to cut into sloping surfaces. Ping-pong balls were thus chosen due to good performance in the tests, lack of porous surfaces which could absorb moisture, and the ease of removing wet soil that may adhere at the contact surface.

The Surface Profile Gage was developed to collect accurate data on erosion and deposition of soft ground surfaces. The length of the gage allows measurements of undisturbed plots without trampling or other human induced surface deformation. Measurements of vertical distances from a supported beam can be repeated accurately at periodic time intervals. Vertical support stakes delineate 15 ft transects across study plots. The gage is positioned on these stakes and the vertical rods are allowed to drop to the ground surface. Each rod has a ping-pong ball attached to the lower end to prevent the rods from penetrating the soil surface. The rods are clamped in position while touching the ground and the gage is removed for measurements. The extended distance of each rod is recorded.

The Surface Profile Gage was designed with specialized features that allow:

1. Measurements without disturbance to the study plot by human foot prints.

2. Long enough span that the vertical support stakes do not affect the study plot.

3. Measurement rods that do not penetrate in soft, pliable ground surfaces.

4. A clamping system that holds the rods in position when the gage is removed from the vertical support stakes.

5. Precise measurements to determine very small differences in ground elevations.

6. Light weight to insure easy operation by two people.

7. Portability to the study site by disassembly for shipping, rafting, and/or backpacking.

8. Durability during field travel.

Construction

The Surface Profile Gage was constructed with an aluminum frame 15-ft long (4.6 m) which positions 58 ping-pong balls, each attached to a 2-ft length of 1/8-in diameter wooden dowel. The frame was made from two beams which were vertically separated 8 inches by short diagonal braces to form a truss (hence the common term of erosion bridge). Each beam was spliced from two 7-1/2-ft lengths of 2-in aluminum angle. Small guide holes were drilled at 3-in spacing intervals.

The gage can release the dowels (allowing free movement) or clamp the dowels in place. A clamping bar was constructed from 1-in aluminum angle and foam weather stripping. The clamping bar rested on the upper beam and could be pressed against the row of dowels to hold them in place or moved away to allow the dowels to slide freely in their guide holes. A mark on each dowel was made to indicate a specific distance from the bottom of the ball. A jig was constructed to provide consistency in marking dowels. Each ball and guide hole were numbered to insure the balls and dowels could be replaced to their original holes if the dowels were removed.

Two larger holes were drilled at the ends of the Surface Profile Gage where the top of the vertical support stakes fit into place for positive gage positioning. A thick piece of metal with a hole was attached to the bottom of the upper beam to guide the vertical support stake to rest in the same position for every measurement. Slots were filed in the lower beam to eliminate problems encountered with aligning the holes at the end of the gage with the vertical support stakes. This construction reduced problems encountered from not driving the vertical support stakes in a true, perpendicular position.

Operation

Transects were established by placing the stakes to support the Surface Profile Gage. The method of setting the stakes consisted of wading in the river from outside the study plot to the selected point on the sandbar and approaching it directly from the water. The stakes were driven into the ground until about one foot remained exposed.

Use of the Surface Profile Gage consisted of positioning the balls close to the lower beam of the bridge and clamping the dowels. After approaching the transect from the water's edge, the gage was carefully placed on the vertical support stakes. The gage support holes were positioned onto the two vertical support stakes. This forced the gage into an upright, rigid position. With the gage in position, the clamping bar was released and the balls fell by gravity to the ground surface. The clamp was reset, holding the measuring rods in place while touching the ground surface. The gage was lifted off the support stakes and carried to a staging area for measurement of each rod in the clamped position. The distance from the upper beam of the gage to the mark on the dowel was measured and recorded.

The elevation of the top of the vertical support stakes was surveyed to established bench marks several times during the study to determine if any elevation changes (of the vertical support stakes) were occurring. The Surface Profile Gage was checked for sag or warping by supporting the gage at each end and stretching a string line over the length of the upper beam. Measurements of the distance from the string to beam center were taken several times each study period. This value remained constant, and was compensated for in the final data analysis.

Fifty-eight data points were acquired for each surface profile measurement. The information was recorded on data forms along with transect identification, date, time, and observers names. Data points which plotted beyond reasonable limits on graphs were discarded from analysis and were probably resultant of either recording error, or measurement error. Elimination of dowel measurements near the vertical support stakes from analyses assured that the remaining data points reflected an undisturbed conditions along the transect.

APPENDIX 3

INTERIM OPERATING CRITERIA FOR FLOW RELEASES FROM GLEN CANYON DAM

On November 1, 1991, the Secretary of the Interior implemented the following criteria for *Interim Flows* for the Colorado River downstream from Glen Canyon Dam. These criteria are to remain in place through the completion of the Record of Decision for the Glen Canyon Dam - Environmental Impact Statement, currently scheduled for December, 1993. The purpose of the *Interim Flows* is to minimize the loss of the natural resources in the Grand and Glen Canyons until a longer term solution is defined through the Glen Canyon Dam - Environmental Impact Statement program.

Parameter		**Flow in Cubic Feet per Second (cfs)**
Maximum Flow		20,000 cfs[1] (566 m^3/s)
Minimum Flow		5,000 cfs - nighttime (142 m^3/s)
		8,000 cfs - 7 a.m. to 7 p.m.[2] (227 m^3/s)
Ramp Rates		
	Ascending	8,000 cfs/ 4 hours not to exceed 2,500 cfs/hour (227 $m^3/s/4$ hours not to exceed 71 $m^3/s/hour$)
	Descending	1,500 cfs/hour (42 $m^3/s/hour$)
Daily Fluctuations		
		5,000, 6,000, or 8,000 cfs[3] (142, 170, or 227 m^3/s)

[1]To be evaluated and potentially increased as necessary for years when delivery to the Lower Basin exceeds 8.32 million-acre-feet (maf).

[2]The 8,000 cfs minimum flow requirement from 7 a.m. to 7 p.m. will be shifted to 8 a.m. and 8 p.m. respectively beginning the last Sunday in October and ending the first Sunday in April, Arizona local standard time.

[3]Daily fluctuation limit of 5,000 cfs in months with release volumes less than 600,000 acre-feet, 6,000 cfs for monthly release volumes between 600,000 and 800,000 acre-feet, and 8,000 cfs for monthly volumes over 800,000 acre-feet.

As the nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental an cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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