Waves and Sandbar Erosion in the Grand Canyon: Applying Coastal Theory to a Fluvial System

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Abstract. Progressive erosion of channel-bank sandbars in Grand Canyon has long been thought to be associated with emplacement and operation of Glen Canyon Dam, although the specific physical mechanisms causing local erosion are poorly understood. A short-term study (order of days) of detailed flow patterns and morphologic adjustments at Stone Creek and Fern Glen sandbars during constant discharge demonstrates that surface-gravity waves and other quasi-periodic flow oscillations are important to the stability characteristics of these alluvial deposits. The primary role of waves is to agitate bottom sediments, entraining them on an intermittent basis. Mean currents associated with recirculating eddies (ordinarily of insufficient strength to entrain sediments) act, in the presence of waves, as a net background drift able to transport sediments away from the bar face and into the main channel. Thus combined wave-current interactions provide for sediment transport possibilities that might not occur in the absence of waves.

Simple models of beach-foreshore equilibria developed for coastal environments show that the faces of Grand Canyon sandbars behave very much like coastal, wave-dominated features. But the wave-dependent equilibria predicted by coastal models are never attained fully because mean eddy-recirculation currents associated with the river play an important role in the fluid-sediment interactions observed on nearshore terraces. Unlike a coastal system where mean alongshore currents owe their existence to wave motion, eddy-recirculation currents in a fluvial system are completely independent of waves, vis-à-vis their hydrodynamic origin. Thus neither a purely fluvial approach nor a purely coastal approach will be completely successful in describing sandbar stability in Grand Canyon, and a hybrid model should be adopted.

Key Words: Grand Canyon sandbars, wave erosion, recirculating eddies, beach features, wave-current interaction, coastal geomorphic theory.

SINCE the days of early river runners, visitors to Grand Canyon have been impressed by the extensive sand deposits that are a sporadic but integral component of the river corridor's physiography. The sand deposits are commonly referred to as "beaches" and are used as campsites by the 20,000 persons that travel through this bedrock gorge each year by boat (U.S. National Park Service 1989). Between 1973–91, the size and number of sandbars used as campsites decreased greatly (Kearsley and Warren 1992). In addition to acting as substrate for riparian communities (Turner and Karpiscak 1980; Stevenson 1983, 1989), older and higher alluvial deposits sometimes contain archaeologic remains (Hereford et al. 1991).

Progressive erosion of sandbars in Grand Canyon has long been thought to be associated with the emplacement and operation of Glen Canyon Dam; details of this association have been under investigation for several years (Howard and Dolan 1981; Beus, et al. 1985,

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1991; Schmidt and Graf 1990). Past geomorphic research, although driven by concerns for sandbar erosion, focused largely on the morphology and sedimentology of depositional remnants of sandbars. Recently, increasing attention has been directed to understanding detailed erosional processes on bar faces (Water Sciences and Technology Board 1987). It is ironic that, despite their common description as "beaches," virtually no research has examined the potential role of wave-induced geomorphic processes on sandbar stability. The term "beaches" is apt because waves with amplitudes up to 0.3 m and periods of a few seconds are not unusual in large eddy-recirculation systems found below major rapids. These waves rework the faces of large sand deposits and the resulting forms bear a striking resemblance to coastal beach features (Fig. 1). Although a limited number of reports of beach-like features and processes along the banks of other large rivers appear in the literature (e.g., Bhowmik and Demissie 1983; Wells, et al. 1984), no one has undertaken a systematic examination of their relative importance from a coastal-geomorphic perspective.

The purpose of this paper is to evaluate the relative importance of surface-gravity waves on sandbar stability in Grand Canyon, in contrast to unidirectional currents that are the primary focus of most fluvial studies. A second objective is to evaluate the utility of coastal geomorphic theory and methodology in the investigation of river sandbar stability. Such information may be useful in the development of management strategies for the Colorado River below Grand Canyon Dam and other regulated rivers where waves are part of the flow field.

Further, the results are germane to understanding sedimentary processes in other geomorphic environments such as embayments and estuaries where both unidirectional and oscillatory motions can dominte the nearshore flow field at different times (e.g., Nordstrom 1992).

Management Context and Geomorphic Framework

Concern about environmental changes induced by emplacement of major dams on large rivers has focused on: (1) immediate and irrevocable inundation of valley or canyon lands upstream from the dam, or (2) long-term alteration of geomorphic and wildlife systems in downstream reaches (e.g., Graf 1992). Although the former cannot be mitigated, management strategies that minimize adverse impacts to downstream river environments are being actively explored for many large dams in the U.S. The research program conducted on the Colorado River through Grand Canyon National Park, primarily under the auspices of Glen Canyon Environmental Studies, has been one of the most extensive programs directed at development of management strategies to mitigate environmental degradation in a regulated fluvial system. The Colorado River is the most highly-regulated river system in North America (Hirsch, et al. 1990, fig. 17), and its flow through Grand Canyon is virtually completely controlled by operation of Glen Canyon Dam (Water Science and Technology Board 1991), located 25 km upstream from Lees Ferry (Fig. 2). The operational effects on downstream geomorphic environments became evident a few years after dam completion in 1963 (Dolan, et al. 1974), and some of these sandbar changes were described by Turner and Karpiscak (1980) and Howard and Dolan (1981).

Proposed revision of the pattern of hourly releases in the early 1980s and the occurrence of unusually large runoff volumes between 1983–86 led to extensive interdisciplinary research by physical, biological, and social scientists in cooperation with water-resource and hydraulic engineers (Water Science and Technology Board 1987, 1991). Many studies documented the history of bar aggradation and degradation (Beus et al. 1985; Schmidt and Graf 1990), the sedimentology and morphology of select bars (Rubin et al. 1990), and the general association of sandbars with recirculating flow (Schmidt 1990). Research related to the hydraulics and sediment transport dynamics of the main channel were summarized by the Water Science and Technology Board (1987) and the U.S. Department of the Interior (1988).

The discharge regime of the Colorado River below Lees Ferry prior to dam closure was characterized by large annual floods in excess of 3000 m^3 s^{-1}, separated by extended baseflow periods of less than 100 m^3 s^{-1} (Turner and Karpiscak 1980). Such extreme hydrologic excursions are thought to have facilitated natural sediment interchanges between perennially-submerged, mid-channel deposits and

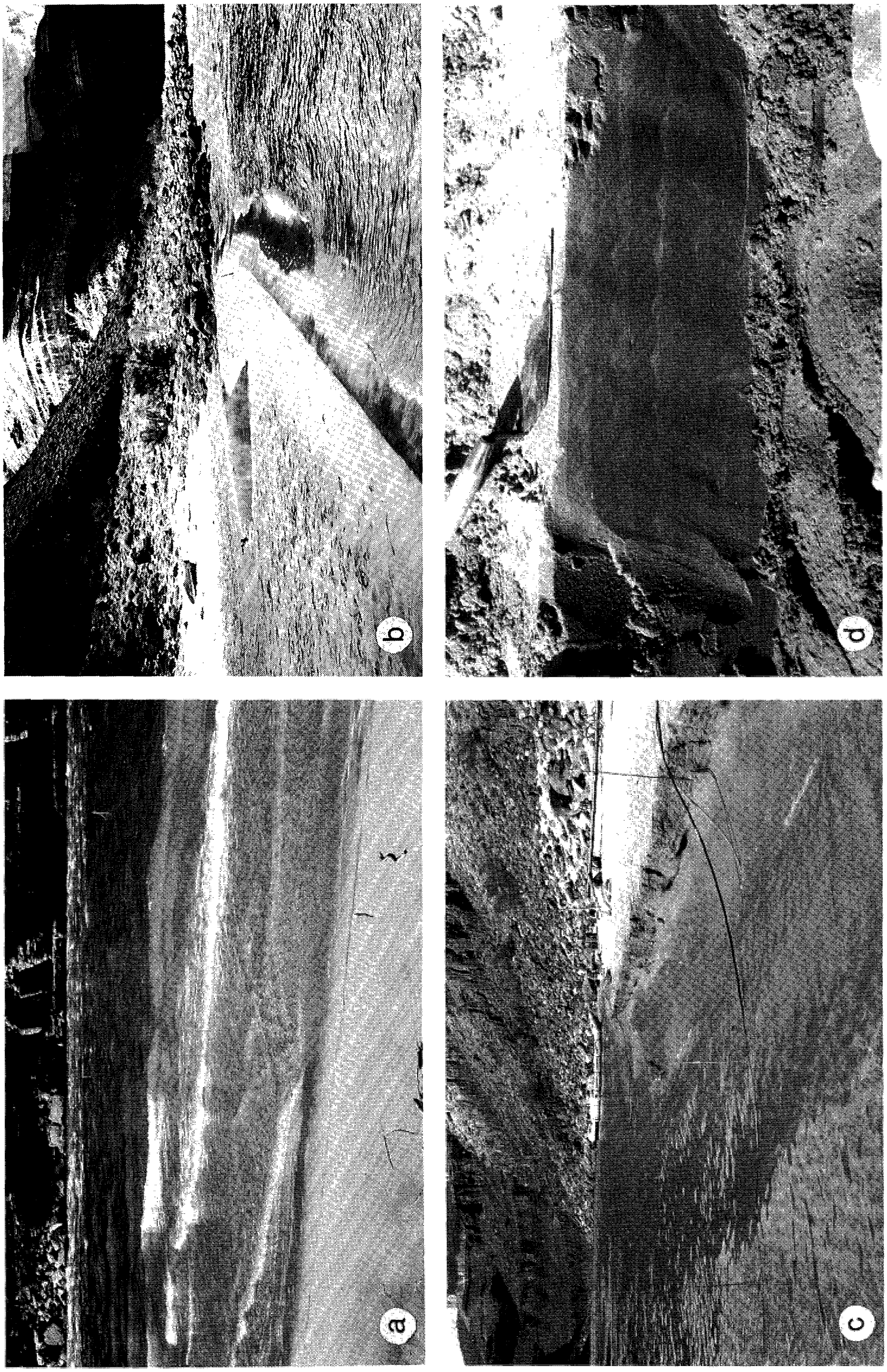


Figure 1. Coastal beach-like landforms along the margins of the Colorado River. (A) Surface-gravity waves shoaling across a shallow nearshore terrace and breaking on the bar face at Fern Glen Rapid, May 26, 1991. Note the rapids in the background where the waves are generated and the accretional berm in the foreground built by swash motion. (B) Surging waves and onshore-migrating overwash deposit blocking on older eddy-return channel at the upstream end of Stone Creek reattachment bar, May 24, 1991. This feature is reminiscent of a baymouth bar found in many coastal environments. (C) Erosional wave-cut scarp carved into the central portion of Stone Creek reattachment bar, May 24, 1991. Note the foreshore slope dominated by swash motion. (D) Stacks of symmetric ripple structures associated with oscillatory flows on a flat, terrace-like surface, Stone Creek, May 24, 1991.

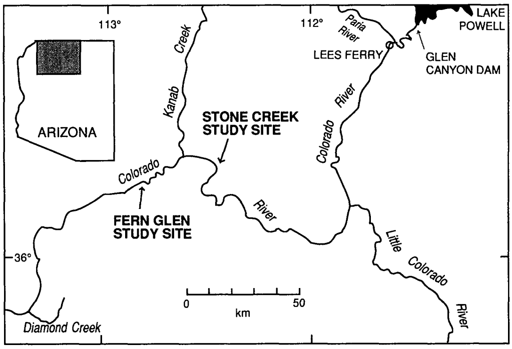


Figure 2. Grand Canyon and study site location.

emergent, channel-bank deposits that sometimes eroded and sometimes regenerated the latter. The presence and operation of the dam has constrained this interchange (Graf 1985). Natural sediment flux through Grand Canyon above the confluence of the Little Colorado River has been reduced markedly because of sediment trapping in Lake Powell. Suspended sediment concentrations at the gauging station at Lees Ferry were commonly in excess of 10,000 ppm (parts per million) before 1959, whereas now they are typically of the order of 200 ppm (Laursen, et al. 1976). In addition, controlled releases from the dam to accommodate flood control and water supply have created a river-discharge regime devoid of seasonal extremities. In its place is a regime that is characterized by daily water-level fluctuations induced by discharge releases that range from lows of about 125 m^3 s^{-1} to highs that do not exceed maximum power plant capacity of about 875 m^3 s^{-1}.

Alluvial sand deposits in Grand Canyon usually occur in association with tributary debris fans that partially block the river's course (Fig. 3). This blockage creates white-water rapids (Leopold 1964; Kieffer 1985) that are the focus of recreational river-running through the park. Typically, there is a zone of constricted flow opposite the debris fan and a downstream expansion in which the channel is wider and deeper than for unconstricted reaches (Schmidt 1990). The constricted high-velocity flow separates from the channel bank at the downstream edge of the debris fan and reat-

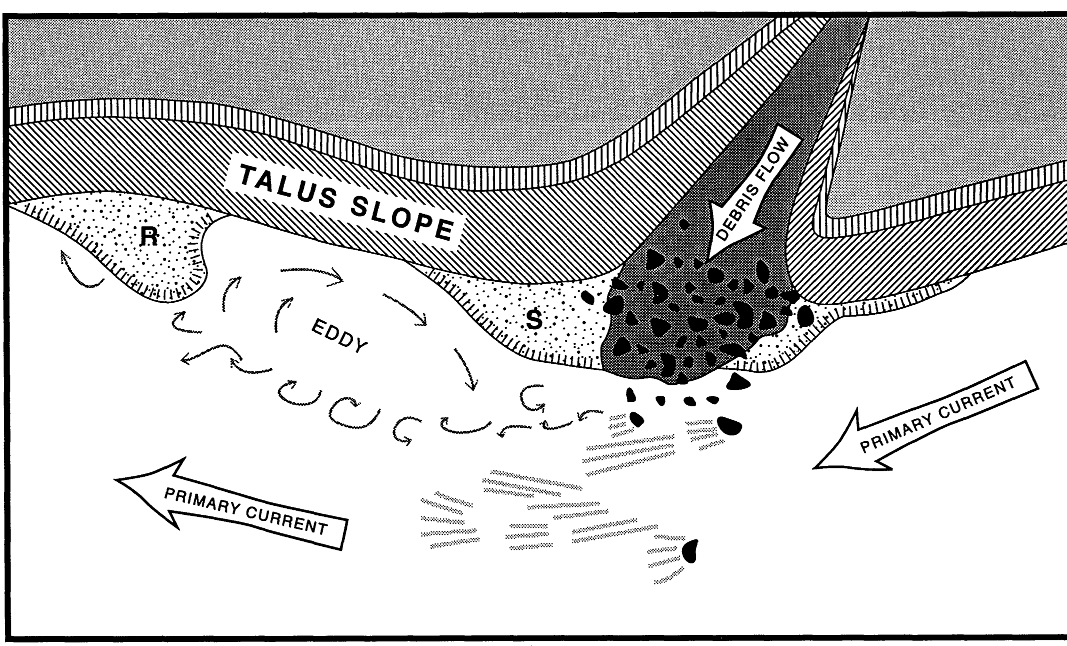


Figure 3. Characteristic location and geometry of channel-bank sand deposits found in association with a debris-fan constriction. "R" refers to a reattachment bar, and "S" refers to a separation bar.

taches to the channel bank within a distance of 1-5 channel-widths downstream from the separation point. The downstream reattachment point is, in fact, a zone over which the reattaching flow oscillates (Rubin, et al. 1990), even under constant discharge, most likely because of vortex shedding and evolution along the eddy fence (zone of fluid shear between main channel and slackwater currents). The region bounded by the reattachment point, separation point, channel bank, and main channel is usually dominated by one large recirculating eddy, as is common for flows around extreme curves or corners (e.g., Leeder and Bridges 1975; Batchelor 1983, 325). The most distinctive feature of the recirculating eddy is a concentrated upstream current along the channel bank that occupies a well-defined subchannel, easily identified at low stage.

The morphology and sedimentology of Grand Canyon sandbars are closely associated with the flow geometry described above (e.g., Rubin, et al. 1990; Schmidt 1990). Indeed, these sandbars have been classified according to their association with components of the recirculating eddy. Reattachment bars are found at the downstream, or distal, end of the recirculating zone. Flow divergence at the reattachment point creates a stagnation zone that is conducive to rapid deposition, and the resulting deposit tends to prograde upstream (Rubin, et al., 1990). Deposits that form at the proximal end of the eddy, near the point of flow separation, are called separation bars—they mantle the downstream portions of large debris fans.

Mechanisms of Sandbar Erosion and the Role of Waves

Relatively little is known about erosional processes leading to sandbar degradation in Grand Canyon, in large part because the sedimentological record retains little such information. Replicate topographic surveys have been used since 1975 to document bar response to changing discharge regimes (Beus, et al. 1985; Schmidt and Graf 1990), and more recently, historical air photographs and oblique photograph replication were used with GIS to provide comprehensive reach-scale analyses of bar stability over periods of between 30–100 years (Clark, et al. 1991; Webb, et al. 1991). Nevertheless, detailed erosional process-response mechanisms can only be investigated and verified through field observation and experimentation.

To date, two groups of processes have been examined in relation to Grand Canyon sandbar erosion. One set is related to groundwater fluctuations caused by short-term changes in river stage. Porewater effluxes associated with rapid dewatering can lead to rill erosion on bar faces and to groundwater sapping that removes basal support (Budhu and Contractor 1991). Of equal importance are changes in effective normal stress induced by cyclical flooding and dewatering of pore spaces or interstices (e.g., Terzaghi 1943). Under the present fluctuating flow regime imposed by operation of Glen Canyon Dam, daily vertical water-level fluctuations along the banks of the Colorado River can be of the order of 0.5–2 m. Repetitive cycles of porewater pumping can decrease the internal strength of sand bodies and lead to mass failures that become evident at low-flow discharges (Carpenter, et al. 1991).

The other suite of processes of importance to sandbar stability are those that are the traditional foci of fluvial studies—tractive force erosion (e.g., Hjulström 1935; Shields 1936). Most fluvial sediment-transport studies have assumed that bed response (erosion or deposition) can be predicted based on the magnitude of calculated bed-shear stress relative to the threshold stress required to entrain bed material. Ordinarily, the boundary shear-stress distribution is calculated on the basis of the main-channel flow field under relatively simple channel geometries (e.g., Lundgren and Jonsson 1964; Dietrich 1982; Nelson and Smith 1989; Pizzuto 1990). In eddy recirculation zones, however, it is the recirculating currents that are relevant. These recirculating currents (order of less than 1 m s^{-1}) are usually much weaker than the main-channel current (order of 1 to 10 m s^{-1}) (Schmidt 1990, table 2), and the recirculating currents are often of insufficient magnitude to initiate sediment motion. Indeed, tractive force analyses of these systems tend to predict net deposition because of the slack-water or stagnation conditions (e.g., Andrews 1991).

Our contention is that surface-gravity waves and other quasi-periodic fluid oscillations are important to the hydrodynamics and morphodynamics of many recirculating eddy systems. Helicopter photos taken at flows between 1500-2800 m^3 s^{-1} show the presence of large waves in these systems. Howard and Dolan (1981) found that there was a general relationship between beach-face slope, sediment size, and intensity of wave energy (qualitatively evaluated) for Grand Canyon sandbars as they existed in the late 1970s. Extensive analysis of preserved sedimentary structures indicates that reversing-flow ripples and other wave-generated forms (see Fig. 1) are the dominant structure in some bars (Rubin, et al. 1992). Given that recirculation eddies are characterized by relatively weak unidirectional flows, surface-gravity waves could play an important role in the sediment-transport dynamics of these zones because the associated oscillatory currents contribute additional energy and shear to the tractive force field. The presence of waves in recirculation eddies might even cause otherwise aggradational systems to degrade because these waves are typically of short period and short wavelength—such steep waves are generally associated with erosional conditions in coastal environments (Komar 1976, 289).

Study Sites

Field experiments were conducted during constant discharge at two locations (refer to Fig. 2): Stone Creek camp at Deubendorff Rapid (river-mile 136, or 252 km downstream from Glen Canyon Dam); and Fern Glen camp at Fern Glen Rapid (river-mile 169, or 307 km downstream from Glen Canyon Dam). Monitoring at the sites took place on May 24-25, 1991, and on May 26-28, 1991, respectively.

Deubendorff Rapid is a 200-m long rapid (Kieffer 1988) that exists because two primary coalescing debris fans emanating from the mouths of side canyons on the right bank of the river constrict the main-channel flow (Fig. 4). Stone Creek camp is located at the downstream end of the constricting debris fan complex, immediately below the point of flow separation from the bank. Because the channel expansion downstream from the Stone Creek debris fan is only slightly wider than the constriction itself, the size of the recirculation zone is constrained, as is the accompanying bar which has a river-parallel length of 110 m and width of only 25 m. Surface flow patterns that submerge the bar at discharges greater than about 600 m^3 s^{-1} demonstrate that aggradation takes place beneath the primary eddy of the recirculation zone, and the deposit is therefore classified as a reattachment bar (Schmidt 1987).

Field observations between 1985–91 and examination of aerial and oblique photographs taken since 1965 indicate that the bar has been in its present position for at least 26 years, but bar surface elevation is now lower than it was in the mid-1970s. At the time of our experiments, the bar surface was nearly flat, except at water's edge where a vertical cutbank was being carved in the central portion of the bar near the reattachment point. The cutbank graded upstream and downstream into accretionary berms (Fig. 4). The upstream berm, closest to the debris fan, blocked the mouth of an abandoned eddy-return channel that had formed at higher stage. The subaqueous part of the bar, beginning at the base of the cutbank, consisted of a narrow, steep foreshore that trended into a flat, nearshore terrace approximately 3-4 m in width. The offshore edge of the terrace was marked by a distinct, steeply-sloping embankment that was part of the main channel.

Rapid cutbank retreat has been noted several times at this site, including June 1985 during a period following rapid decrease in discharge from 1130 m^3 s^{-1} to 990 m^3 s^{-1}. Schmidt and Graf (1990) reported that a 0.25–0.35 m high cutbank eroded 0.80–1.10 m during a 12-hr period. This cutbank was located downstream from a newly-established reattachment point. Schmidt and Graf (1990) argued that the measured erosion occurred in response to exposure of the flank of the bar to downstream flow as a result of upstream migration of the reattachment point. The influence of waves was not considered.

Fern Glen Rapid is formed by a large debris fan at the mouth of Fern Glen Canyon (Fig. 5). Our study site was located on the 150-m-long by 125-m-wide separation bar that mantles the downstream portion of the debris fan. This bar has been excavated extensively, and Rubin et al. (1992) have identified a series of inset depositional units with abundant oscillatory-flow sedimentary structures. The relief of the subaerial portion of the bar is pronounced with a series of degraded cutbanks and terrace-like surfaces that can be related to known high-flow inundations during the period 1983–86.

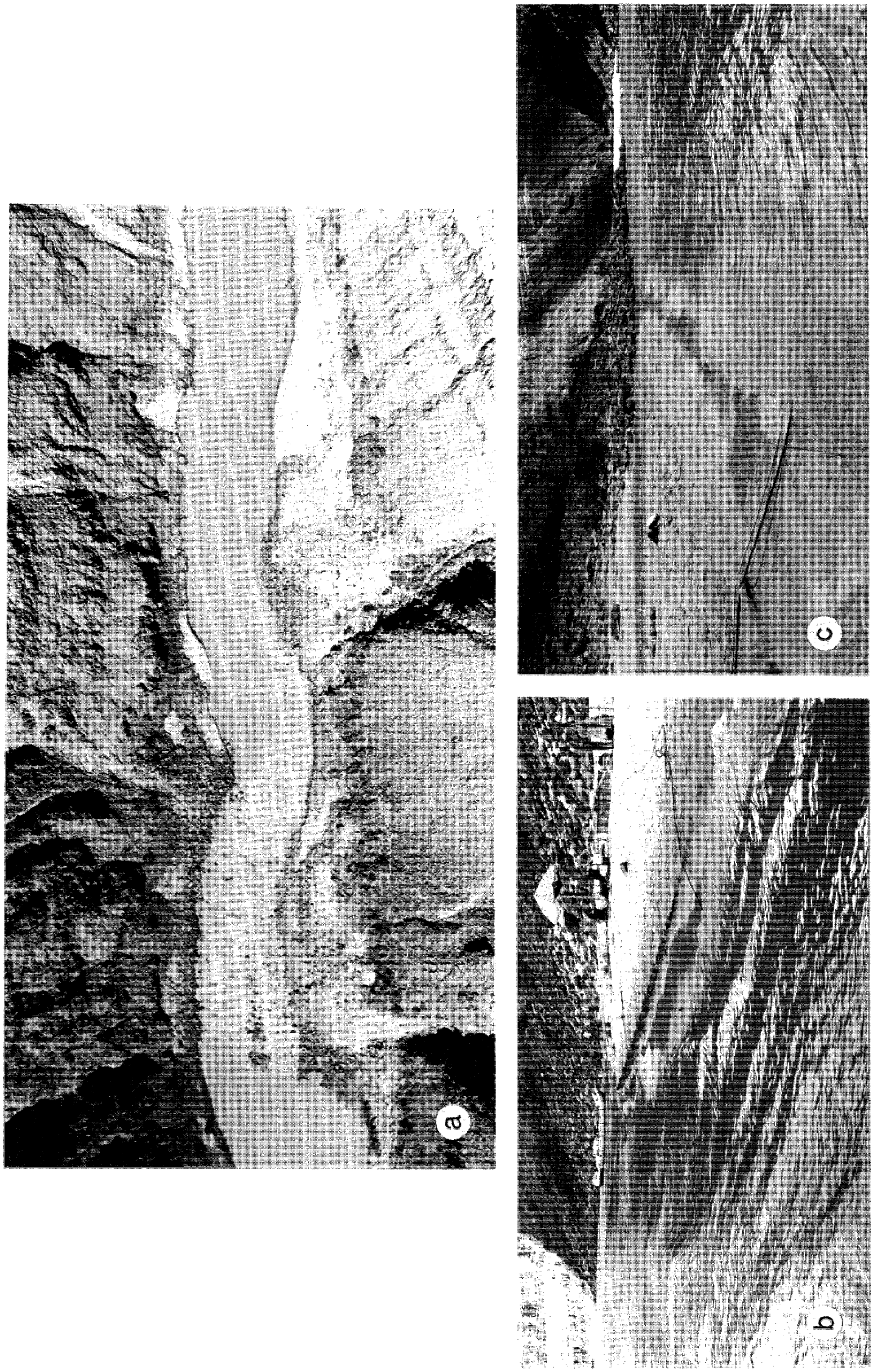


Figure 4. Stone Creek study site. (A) Air photo showing the Stone Creek reattachment bar at the lower right of the photo. (B) Downstream oblique view, May 24, 1991. (C) Upstream oblique view, May 24, 1991. Note how the erosional cutbank in the central portion of the bar trends into an accretional berm that was periodically overtopped by swash motion in the upstream portion of the bar. A closer view of this upstream portion appears in Figure 1b.

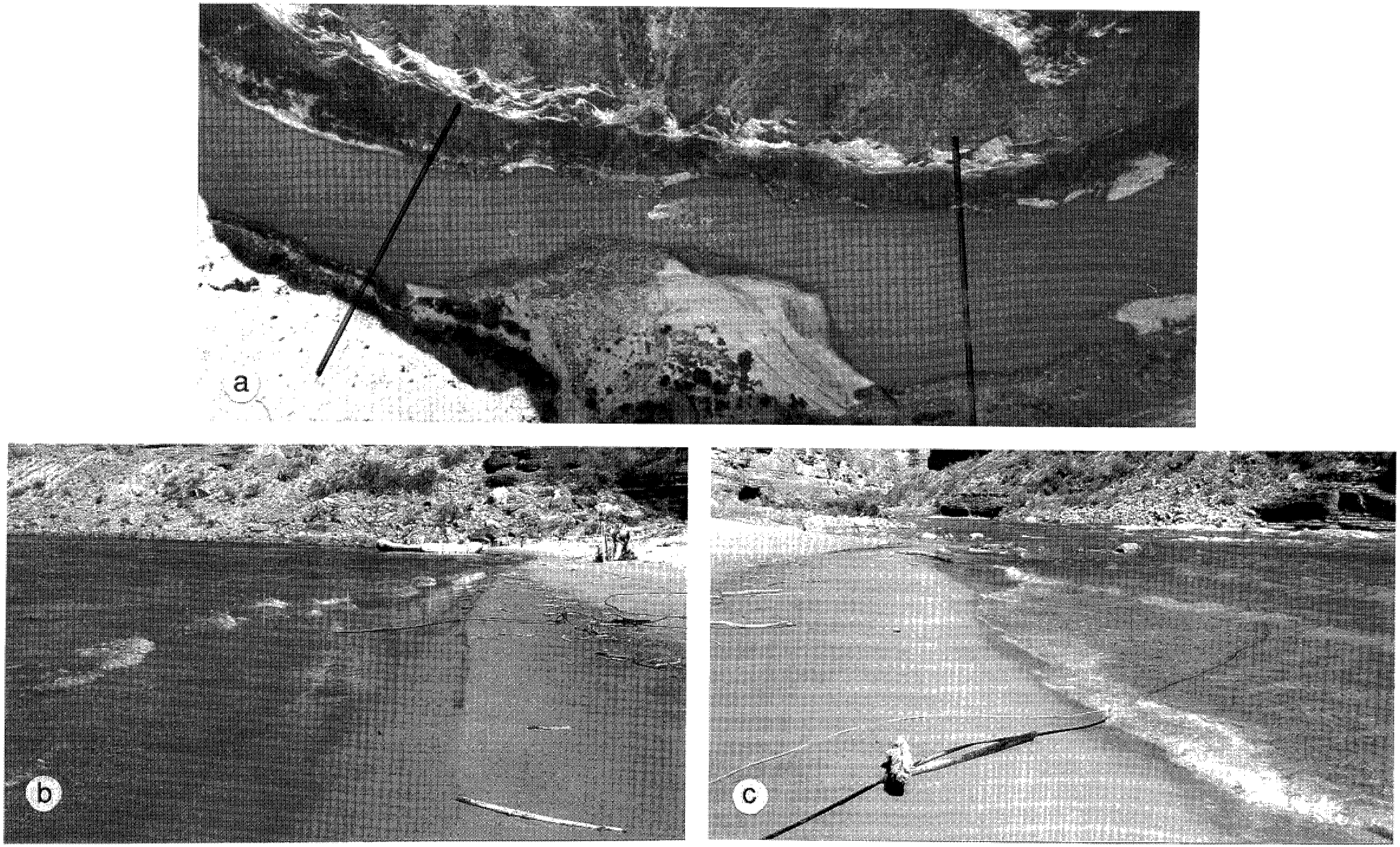


Figure 5. Fern Glen Study Site. (A) Air photo showing the Fern Glen separation bar at low stage. (B) Downstream oblique view, May 27, 1991. (C) Upstream oblique view, May 28, 1991. Note how the entire bar was rimmed by an accretionary berm at the high-water line, although the berm lost its definition in the downstream portions of the bar.

The overall planform of the bar has remained essentially constant for at least 26 years, and likely for as much as 100 years.

The subaqueous part of the bar is an upstream-migrating sand wedge or "shoal." At the time of our study, the wedge was narrowest at the downstream or distal end, and widest and shallowest at the upstream or proximal end. The upstream portion did not coalesce with the boulders of the debris deposit, but instead was truncated at a distinct slipface or avalanche slope that dropped off into an ill-defined eddy-return channel. The subaerial portion of the bar was rimmed by an accretionary berm at water's edge (Fig. 5), although the berm was poorly defined in the downstream direction because the foreshore slope became progressively steeper.

Rapid erosion rates at this site have been documented in the past. Schmidt and Graf (1990) reported large erosion rates between October 1985 and January 1986, when discharge fluctuated daily between 140 $m^3 s^{-1}$ and 570 $m^3 s^{-1}$. These fluctuating flows occurred for the first time in nearly 30 months during a period when significant erosion was documented everywhere in Grand Canyon.

Experimental Design and Instrumentation

At both field sites, fluid currents were measured using electromagnetic current meters (Aubrey and Trowbridge 1985; Guza 1988) fixed on mounts that were embedded in the substrate. These biaxial, rapid-response instruments provided information about the mean and time-varying flow field in the alongshore (river-parallel) and cross-shore directions. Submersible pressure sensors were deployed alongside the current meters to document the periodicity and height of water-elevation fluctuations associated with surface-gravity waves or other propagating surface disturbances. The electronic sensors were cable-linked to a land-based data-acquisition unit consisting of a signal-processing card installed in a laptop computer. The data-acquisition protocol was software controlled, and the data were stored directly to hard disk. Instrument signals were sampled at 4 Hz for 1026 seconds (17.1 minutes). Topographic surveys of the subaerial and subaqueous portions of the sandbars were made using an electronic distance meter and optical prism rod. Depth-of-disturbance pins (DOD) were emplaced alongside the current meters and in cross-shore arrays starting at the berm crest or cutbank and trending into deeper water to monitor erosional or depositional trends (Greenwood and Mittler 1984) and to measure accurately the changing position of shoreline features. Mean grain diameters were derived from surface grab samples that were dry-sieved at 1/4-phi intervals, weighed, and analyzed using graphical measures and the method of moments.

At Stone Creek, the electronic instruments were deployed in a river-parallel array in the zone through which oscillation of the reattachment point occurred. A current meter/pressure sensor pair (designated 'B') was located at the time-averaged reattachment point; a second instrument pair (designated 'A') 10 m upstream from 'B'; and a third current meter (designated 'C') 10 m downstream from 'B'. All the instruments were positioned in average water depths of approximately 0.40 m, just landward from the break in slope that defined the edge of the main channel. The instruments were fixed at 0.25 m above the bottom, and at each location, a cross-shore transect of DOD rods was emplaced and monitored for erosional trends. Instrument position 'A' was at the transition between the upstream accretionary berm and the erosional cutbank, whereas the other two positions were offshore from the cutbank.

At Fern Glen, the primary configuration consisted of an alongshore array of instruments and DOD rods similar to that used at Stone Creek. All the sensors were installed at 0.25 m above the bed. A current meter/pressure sensor pair was positioned approximately 10 m from the shoreline in 0.48-m average water depth (designated 'A'). A single current meter (designated 'B') was located approximately 20 m downstream from 'A', about 6 m from the shoreline in 0.52-m average water depth. The other current meter/pressure sensor pair ('C') was located approximately 40 m downstream from 'A', about 5 m from the shoreline in 0.58-m average water depth. These instruments were arranged to characterize shoreline fluid motions of greatest interest to nearshore erosional processes. In a different configuration, a current meter/pressure sensor pair (designated 'D') was located approximately 35 m from shore and 10 m upstream of the 'A' instrument transect, in about 0.85-m water depth. The latter position corresponds to the slipface or avalanche slope of the apex of the sand wedge, and the instruments placed there give an indication of the "deep-water" fluid motions incident from the main channel before depth modulation across the sand wedge (i.e., wave refraction and shoaling).

The data were analyzed using a mainframe version of BMDP-1T, a univariate and bivariate time-series routine (Dixon 1985). Summary statistics were calculated, and the time-series were detrended prior to the spectral procedures. Peak wave periods were taken directly from the energy-density spectra, and root-mean-square (RMS) currents were calculated from the total variance of each record (CERC 1984). The RMS magnitudes are indicators of composite energy levels attributable to the entire spectrum of periodic motions rather than a single monochromatic wave train. Therefore, the current meter spectra must be interpreted with care since periodic motions at different frequencies could have origins in either surface-gravity waves or in flow unsteadiness not related to wave-like deformations of the water surface.

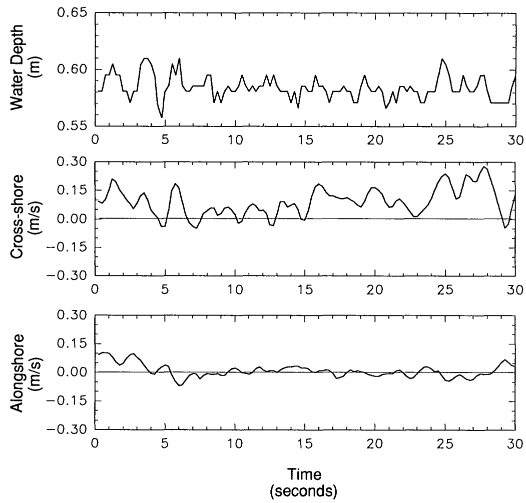


Figure 6. First 30 seconds of a time-series trace taken at the reattachment point at Stone Creek on May 24 beginning at 20:48 hours. "Water depth" refers to the height of the water column above the pressure sensor (i.e., mean height plus surface elevation fluctuations due to waves or other propagating disturbances). "Cross-shore" refers to on-offshore currents where positive numbers indicate onshore flows. "Alongshore" refers to shore-parallel currents where positive numbers indicate downstream flows. Note how the cross-shore and water-depth peaks and troughs are well-defined and positively correlated, indicating surface-gravity waves. The alongshore record shows only small fluctuations about a mean of approximately zero that are not easily correlated with the other traces.

Results

Waves and Currents

A portion of a typical time-series trace from a colocated pressure sensor and current meter pair at Stone Creek is presented in Figure 6. The associated energy-density spectra are presented in Figure 7. Although individual waves are identifiable in the time-series trace, statistically-significant energy-density peaks only appear in the cross-shore spectrum. This implies that, from a statistical viewpoint, there are few clearly identifiable wave periodicities that dominate the alongshore motion. Nevertheless, the overall shapes of these spectra are similar to those from many coastal environments. That is, there is a low-frequency ramp (0.0–0.1 Hz) of undifferentiable energy that terminates in a low-frequency energy trough (0.1–0.2 Hz) that rises abruptly to a broad-banded section of energetic motions at incident wave frequencies (0.2–0.5 Hz). The high-frequency portion of the spectrum (greater than 0.5 Hz) is more energetic than in most coastal wave environments, but this energy, perhaps due to random turbulence generation, is not of concern to the ordered sediment-transport processes under investigation.

A summary of the mean and RMS currents from the current meter records at Stone Creek are presented in Table 1 and in graphical form in Figure 8. The alongshore mean currents demonstrate that the instrument array bracketed the zone of flow reattachment. Instability in the exact location of the reattachment point through time is such that a broad zone of alternating upstream and downstream low velocity exists. At position 'A' the flow was consistently upstream (-25 cm s^{-1}); at 'C' the flow was consistently downstream (15 cm s^{-1}); at 'B' the flow oscillated between upstream and

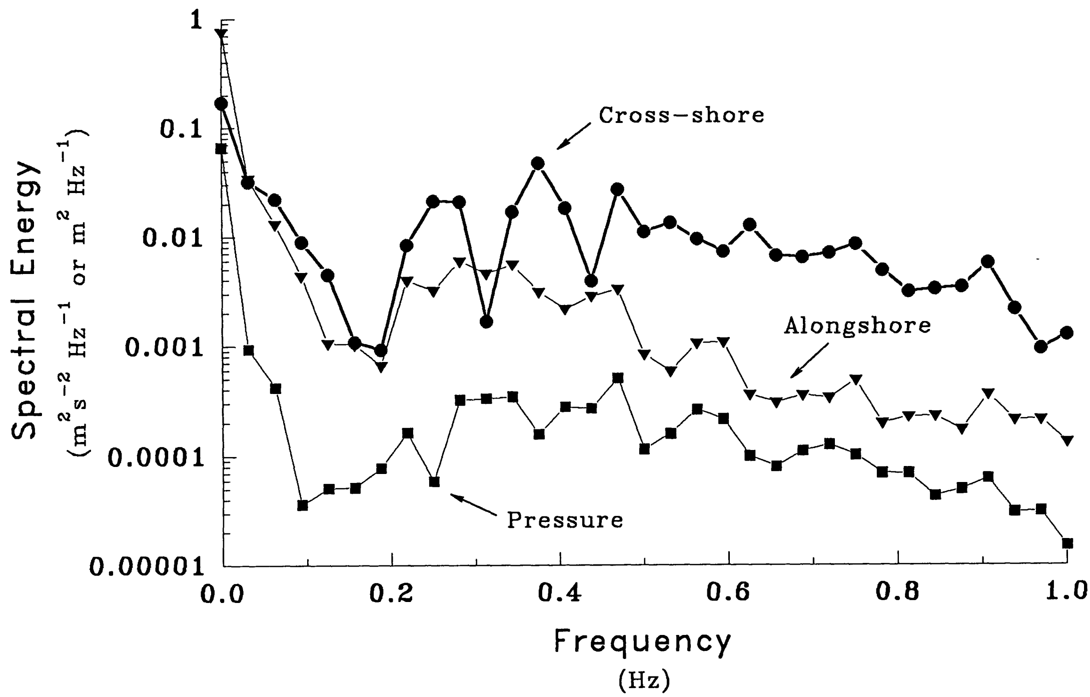


Figure 7. Energy-density spectra derived from the full time series referred to in Figure 6. The 95-percent confidence bar on the energy-density estimates is approximately equal to one-half of one logarithmic unit on the vertical axis. Note how the shape of the cross-shore current spectrum differs from the alongshore current spectrum—the latter having no statistically-significant peaks and much lower overall energy levels.

downstream components, producing a weak upstream mean (-2 cm s^{-1}). The cross-shore mean currents were small (less than 8 cm s^{-1}) and directed onshore. Thus the mean current pattern corresponds to expectation for a reattachment-point environment—onshore flows with streamwise flow divergence away from the stagnation zone. In general, the mean current field was not strong enough to entrain or transport sediment, and most sediment sizes greater than about 0.25 mm would have been deposited at the reattachment point if transported shoreward by the main channel flows (cf., Hjulström 1935).

The RMS currents in both the cross-shore and alongshore directions were of the order of 20 cm s^{-1}. These oscillations were centered about nonzero mean currents, and therefore the extreme values of the combined wave-current motions often exceeded the threshold for sediment motion—maximum orbital currents associated with bursts approached 50 cm s^{-1}. Thus inclusion of the RMS currents induced by superposed waves of RMS heights of only 5-7 cm provides for sediment transport possibilities that are not likely when mean currents are considered alone.

Characteristic energy-density spectra for Fern Glen are presented in Figure 9. The pressure sensors measured RMS wave heights of about 9–12 cm at Fern Glen, slightly greater than at Stone Creek. The dominant spectral-energy peaks were pronounced and the high-frequency energy (> 0.5 Hz) was not as appar-

Table 1. Cross-Shore and Alongshore Mean and Root-Mean-Square Currents at Stone Creek, May 24, 1991[a]

	'A'		'B'		'C'	
	x	y	x	y	x	y
Mean	5	–25	8	–2	3	15
RMS	19	23	23	25	18	21

[a]All velocities in cm s^{-1}.
'x' indicates cross-shore flow; +ve is onshore.
'y' indicates alongshore flow; +ve mean is downstream.

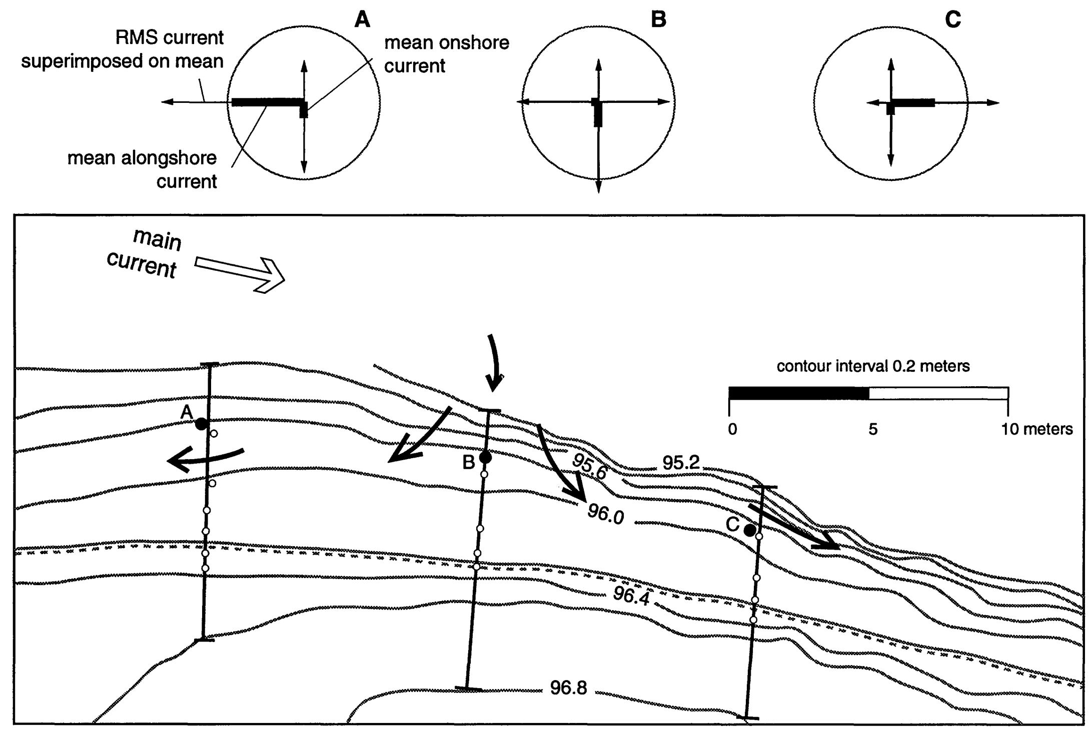


Figure 8. Stone Creek study site—topography, instrument locations, and currents. On the topographical map, the dashed line refers to the mean water line, the large open arrow refers to the direction of the primary main-channel current, and the solid arrows indicate the direction of the secondary reattachment-point currents with upstream and downstream components close to shore. Instrument positions are indicated by large solid circles and letters (current meters and pressure sensors) and by small open circles (DOD rods). Survey profiles are shown as straight black lines with ends. The circular graphs outside the box indicate the magnitude of on-offshore and alongshore velocity vectors at instrument positions A, B, and C. The circles correspond to a magnitude of 25 cm s^{-1} and the center of the circle is zero velocity. Solid bars indicate quadrant directions and magnitude of on-offshore and alongshore MEAN currents. Arrows indicate the magnitude of RMS oscillations centered about the mean.

ent. This is indicative of a stronger signal-to-noise ratio at incident wave frequencies (0.3–0.5 Hz) relative to the rest of the spectrum. The broad-bandedness of the incident energy peaks is likely due to the small wave-propagation distance between the shoreline where measurements were taken and the rapids where the waves were generated. This limited travel distance minimizes the potential for "wave sorting" due to dispersive processes, as is commonly observed in marine and lacustrine environments. The summary statistics for the alongshore transect of instruments at Fern Glen are presented in Table 2 and graphically in Figure 10. The alongshore mean currents show that flow close to shore was consistently upstream, as would be expected for locations in the upstream part of the primary eddy. These currents were of the order of 35 cm s^{-1}. The cross-shore mean currents indicate that the flow was weakly onshore at the downstream location ('C'), but became weakly offshore further upstream ('B' and 'A').

The RMS currents at 'C' were about 20 cm s^{-1} and became progressively stronger at 'B' and 'A'. Maximum orbital velocities were greater than 60 cm s^{-1} in some cases. The combined wave-current flow pattern appears to be capable of eroding the bar face and transporting entrained sediments upstream toward the slipface of the broad sand wedge. Indeed, the current meter emplaced at the lip of the slipface (position 'D') measured mean offshore flows of about 15 cm s^{-1} and mean upstream flows in excess of 35 cm s^{-1}, with RMS currents in both directions greater than 30 cm s^{-1}. It is

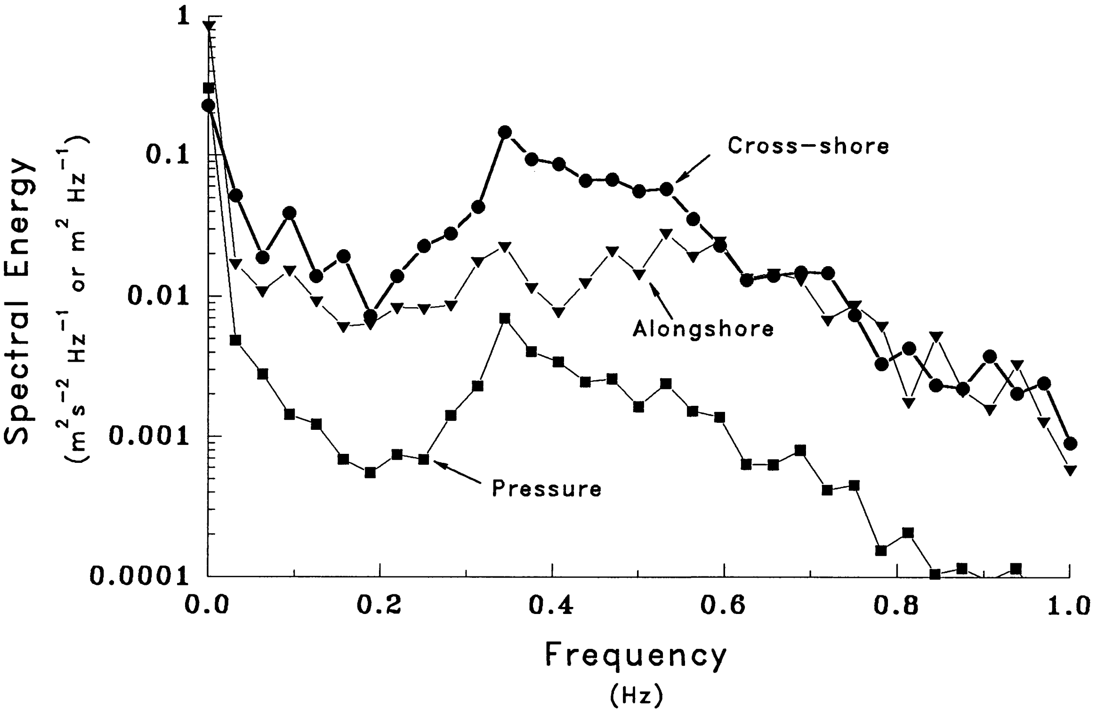


Figure 9. Energy-density spectra derived from time-series measured at Fern Glen on May 28, beginning at 10:00 hours. Refer to Figure 7 for explanation.

unlikely that net deposition could have occurred at this location under these flow conditions.

Topographical Changes

Three cross-shore profiles (corresponding to instrument positions) measured at Stone Creek on May 24 are presented in Figure 11. The erosional cutbank was most pronounced in the central portion of the bar ('B'), and the foreshore slope below this cutbank was the steepest. Upstream and downstream from the reattachment point, the erosional cutbank graded into an accretional berm, and the adjoining foreshore slopes became progressively shallower. A subaqueous terrace aproned the sandbar, and the terrace was widest upstream from the reattachment point (approximately 4–6 m) and became progressively narrower in the downstream direction (approximately 2–3 m). Table 3 shows the changes in the profiles after 18 hours of monitoring (May 24; 14:00 to May 25; 8:00). Linear erosion rates of the cutbank were between 0.5–0.6 m day^{-1}. Associated with this cutbank retreat was a widening of the foreshore ramp and a decline in foreshore slope angle. No significant erosion or accretion on the subaqueous terrace was measured.

Three cross-shore profiles for Fern Glen on May 26 are presented in Figure 12. The downstream profile ('C') was steep and essentially featureless. In contrast, the upstream profile ('A') had an extensive subaqueous terrace of shallow gradient that extended almost 35 m offshore before it plunged into the main channel. At the interface between the terrace and

Table 2. Cross-Shore and Alongshore Mean and Root-Mean-Square Currents at Fern Glen, May 28, 1991[a]

	'A'		'B'		'C'	
	x	y	x	y	x	y
Mean	−10	−30	−6	−38	1	−35
RMS	36	27	27	23	20	18

[a]All velocities in cm s^{-1}.
'x' indicates cross-shore flow; +ve mean is onshore.
'y' indicates alongshore flow; +ve mean is downstream.

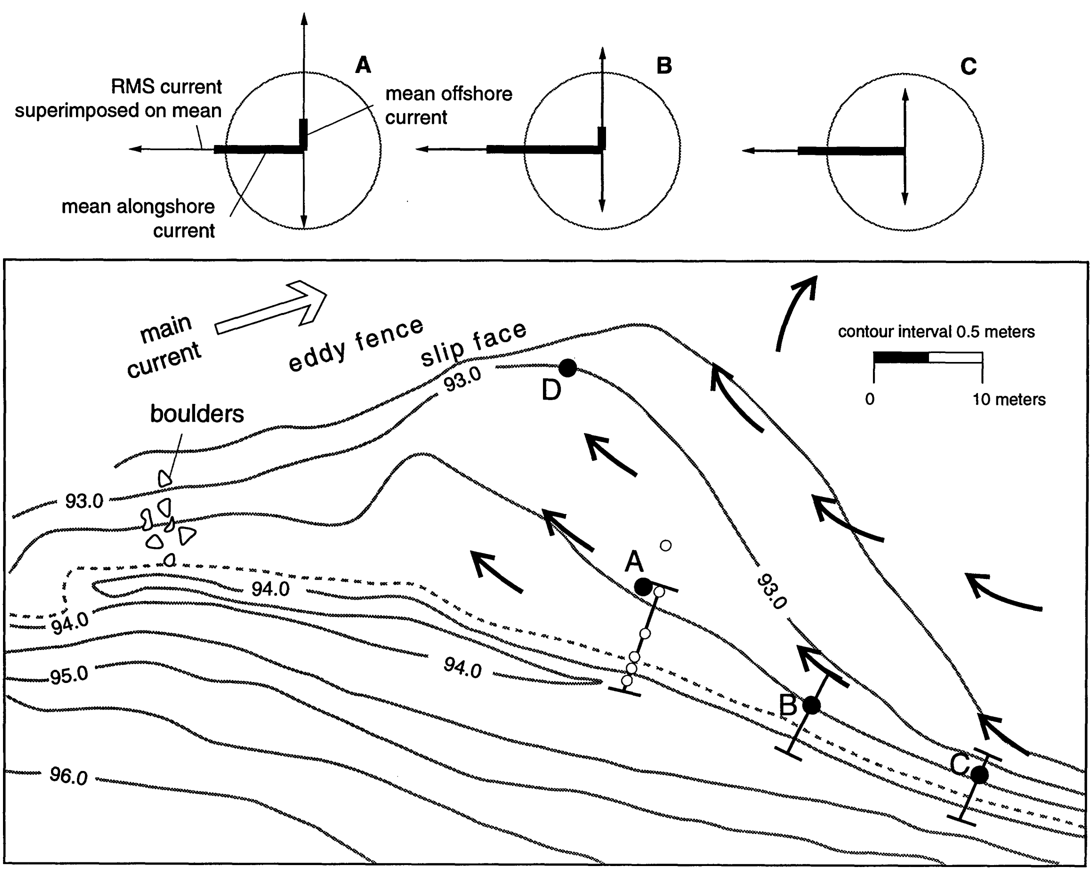
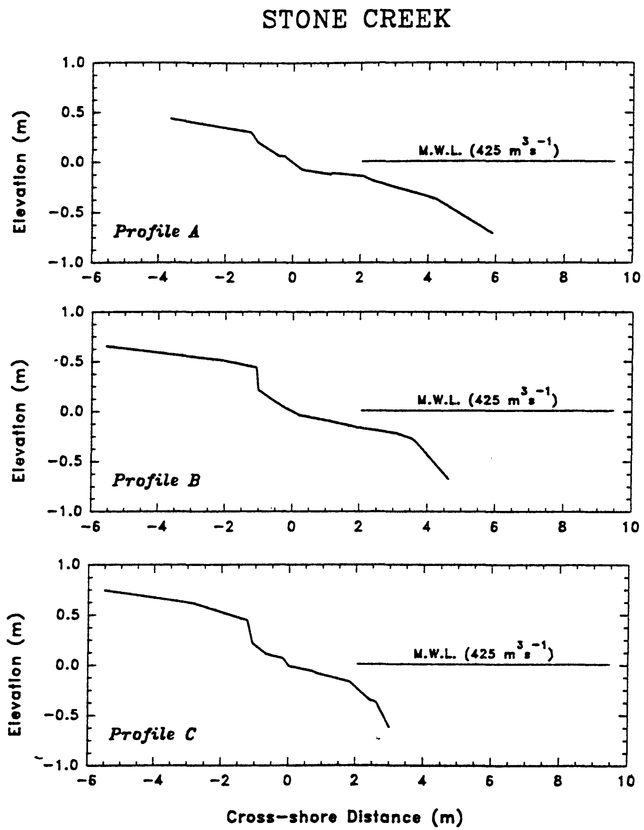


Figure 10. Fern Glen study site—topography, instrument locations, and currents. Refer to Figure 8 for explanation of symbols.

the foreshore, there was a distinct break in slope and an accretional berm was being built by the swash motion. Table 4 reports the topographical changes measured along profile 'A' from May 26–28. The foreshore retained essentially the same slope angle (about 0.16) despite lateral retreat of the foreshore of 0.55 m over the two-day measurement period. The corresponding linear erosion rates (0.25 m day^{-1}) are about half those measured at Stone Creek.

Prediction of Beach Equilibria

The survey data show that the sandbars at both study sites were being eroded progressively during this short-term study. Clearly, linear erosion rates of the magnitude measured cannot be sustained indefinitely because the entire deposit would be eliminated in matters of weeks. Negative feedback processes must ultimately prevail because bars at both study sites have persisted for decades, including a 14-year period from 1966–79 when annual peak discharges did not overtop either bar. The short-term geomorphic response of a particular sandbar must depend not only on the characteristics of the contemporaneous local hydrodynamic environment, but also on antecedent conditions and flow history. The flow history prior to our study was somewhat unusual. For the 10-day period before May 21, discharge releases from the dam were constant at 285 m^{3}s^{-1}. On May 21, discharge was raised to 425 m^{3}s^{-1}, and these flows remained steady for the rest of the month. Thus the study sites were likely in disequilibrium immediately after May



igure 11. Selected cross-shore profiles for Stone Creek, May 24, 1991. rofile designations A, B, and C refer to instrument positions shown in Figure .

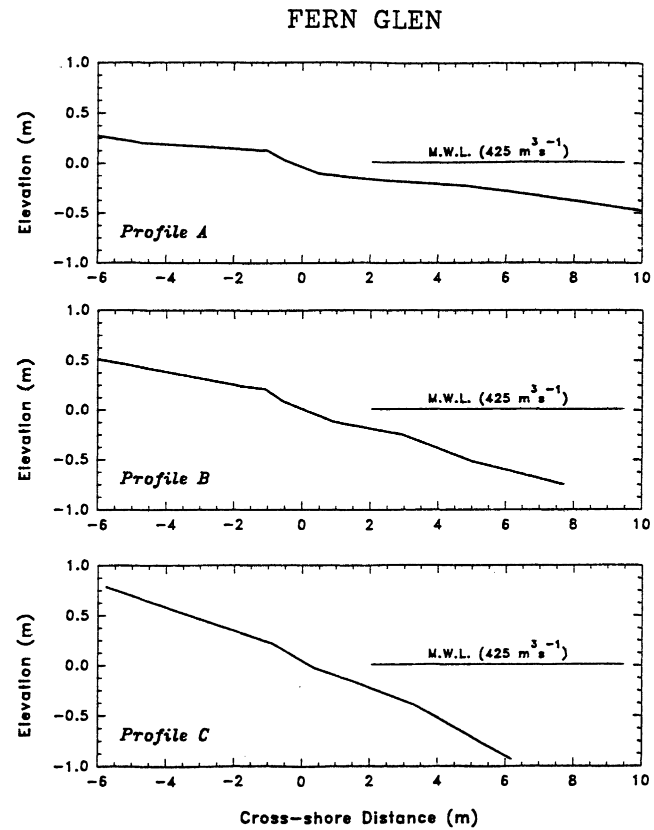


Figure 12. Selected cross-shore profiles for Fern Glen, May 26, 1991. Profile designations A, B, and C refer to instrument positions shown in Figure 10. Note that the scale in this figure is the same as that in Figure 11, and therefore differences in profile shape are truly represented.

Table 3. Stone Creek Erosion Rates, May 24–25, 1991

Profile	Foreshore slope	Linear erosion	Duration
'A'	.138 → .112	46 cm (61 cm/day)	18 h
'B'	.208 → .182	45 cm (60 cm/day)	18 h
'C'	.156 → .135	38 cm (47 cm/day)	18 h

Table 4. Fern Glen Erosion Rates at Profile 'A', May 26–28, 1991

Time	Foreshore slope	Linear erosion	Duration
26:16:45	.152		
27:09:40	.163	21 cm (25 cm/day)	20 h
28:10:40	.158	19 cm (25 cm/day)	18 h
28:18:30	.172	15 cm (30 cm/day)	12 h

21 while the sandbar faces were adjusting to newly imposed flow conditions. The rapid erosion rates observed during our study are consistent with speculations by Schmidt (1987) that bar erosion is most pronounced immediately following large changes in reservoir-release regime.

A major disturbance in the state of a geomorphic system usually initiates a sequence of adjustments that tends to take the system toward equilibrium conditions thought to be associated with recognizable characteristic forms. The coastal-process literature is replete with empirical relations that purport to predict nearshore equilibrium slopes on the basis of such parameters as wave steepness, wave period, grain size, or grain settling velocity (e.g., Bowen 1980; Dean 1977; Dean and Maurmeyer 1983; Eagelson et al. 1963; Watanabe, et al. 1980). An empirical equation proposed by Sunamura (1984) is particularly useful in the case of Grand Canyon sandbars because the relation predicts equilibrium foreshore-slope angles,

$$\tan\beta = 0.12\left(\frac{H_b^2}{gDT^2}\right)^{-1/4} \quad (1)$$

where H is wave height, D is grain size, T is wave period, g is gravitational acceleration, $\tan\beta$ is foreshore slope angle, and subscript 'b' refers to breaking conditions. For Stone Creek and Fern Glen, RMS wave heights were estimated from the pressure sensor records which were rectified for depth attenuation (e.g., CERC 1984). Wave periods were determined using the energy-density spectra—a range of wave periods was identified for each spectrum, corresponding to the upper- and lower-frequency bound of the dominant, broad-banded incident-wave-energy peak. Incorporating these values into equation (1), yields a range of potential equilibrium slopes of $.17 < \tan\beta < .20$ for Stone Creek (Profile B), and of $.10 < \tan\beta < .12$ for Fern Glen (Profile A). Comparing these predictions to the values reported in Tables 3 and 4 shows that there is good agreement between the measured and predicted equilibrium slopes for Stone Creek, but for Fern Glen, the measured slopes are steeper than the equilibrium values. On the basis of these results alone, one might be tempted to conclude that the Stone Creek foreshore was "in equilibrium" with incident wave motion and should have been relatively stable, whereas the Fern Glen foreshore was not "in equilibrium" with the wave motion and should have been susceptible to greater change. The linear erosion rates reported in Tables 3 and 4 clearly indicate, however, that Stone Creek was experiencing greater change.

It is of interest to determine whether coastal theory is able to assess correctly the observed erosional tendency of both sandbars. An empirical relationship proposed by Sunamura and Horikawa (1974) can be used to predict nearshore profile response to imposed wave conditions,

$$C_s = \frac{H_0}{L_0}(\tan\beta)^{0.27}\left(\frac{D}{L_0}\right)^{-0.67} \quad (2)$$

where H is wave height, L is wave length, D is grain size, $\tan\beta$ is foreshore slope, and subscript 'o' refers to deep-water conditions. A value of the parameter C_s less than 4 indicates an accretionary system, whereas a value of C_s greater than 8 indicates erosive conditions. In our study, deep-water wavelengths were determined using upper- and lower-frequency bounds of spectral-energy peaks to solve for wavelength using linear-wave theory (e.g., CERC 1984). First- or second-order Cnoidal theory yields solutions that are not significantly different from linear theory, and the added precision is not justified given inherent uncertainties in the data-collection methods. Incorporating these values in equation (2) predicts values for C_s of about 4-6 for Stone Creek and of about 10-13 for Fern Glen. These results imply that the Stone Creek foreshore should have been relatively stable, contrary to observation, whereas the Fern Glen foreshore should have been erosional, which it was. A different model of beach change, based on wave steepness and sediment fall velocity (Dean 1973), yields similar predictions and corroborates the results of equation (2).

One of the distinctive morphological features at both study sites was an accretionary swash berm at the high-water line. This was especially prevalent at Fern Glen where the berm rimmed the water's edge along the entire length of the bar. Even at Stone Creek, only the central portion of the bar had a scarp, and the upstream and downstream ends were capped by a berm. An empirical relationship proposed by Takeda and Sunamura (1982) can be used to predict the expected height of a berm that would be built on a beach by swash motion. This relationship depends only on average height of breaking waves and on average wave period,
Using the range of wave periods indicated by the energy-density spectra yields a range of

$$Z_{bm} = 0.125\bar{H}_b^{\frac{5}{8}}(g\bar{T}^2)^{\frac{3}{8}} \quad (3)$$

expected berm heights of 0.12–0.14 m for Stone Creek, and of 0.12–0.17 m for Fern Glen. Although berm heights were not measured directly during this study, the photos in Figures 1, 4, and 5 demonstrate that these predictions are consistent with field conditions.

Discussion

One of the objectives of this study was to evaluate the potential utility of coastal-geomorphic theory for analyzing sandbar stability in Grand Canyon. For Stone Creek, the theory correctly predicted foreshore slope angle, but incorrectly predicted bar-face response. For Fern Glen, the observed erosional trend was predicted correctly, but foreshore slope angle was under-predicted. At both sites, observed berm heights were predicted reasonably well. There are at least two ways to rationalize such mixed results: (1) the theory is inadequate, or (2) the theory has been applied inappropriately.

There are myriad shortcomings to the theory, in large part, because many of the models of beach-face evolution are two-dimensional whereas most natural systems are three-dimensional and complex. Komar (1976, 308) summarized the situation as follows,

> It is apparent that there are several variables which affect the slope of the beach face. The most important is the grain size of the beach sediment, coarser beaches having steeper beach slopes. Added to this is the effect of the wave energy level: for a given grain size, higher energies (wave heights) produce lower beach slopes. Other factors are the wave steepness (storm versus swell profile), the degree of sediment sorting, the level of the water table in the beach, and the stage of the tide. With all these semi-independent factors acting together, a considerable variation in the beach face slope is produced which is generally difficult to sort out and understand. Because of this, quantitative predictions of beach slopes are still remote.

We have tried to accommodate some of this inherent uncertainty in our study by calculating ranges of expected values, rather than specific values, to be used as crude indicators only.

It could also be argued that, since equations (1)-(3) were developed for coastal systems, it is not appropriate to apply them to a fluvial environment. Despite the truism, reflection on why an observed system looks or responds differently from what theory suggests often provides insight into natural processes. In this context, it is instructive to consider a simplified, two-dimensional, conceptual model of coastal-beach response in the presence of 'swell' and 'storm' waves (Fig. 13). It has been recognized for some time (see the summary in Komar 1976, ch. 11) that waves of small steepness (H_0/L_0 less than approximately 0.015) tend to be associated with 'swell' profiles that decay exponentially offshore and are essentially featureless except for a pronounced subaerial berm. This concave, bermed profile is created by onshore transport of sand and subsequent deposition on the foreshore by swash motion. In contrast, steep waves (H_0/L_0 greater than approximately 0.03) tend to be associated with

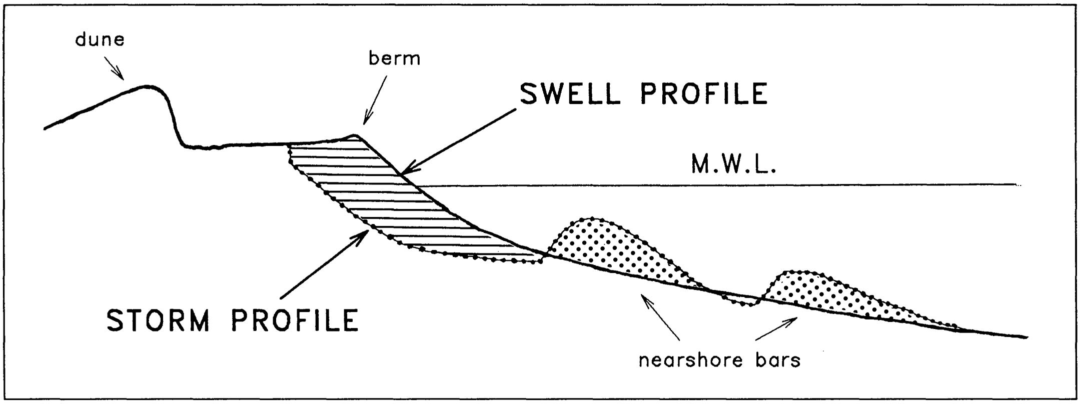


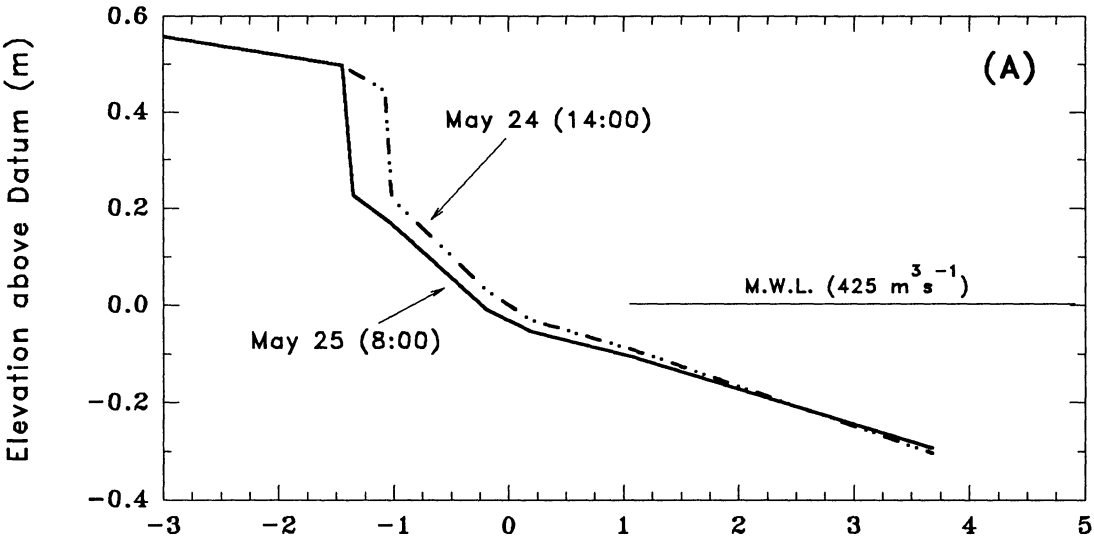
Figure 13. Conceptual model of coastal beach response to varying wave conditions. The "swell" profile occurs under constructional swell waves and has an exponential profile with an accretional berm. The "storm" profile occurs under erosive storm waves and has a sequence of nearshore bars. The lined portion is the volume of sediment eroded from the swell profile and it is equal to the stippled portion deposited offshore as nearshore bars. Under constructional swell, the stippled volume is transported onshore and a new berm is built.

erosion of the subaerial beach, offshore sand transport, and creation of a sequence of nearshore bars—the 'storm' profile. Periodic exchanges of sediment between subaqueous nearshore bars and the subaerial berm are driven solely by changes in incident wave conditions. Total volume of sediment in the nearshore prism of this two-dimensional system remains essentially constant because the nearshore bars act as temporary sediment storage reservoirs until fair-weather swell waves are able to move sediments back onshore to rebuild the berm.

In the eddy-recirculating systems of Grand Canyon, such two-dimensional, cross-shore sediment exchanges are unlikely for two reasons. First, the character of the wave field is not linked directly to meteorological events such as wind storms. Rather, the waves are generated by quasi-ordered turbulent processes in the rapids or along the eddy fence. For any fixed debris fan geometry, the character of the turbulence in the rapids, the location of the separation and reattachment points, and the intensity of vortex-shedding are related only to discharge. Under these constraints, the only way to alter the wave field is to change discharge, but associated with a change in discharge is a vertical shift in mean water level, and therefore a horizontal displacement of the water line and location of incident wave energy. Thus different types of waves (i.e., erosional 'storm' waves versus constructional 'swell' waves) act on different vertical sections of the sandbar, or alternatively, the same types of waves always act on the same portion of the bar. This relationship may remain constant for decades until the entire geometry of the debris-fan bathymetry is reconfigured, as has occurred in the past when flash floods in the side canyons have delivered cobbles and boulders to the debris-fan system, or during extreme floods in the main channel that rearrange the large boulders underlying the rapids (Kieffer 1988).

Second, the offshore transport of sand in a fluvial system rarely creates sediment storage reservoirs such as nearshore bars. The nearshore terraces that apron most sandbars are usually narrow, steeply-inclined, and affected by three-dimensional mean current fields that have dominant vectors in the alongshore direction. Sediments stripped from the foreshore by waves are transported toward the main channel where they are effectively lost from the nearshore system. Nearshore bars never have the opportunity to form, and the constructional phase of the coastal model is never realized.

Figure 14 shows measured nearshore profile changes at Stone Creek and Fern Glen. We believe that both sandbars experienced erosion for essentially the same reason—an inade-



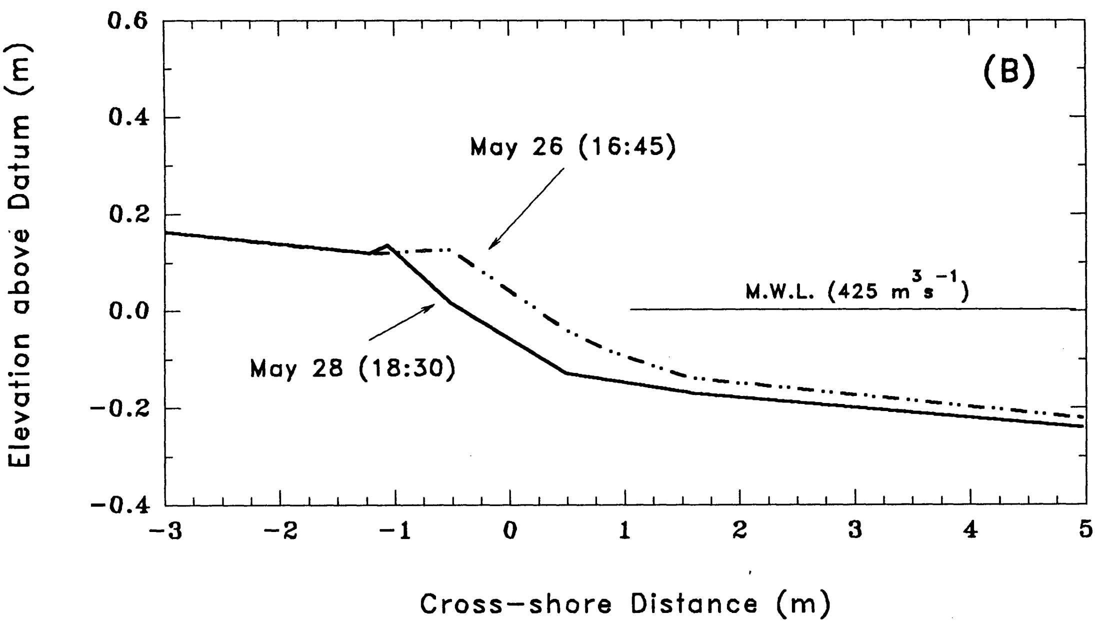


Figure 14. Measured change in foreshore profiles at (A) Stone Creek, and (B) Fern Glen. Note that the profiles are represented at the same scale.

quate supply of sediment available to the foreshore swash system. For the case of Stone Creek (Fig. 14a), it is noteworthy that the erosional trend was not predicted by coastal theory, despite the presence of constructional 'swell' waves with maximum steepnesses less than 0.005 *and* despite onshore-directed mean currents. Had there been an adequate supply of sediment on the nearshore terrace, the foreshore might have been stable or accretional.

But no sediment was being injected into the eddy from the main channel via the reattachment currents because the main-channel flow was relatively sediment-free during our study. Nor was there a nearshore bar on the narrow terrace to act as a local sediment supply for the constructional swell waves. Thus each cycle of wave uprush and backwash on the foreshore produced net erosion of the bar face because the uprush phase was relatively free of sediment upon entering the foreshore. The turbulence of the uprush entrained sediments on the foreshore and occasionally undermined the base of the scarp. The backwash phase carried these entrained sediments down to the base of the foreshore where they were transported alongshore (upstream and downstream) by the diverging branches of the recirculation currents. A slight decline in foreshore slope angle and concomitant widening of the foreshore ramp occurred because linear retreat of the cutbank scarp was faster than linear migration of the foreshore toe. In the central portion of the bar, the top of the erosional scarp was always higher than the vertical extent of the swash motion. Thus overtopping of the cutbank was not possible and an accretionary berm could not be built, as was the case farther upstream and downstream.

Profile adjustment at Fern Glen (Fig. 14) was characterized by parallel retreat of the foreshore and berm assemblage. This retreat involved linear erosion of the foreshore face, as predicted by theory, and the maintenance of a constant foreshore slope angle (Table 4) greater than that predicted by theory. Again, the erosional trend may be associated with sediment-starved conditions at the base of the foreshore. The mean currents on the nearshore terrace were directed offshore and upstream, as expected for an eddy-recirculation system. Note that these mean currents need never have exceeded the threshold for sediment motion in order for net erosion of the terrace surface to have occurred because the superimposed wave motion acted as a sediment-agitation mechanism—the currents merely provided a net directional drift to the transport system. Sediments entrained on the foreshore by swash processes were either dragged to the base of the foreshore, where they were transported offshore and upstream to the slipface of the eddy-return channel, or moved upslope and deposited on the berm (during large uprush excursions). Deposition at the base of the foreshore, as suggested by the two-dimensional coastal model (Fig. 13), was made improbable by the three-dimensionality of the recirculating eddy.

Summary and Conclusions

Eddy-recirculation systems downstream from major rapids in bedrock canyons are special (but not unusual) fluvial environments because the main-channel flow field is not the sole determinant of depositional or erosional processes along the shore. Surface-gravity waves and secondary recirculation currents associated with streamline separation and flow reattachment are also important in determining the pattern of sediment storage and redistribution in eddy systems. Tractive force models that ignore waves will typically predict net deposition in the slack-water environment of the eddy as a response to relative velocity difference between the main-channel and recirculating currents, or to sediment concentration gradients (e.g., Andrews 1991; Nelson 1991). Addition of waves to the overall flow field, however, creates sediment entrainment and transport possibilities that are otherwise unlikely. Mean recirculating currents that are below the threshold of motion can be erosive in the presence of waves because sediments can be put into motion locally by the agitating effect of oscillatory currents. Under this scenario, sediments stored in the eddy system might be stripped away, causing net erosion of the bar deposit, and sediments introduced to the eddy from the main channel might pass through the system altogether with no net deposition. Predictions of bar aggradation and regeneration at high stage should therefore take into account the oscillatory overprint described in this report.

A comprehensive explanation of process-response relationships observed at our Grand Canyon study sites incorporates the interactive and reinforcing roles of waves and currents. The foreshore and berm assemblages were, in large part, controlled by the character of the swash motion, and therefore had the form of a coastal, wave-dominated beach. The foreshore slopes, however, did not reach the full equilibria predicted by coastal theory because there was an inadequate supply of sediment being delivered to the swash motion from offshore. This sediment-starved condition was a direct consequence of the entire offshore region being dominated by relatively persistent unidirectional currents associated with the fluvial recirculation eddy. Sediments delivered to these currents from the foreshore were transported offshore and alongshore toward the main channel. On the foreshore, sediments were being rearranged intermittently by swash motion, and some sediment even accumulated on the berm when swash excursions were large enough to overtop it. The net effect of a sequence of uprush and backwash cycles, however, was an erosive one.

A great deal of geomorphic research has addressed the existence of characteristic forms that are thought to be indicative of equilibrium process-response relationships in geomorphic systems. The results of this study, although not contrary to this notion, argue for a careful and circumspect interpretation of geomorphic form, especially in the absence of process measurements. Specifically, certain landscape features, such as the foreshore and berm assemblage at Fern Glen, can have a pronounced accretional appearance, even though the dominant process is erosional. From a management perspective, the presence of waves in eddy-recirculation systems confounds a simple inventory of the stability characteristics of sandbars on the basis of geomorphic form or mean surface-flow patterns only. How the Stone Creek and Fern Glen eddy systems might have responded geomorphologically under similar hydrodynamic conditions as during our study, but with large influxes of sediment from the main channel, is unclear. Similarly, the relationship between discharge regime and the character of the wave field downstream of major rapids is a critical component of sandbar stability that has yet to be determined.

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