RECIRCULATING FLOW AND SEDIMENTATION IN THE COLORADO RIVER IN GRAND CANYON, ARIZONA[1]

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ABSTRACT

Debris fans debouching into the bottom of Grand Canyon create rapids and flow separation in the Colorado River. The patterns of flow and the behavior of recirculation zones formed by flow separation are consistent throughout the Canyon's length. Zones of recirculating flow occur along the margin of channel expansions. Recirculation zones are comprised of one primary eddy; secondary eddies and areas of unorganized low velocity may exist upstream from the primary eddy. The longest recirculation zones are formed by channel constrictions of low width-to-depth ratio. Recirculation zones increase in length with increasing discharge. Sand bars form beneath recirculation zones, especially near separation and reattachment points. Reattachment bars project upstream from the reattachment point and underlie primary eddies. Separation bars mantle the downstream parts of the debris fans and form beneath secondary eddies and low-velocity areas. Sediment that forms reattachment bars is dominated by sizes characteristic of suspended load, while sediment that forms separation bars is finer. Reattachment bars are more common than separation bars, and both occur more frequently and are larger in wide reaches. The form and location of these bars is consistent with the location and behavior of stagnation points; however, the locations of these stagnation points change. Although velocity increases in the main channel at high discharges, velocities near the separation and reattachment points remain low. Sedimentation can occur in a bedrock gorge at high discharges and low transport rates, although the location of high-discharge sand bars may differ from those deposited at lower flows.

INTRODUCTION

Zones of recirculating current exist in most rivers wherever flow separation occurs, such as just downstream from sharp meander bends, elsewhere near meander bends, and near bank irregularities. Sedimentation within these zones reflects local current direction, which may be opposite the main current direction, and may be a cause of anomalous paleoslope indicators in paleogeographic studies of fluvial sedimentary rocks (Taylor et al. 1971). Although recirculating currents typically constitute a minor portion of the total volume of streamflow in alluvial settings, these zones comprise larger portions of streams where width is constrained by bedrock, such as the Colorado River in Grand Canyon. Study of the patterns of flow and sedimentation in a river with large persistent recirculating currents provides insight into the behavior of these processes elsewhere.

This paper examines recirculating flow in Grand Canyon. It describes (1) the channel expansions where large zones of recirculating current exist, (2) patterns and hydraulic characteristics of recirculating flow, and (3) topographic and sedimentary characteristics of associated bars. These results suggest that, in some rivers, changes in flow pattern may be as important as changes in hydraulic conditions in determining where sedimentation and erosion occur.

PREVIOUS WORK

Matthes (1947) catalogued many forms of macroturbulence in rivers, including the type discussed here. Page and Nanson (1982) and Nanson and Page (1983) described concave-bank benches formed by recirculating currents. Leeder and Bridges (1975) related the occurrence and size of the zone of recirculating currents at meanders to channel width and bend curvature. Alluvial "slackwater" deposits formed by flood-stage recirculating currents have been identified in many paleohydrologic studies (Baker 1974, 1977; Baker et al. 1983).

McKee (1938) described the sedimentology of flood-discharge alluvial deposits, and Howard and Dolan (1981) related the location of sand bars in Grand Canyon to recirculating currents at low discharge. Kieffer (1985, 1987, 1988) described hydraulic characteristics and measured surface velocities of floats

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at some large rapids. Schmidt (1986) proposed the terms separation deposit, reattachment deposit, and eddy-center deposit for bars formed near the separation point, reattachment point, and center of the primary eddy, respectively. Schmidt (1987) and Schmidt and Graf (1990) found that reattachment deposits were more extensively eroded by high discharges between 1983–85 than were separation deposits.

Many open-channel flume experiments have considered the nature of flow separation (e.g., Abbott and Kline 1962; Chang 1966; Durst et al. 1974; Kindsvater and Carter 1954; Rouse et al. 1951). Most laboratory experiments have analyzed flow separation at subcritical flow conditions with width-to-depth ratios of 3–10; the Colorado River in Grand Canyon has width-to-depth ratios of 7–50. Allen (1984) summarized extensive research concerning sedimentation in recirculating currents in the lee of ripples and dunes but did not discuss these processes on a larger scale.

STUDY AREA AND RECENT FLOWS

The study area was 375 km of the Colorado River in Grand Canyon, between Lees Ferry and Diamond Creek, Arizona (fig. 1). Glen Canyon Dam is 25 km upstream from Lees Ferry. Badger Creek Rapids, the subject of many examples in this paper, is located 12 km downstream from Lees Ferry and is the first major rapids encountered by river float trips.

Closure of Glen Canyon Dam in 1963 greatly reduced sediment transport by the Colorado River. The average annual suspended load at Lees Ferry for the period 1963–65, prior to discontinuance of these measurements, was 89% less than the average load of the 11 yr period immediately prior to dam construction (Laursen et al. 1976). In 1983, mean grain size of suspended sand sampled at five gaging stations in Grand Canyon was 0.29 mm (fig. 2, curve 1). About 40% of the suspended sand load was finer than 0.25 mm, and about 43% was between 0.25 and 0.50 mm. Much of the bed was of similar size. Mean thalweg grain size at the same gages was 0.3 mm, and more than 60% of the bed material was between 0.25–0.50 mm (fig. 2, curve 2). At times when tributaries downstream from the dam contributed flow to the

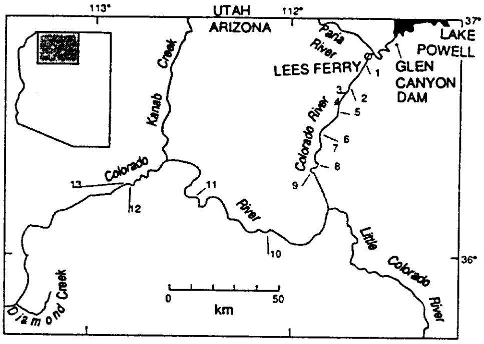


FIG. 1.—Location of study area and study sites listed in table. 1.

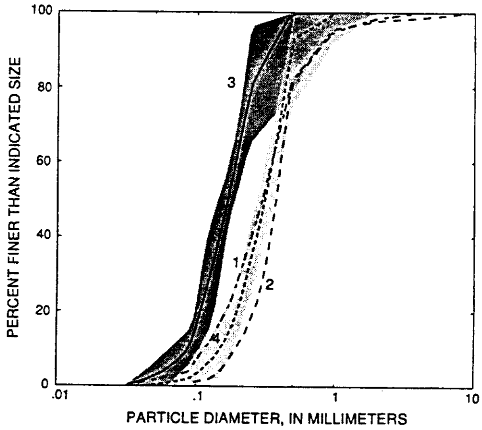


FIG. 2.—Graph showing composite particle-size distributions for samples of suspended sand and thalweg bed material sampled in 1983 and of separation and reattachment bars deposited by high flows between 1983–85. 1 (long and short dashed line) = composite of 1983 suspended sand load at 5 gaging stations (Randle and Pemberton 1987); 2 (long dashed line) = composite of thalweg sampled in 1983 at five gaging stations (Pemberton 1987); 3 (solid line) = composite of 26 samples of separation bars collected at 12 sites; 4 (short dashed line) = composite of 26 samples of reattachment bars collected at seven sites. Shaded area of 3 and 4 is within 1 standard deviation of sample mean.

Colorado River, suspended sediment finer than 0.0625 mm sometimes exceeded 90%. At other times, the percentage typically was between 5–20% (Pemberton 1987).

An unusual flow regime between 1983–86 provided an opportunity to observe formation and reworking of sand bars. Unprecedented post-dam discharges in excess of 2,800 m^3/s in 1983 had eroded and deposited sediments adjusted to the regime of the preceding 18 yr (Beus et al. 1985; Brian and

TABLE 1

LENGTH OF RECIRCULATION ZONES AT 13 SITES

Site Number	Site Name	Unconstrained recirculation-zone length, in meters, at indicated regime[a]		
		Low	Moderate	High
1.	Above Cathedral Wash	110	130	180
2.	Badger Creek Rapids	220	290	310
3.	Soap Creek Rapids	0	290	320
4.	Below Salt Water Wash	250	270	360
5.	Eighteen Mile Wash	180	200	200
6.	Twentynine Mile Rapids	240	330	320
7.	Nautiloid Canyon	230	460	. . .
8.	Eminence Break Camp	300	510	700
9.	Saddle Canyon	. . .	280	360
10.	Granite Rapids	. . .	270	300
11.	One Hundred Twentytwo Mile Creek	. . .	270	280
12.	National Rapids	230	270	. . .
13.	Fern Glen Rapids	. . .	550	550

[a] See text for definition of regimes; for discharge at time of each measurement, see Schmidt and Graf, 1990, table 1.

Thomas 1984; Schmidt and Graf 1990). During the study period, releases from Glen Canyon Dam were higher and more steady than those which occurred since completion of the dam. Mean discharge of releases from Glen Canyon Dam was 765 m^3/s, more than twice the mean discharge of 310 m^3/s of the period 1965–82. During the 1983–85 period, median monthly discharge fluctuation, defined as the difference between monthly average maximum discharge and monthly average minimum discharge, was 80% less than during the period 1976–82. Discharge during the period 1983–85 included sudden shifts from one prevailing regime of steady flow to another. For example, discharge averaged about 1,275 m^3/s for two months but was decreased during a four-day period to about 850 m^3/s in 1985. Once this lower discharge was reached, the new rate persisted for several months. Each precipitous decrease in discharge exposed sand bars that had adjusted to the previous higher flow regime.These decreases permitted comparison between flow conditions and sand bar location and form.

DATA COLLECTION AND METHODS

Field data were collected during five river trips between August 1984 and January 1986. Topographic surveys, photograph replications, maps of surface-flow patterns at different discharges, velocity measurements, surveys of water-surface slope, and descriptions of sandbar sedimentology were made at 13 sites at three different discharge regimes: high discharges of about 1,275 m^3/s, moderate discharges of about 710 m^3/s, and low discharges <150 m^3/s. Some of these data were also collected at 28 other sites at discharges between 85–1,275 m^3/s. Only those data not included by Schmidt and Graf (1990) are listed in table 1.

Several geometric properties of the channel and recirculation zones were measured in the field and on air photos (U.S. Bureau of Reclamation 1984, scale 1:3,000) taken when discharge was 150 m^3/s. *Constriction ratio,* defined as the ratio of channel topwidth at a constriction divided by average upstream channel width, and *expansion ratio,* defined as the ratio of the widest part of the expansion divided by the width of the constricted channel, were measured on air photos at 70 sites. *Unconstrained recirculation-zone length* was defined as the distance between the intersections of the along-shore projections of the banks of the channel expansion and the onshore projections of the eddy fence and was measured at different discharges at 13 field sites (fig. 3). *Scaled, unconstrained recirculation-zone length* was defined as the unconstrained length of the zone divided by the width of the constriction at low discharge. Computed values are sensitive to the discharge at the time of measurement of constriction width, but this value does not

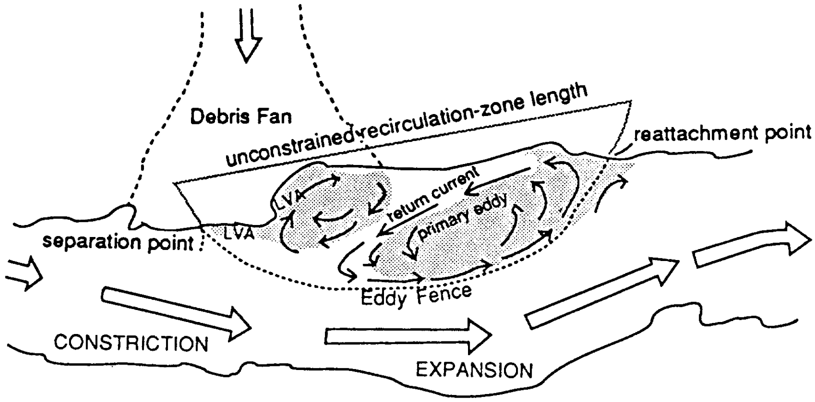


FIG. 3.—Flow patterns at moderate or high discharge in the vicinity of a debris fan. Upstream shaded area is separation bar; downstream shaded area is reattachment bar. Arrows indicate directions of surface flow. LVA = low-velocity area.

change greatly for small changes in discharge in Grand Canyon.

Mean-section velocity of the main channel was estimated and compared to measured velocity in parts of recirculation zones at a range of discharges at Badger Creek Rapids. Mean-section velocity estimates were made by surveying water-surface elevation at three different discharges between 85–1,275 m^3/s and estimating the channel cross-section on the basis of channel-thalweg data (Graf 1987; U.S. Bur. Reclamation 1987, Glen Canyon Envir. Studies Office unpub. data; Wilson 1986). Water-surface elevations at a discharge of 2,800 m^3/s were determined by surveying the water's edge mapped from a 1956 photograph of the rapids (Turner and Karpiscak 1980, fig. 36A). Flow patterns and the location of the eddy fence were mapped at the three observed discharges and estimated for the 2,800 m^3/s condition. Mean-section velocity was determined by dividing the known discharge by the cross-section area of downstream-directed main-channel flow. Froude number was calculated as mean-section velocity divided by the square root of the product of the acceleration of gravity and mean depth.

These velocity estimates are only first-order approximations because they are based on three assumptions: (1) that the constricted channel cross-section is rectangular at elevations not exposed at low discharge, (2) that bed elevations remained constant in the main channel at these discharges, and (3) that eddy fences project downward from the surface with the same orientation at all discharges. The first assumption affects estimates of hydraulic conditions in the constricted channel while the third assumption affects estimates of flow in the channel expansion. The first assumption has been shown to be reasonable by Kieffer (1985). The second assumption is reasonable for the constriction because river runners did not report any changes in Badger Creek Rapids due to the flows of 1983–85. The second assumption is reasonable for the expansion because a large volume of sand had already been removed from the expansion between 1973–85 (fig. 4), indicating that the channel was in a degraded state during the study period. The third assumption is not valid at some sites at high discharges due to plunging flow

THE GEOMETRY OF CHANNEL EXPANSIONS

Debris fans located at the mouths of steep ephemeral tributaries partially block the river's course (fig. 5), and the riffles or rapids that result dominate the longitudinal profile (Leopold 1964). Notable geomorphic features of the river channel in the vicinity of debris fans are (1) shallowing and narrowing of the channel as it passes around the apex of the debris fan; (2) a scour hole immediately downstream from most channel constrictions; and, (3) a channel-width expansion whose widest part is typically located downstream from the scour hole. At 59 sites between Lees Ferry and the Little Colorado River, channel depth at the constriction decreases to as little as 0.30 times the upstream depth and increases in the scour hole to as

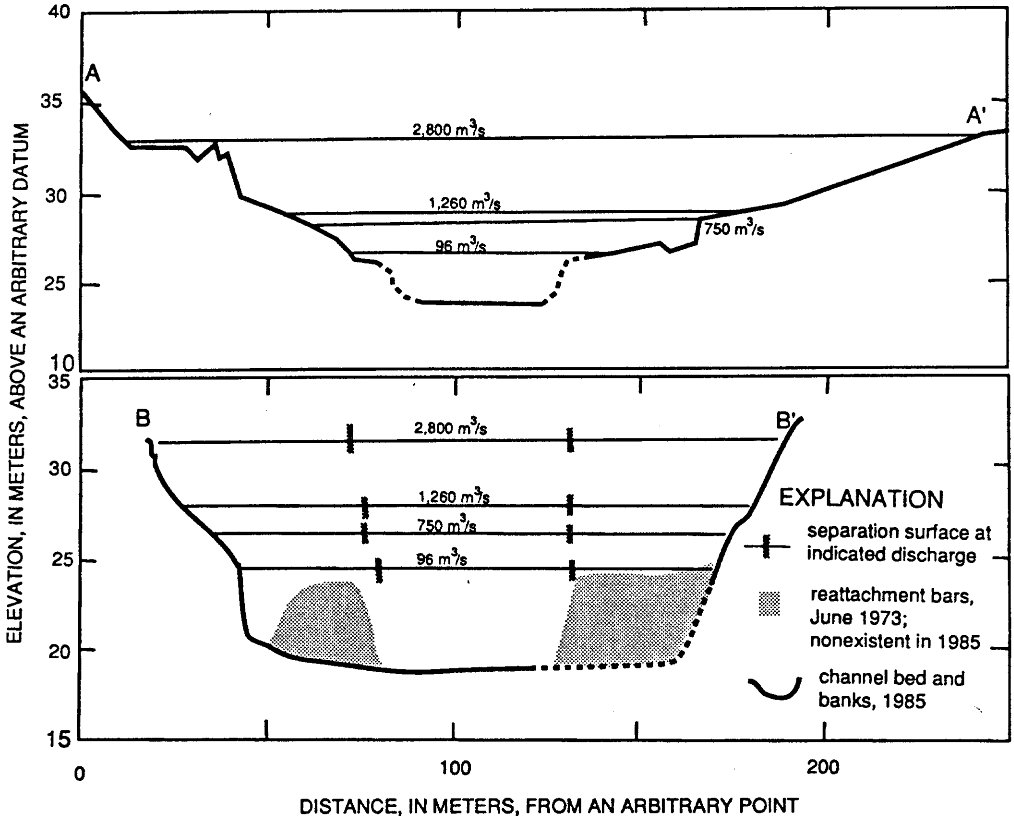


FIG. 4.—Colorado River channel in the vicinity of Badger Creek Rapids. Cross-sections are located on figure 7.

much as nine times the constriction depth at moderate discharge.

Debris fans narrow the channel to a mean constriction ratio of about 0.5 (Kieffer 1985; Schmidt and Graf 1990). The mean expansion ratio is about 2.9. Figure 6 is a scatterplot of the inverse of the constriction ratio plotted in relation to the expansion ratio at 70 sites between Lees Ferry and the Little Colorado River, as well as the sites listed in table 1. If the width of channel expansions were equal to the average upstream width, sites would plot along the indicated line of symmetry. This figure shows that the width of expansions typically exceeds average channel width, suggesting that flow in expansions has widened the channel beyond its average upstream condition. At some point downstream from the expansion, the channel narrows to "average" conditions. This attribute of channel geometry restricts the length to which recirculation zones extend.

FLOW PATTERNS IN CHANNEL EXPANSIONS

Accelerated flow entering the constriction may be supercritical or subcritical, depending on local conditions. An expanding jet emerges from the constriction into the channel expansion (Kieffer 1989); recirculating currents exist between the jet and the banks. The jet may plunge into the scour hole, creating vertical components of flow within the expansion.

The separation point, at the upstream end of the recirculation zone, occurs on the debris fan and not upstream or downstream from the fan (fig. 7). The reattachment point, where downstream flow is again adjacent to the banks, occurs within or at the downstream end of the expansion. The boundary between the expanding jet and the recirculation zone, called the eddy fence, is a vertically oriented plane separating the recirculating current from the main downstream flow. The eddy fence appears continuous and un-

FIG. 5.—Badger Creek Rapids and channel expansion, June 16, 1973. Discharge is about 140 m^3/s. Flow is from right to left. Note channel expansion downstream from rapids with reattachment bars at the downstream end. Separation bars mantle the downstream parts of the debris fans.Compare with fig. 7.

broken at the water surface at steady discharge. Debris within a recirculation zone does not typically float across the eddy fence into the main current.

Eddy fences with abrupt discontinuities were observed immediately after a sudden increase in discharge from 850 to 1,275 m^3/s in 1986. At these discontinuities, boils rising to the surface within the recirculation zone migrated across the eddy fence and into the main current. These migrating boils appeared to have higher suspended-sediment concentration than other parts of the channel, and the migration of these boils may be an important process exchanging sediment between recirculation zones and the main channel.

The pattern of recirculating currents is remarkably consistent (fig. 3). Recirculating currents are organized into one primary eddy with a vertical axis of rotation filling between 50–90% of the recirculation zone. In a typical primary eddy, about 60% of the surface area flows toward the shoreline. This water collects into a narrow, deep primary-eddy return current. The primary eddy always fills the downstream part of the recirculation zone, but not necessarily the upstream part. In areas upstream from the primary eddy, secondary eddies or areas of variable-flow direction exist. One persistent area of low-velocity variable-flow direction is near the separation point.

Variability in Recirculation-Zone Length with Site Characteristics.—At the same discharge, recirculation zones vary greatly in length throughout Grand Canyon. At mod-

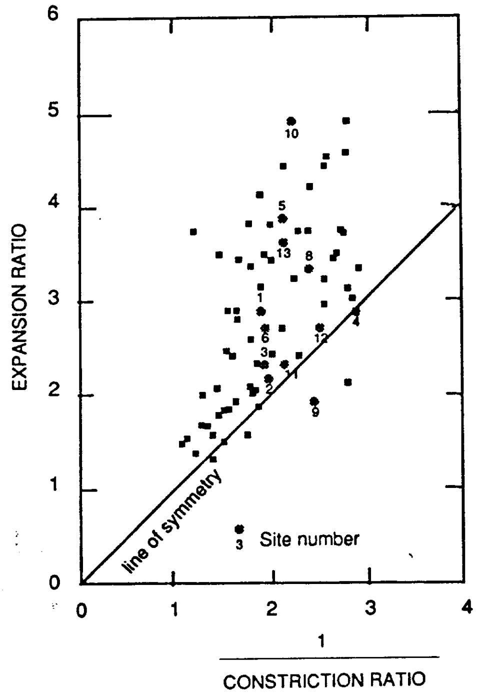


FIG. 6.—Channel-geometry characteristics at 70 debris fans between Lees Ferry and the Little Colorado River and at other detailed study sites. Solid squares = debris fans; circles and numbers = site number. Site 7 (constriction ratio = 6, expansion ratio = 8) not shown.

erate discharge, the length of recirculation zones at 13 sites varied from 150–500 m. Longer recirculation zones are formed by flows issuing from constricted channels of low width-to-depth ratio and high unit discharge, and not necessarily from major rapids (fig. 8), consistent with studies reported by Izbash and Khaldre (1970). Although Rouse et al. (1951) show that recirculation zones are longer at higher Froude number, no relation was found between constrained or unconstrained recirculation-zone length and (1) Froude number of flow in constrictions, (2) steepness of the water-surface slope in the rapids, or (3) dimensions of the channel expansion.

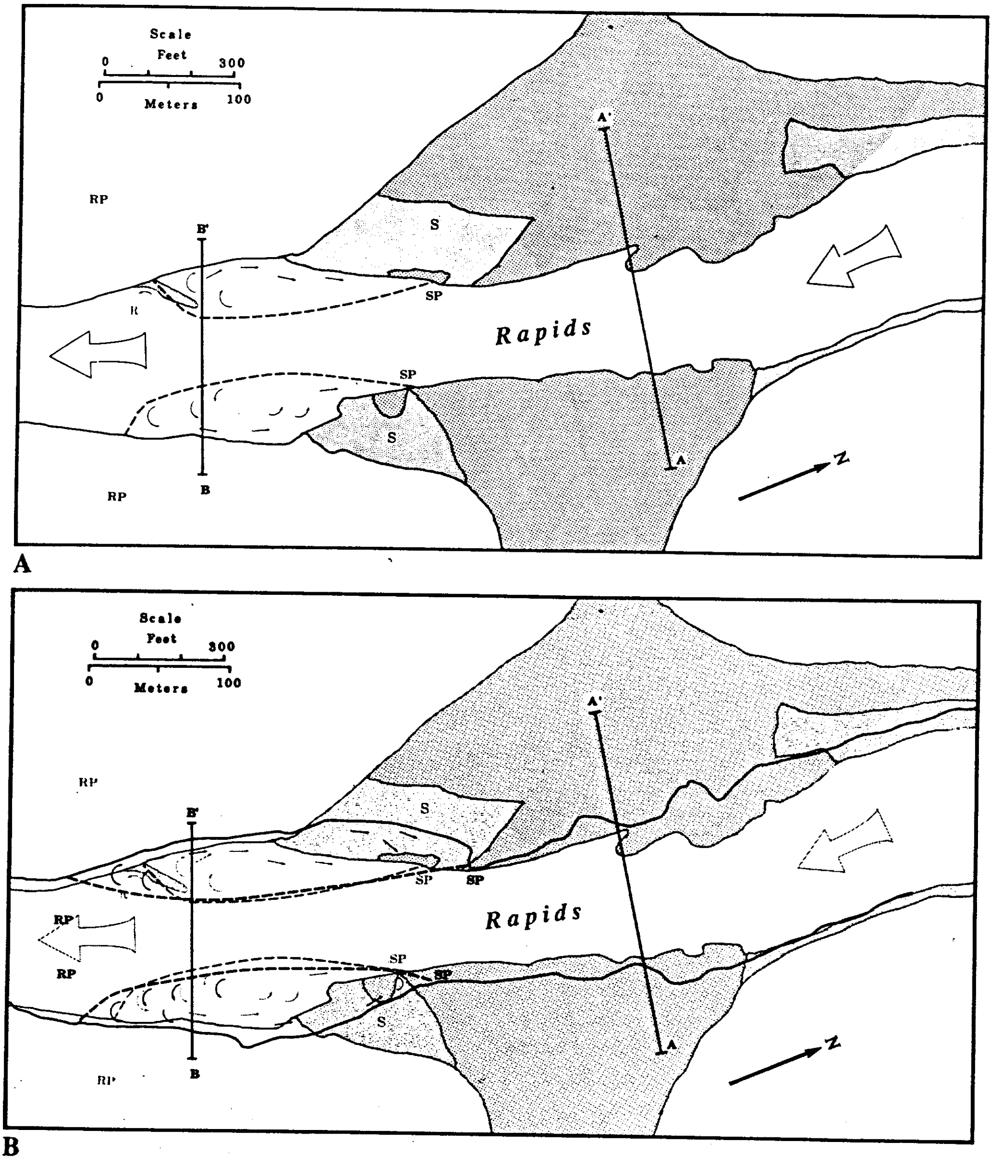
All recirculation zones increase in length with increasing discharge, up to some limiting value. The greatest changes in length of these zones occur due to downstream lengthening of the primary eddy. Where there is upstream migration of the separation point, there is little upstream lengthening of the primary eddy onto the increasingly flooded debris fan. Instead, the area upstream from the primary eddy is filled by secondary eddies or areas of variable-flow direction (fig. 3). Figure 9 shows that the difference between distance of downstream migration of the reattachment point and distance of upstream migration of the separation point is typically greatest at those recirculation zones that lengthen most between low and high discharge.

There are limits, however, to the lengthening of recirculation zones. Separation points do not migrate upstream from the fan apex, presumably because debris fan geometry creates flow separation even when fans are flooded. Reattachment points do not migrate beyond the end of the expansion.

Hydraulic Characteristics and Changes with Discharge.—The average surface velocity of the primary eddy return current is typically greater than other parts of the recirculation zone (table 2). Measurements at three sites indicate that the average ratio of velocity of the primary eddy return current to velocity of the adjacent main current is 0.2–0.4. Allen (1984) showed experimentally that the primary eddy return current velocity varied between 0.1–0.3 times that of the average downstream velocity. Areas near the separation and reattachment point have lower velocities. This condition must exist because instantaneous velocity must be zero at stagnation points.

At Badger Creek Rapids, water-surface slope flattens, Froude number of constricted flow increases and then decreases, the constriction is progressively drowned, and recirculation zones progressively lengthen as discharge increases (fig. 10). At discharges greater than about 1,300 m^3/s, mean-section velocity in the rapid increases at a slower rate than at lower discharges, and is actually less at 2,800 m^3/s than at 1,275 m^3/s (fig. 11). The decrease in average velocity and Froude number occurs because the debris fans that form Badger Creek Rapids are overtopped, and the cross-section area of the constricted channel nearly triples from 380 to 1,120 m^2 (fig. 4*A*). Because flow through the rapids is deeper than over the flooded debris fan, velocity in the center of the flow must be greater than mean-section velocity (Kieffer 1985, 1988).

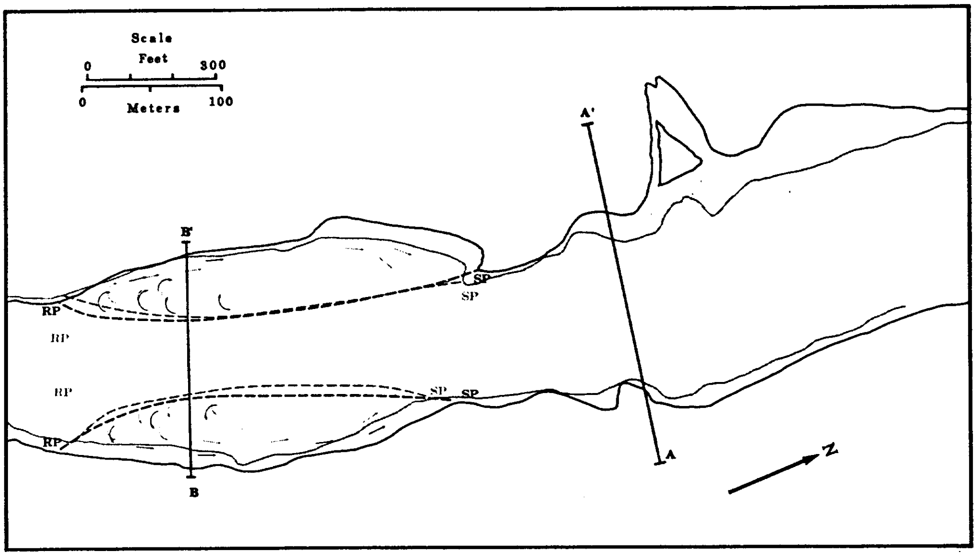
With widening of the constriction and the



A

B

FIG. 7.—Surficial geology and hydraulic features at Badger Creek Rapids at four discharges shown in order of increasing discharge. In *B, C,* and *D,* preceding figure is also shown for purposes of comparison. *A*. On October 5, 1985, discharge 96 m^3/s. *B*. On July 31, 1985, discharge 750 m^3/s. *C*. On May 19, 1985, discharge 1,260 m^3/s. *D*. June 19, 1952, discharge 2,800 m^3/s. Light dotted pattern = river-deposited sand. Dark dotted pattern = debris fan boulders mixed with cobbles, gravel, and sand. Talus or bedrock extends continuously away from channel, debris fan, and sand. S = separation bar. R = reattachment bar. Arrows indicate direction of surface flow. SP = separation point at indicated discharge. RP = reattachment point at indicated discharge. Dark solid line adjacent to channel = water's edge at indicated discharge. Dark dashed line in channel = eddy fence at indicated discharge.



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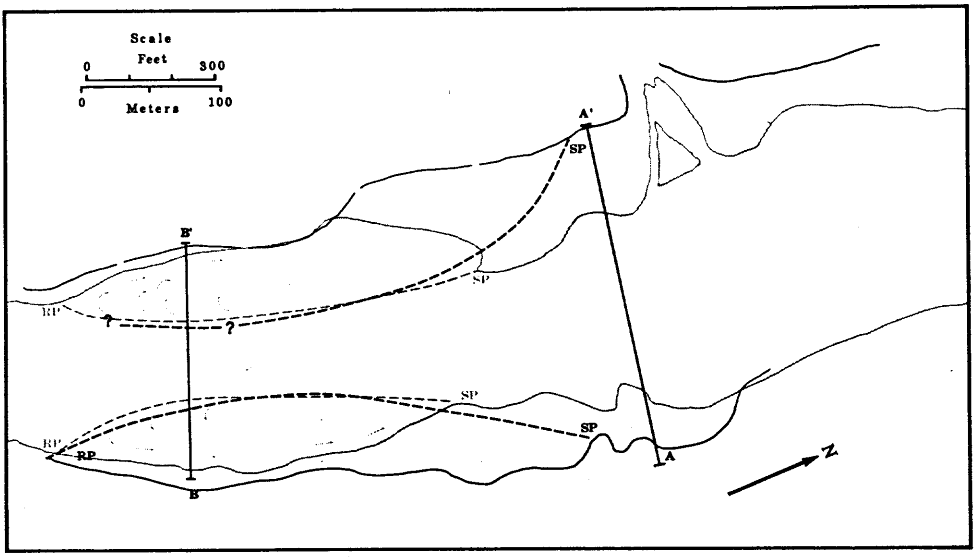

D

shoreward movement of separation points, the surface area of downstream-directed flow in expansions typically increases. Width of recirculation zones decreases, and their length-to-width ratio increases if canyon side walls are steep. Comparison of figures 7*C* and 7*D* shows that overtopping of the debris fan also results in slight reorientation of the direction of main-channel flow.

Uncertainty about the orientation of submerged parts of the eddy fence introduces considerable error into estimates of mean-section downstream velocity. If the orientation is perpendicular to the water surface, mean-section velocity would be approximated by the B-B′ (maximum) line on figure 11. If eddy fences project downward with a 45° onshore orientation, then the volume of recirculating flow is less and mean-section velocity of downstream flow would be approximated by the B-B′ (minimum) line on figure 11. In either case, the difference between velocity in the constriction and in the expansion is greatest at those discharges

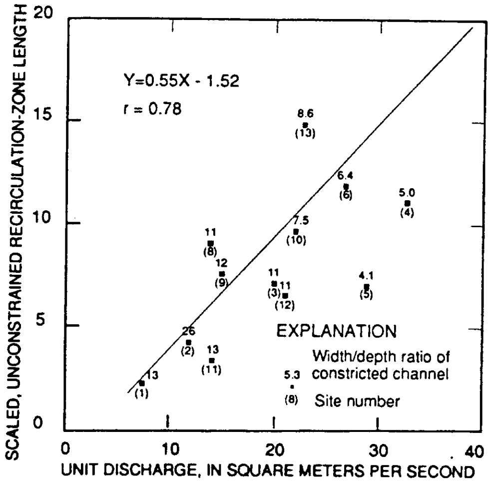

FIG. 8.—Unit discharge of constricted flow and scaled, unconstrained recirculation-zone length at 13 sites at moderate discharge.

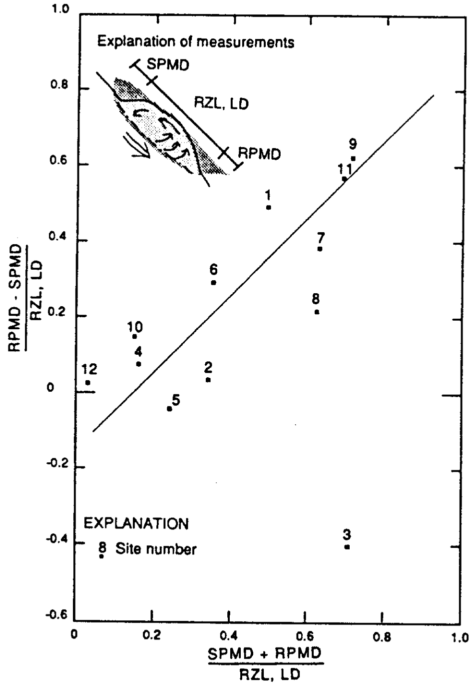

FIG. 9.—Change in recirculation-zone length and proportion of change due to reattachment or separation point migration. RZL, LD = recirculation-zone length, low discharge. SPMD = separation point migration distance. RPMD = reattachment point migration distance. Light shaded area = recirculation zone at low discharge. Dark shaded area = additional area within recirculation zone at high discharge, due to migration of separation and reattachment points.

slightly less than the rate necessary to overtop the debris fans (about 1,300 m^3/s). Because head losses are proportional to the difference between average velocity in the constriction and in the expansion (Henderson 1966), the role of flow separation in decelerating main channel flows may be greatest at discharges incipient to flooding of the debris fan.

Velocities in recirculation zones increase at a much slower rate than in the main channel. Velocity of the primary eddy return current likely remains less than 1 m/s at discharges less than 3,000 m^3/s. Velocity in the area of unorganized flow near the separation point is even lower. These data show that although downstream velocity increases with increasing discharge, the rate of increase in velocity in recirculation zones is less than in the main channel, and the absolute velocity in recirculation zones is much less than in the main channel. Therefore, areas of very low velocity and potential sedimentation persist in the Colorado River, even at high dis-

TABLE 2

SUMMARY OF HYDRAULIC AND SEDIMENT-TRANSPORT CHARACTERISTICS IN THE VICINITY OF RECIRCULATION ZONES

Location	Range of measured velocity (m/s)	Average velocity (m/s)	Average depth (m)	Estimated range of fine sand-transport rate (Mg/d/m)
Main channel	1.6–7.7	...	9.1–18	360–36,000
Primary-eddy return current	.37–1.2	...	1.5–6.1	3.6–36
Reattachment-point area	.091–.76	.46	.30–1.2	3.6–36
Secondary eddy; low-velocity area near separation point	.061–.49	0.30	.30–0.91	.36–3.6

NOTE.—Transport rates based on average velocity and depth and Colby (1964, fig. 26).

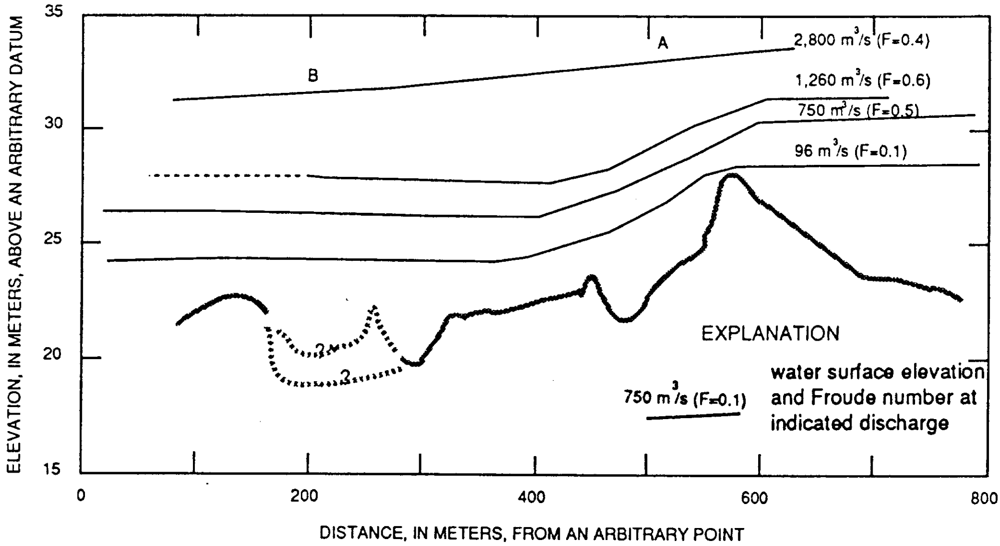

FIG. 10.—Longitudinal profile of thalweg, water-surface, and Froude number of constricted flow at four discharges at Badger Creek Rapids. See figure 7 for location of channel cross-sections. Lower line is bed elevation in 1984 and 1985. Letters A and B are location of cross-sections shown in figure 4.

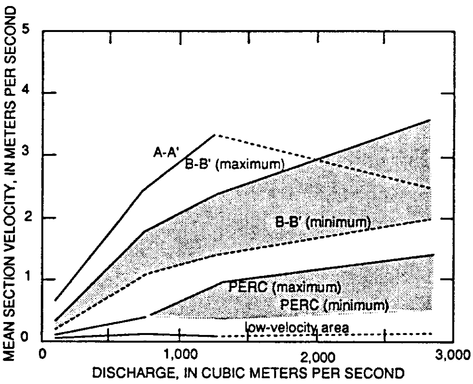

FIG. 11.—Velocity and discharge at Badger Creek Rapids at different discharges. Cross-sections are shown on figure 3. PERC = primary-eddy return current. Velocity of PERC at high discharge estimated as 0.2–0.4 times velocity at B-B′.

charges. However, the locations of these low-velocity areas change because the length of recirculation zones change with discharge.

SEDIMENTATION AT CHANNEL EXPANSIONS

Classification.—The consistency of flow patterns and behavior of recirculation zones causes consistency in the location, form, and large-scale characteristics of bars forming in channel expansions. The loci of deposition of these bars are in areas where velocity and therefore sediment transport capacity is least—near the separation and reattachment points, center of the primary eddy, and the eddy fence. At one end of a recirculation zone, separation bars mantle the downstream part of the debris fan that creates the channel constriction (fig. 3). Reattachment bars are located in the downstream part and beneath the primary eddy (fig. 5). Observations at low discharge show that what had previously been distinguished as reattachment deposits and eddy-center deposits (Schmidt 1986) are actually one continuous bar.

Bar Shape, Location, and Sedimentary Structures.—Reattachment bars project upstream in the form of spits (fig. 12). Typically, the bars also project perpendicularly into the channel in the vicinity of the reattachment point. The highest part of these bars is at their downstream end, and the longitudinal crest line of the bars plunges in elevation in the upstream direction. The upper surface of these bars is typically flat, although the bars may have an upward convex shape beneath the center of the primary eddy.

Migration directions inferred from bedforms and climbing-ripple sedimentary structures show that sedimentation occurs on both sides of the reattachment point and shoreward from the eddy fence. Typically, at least

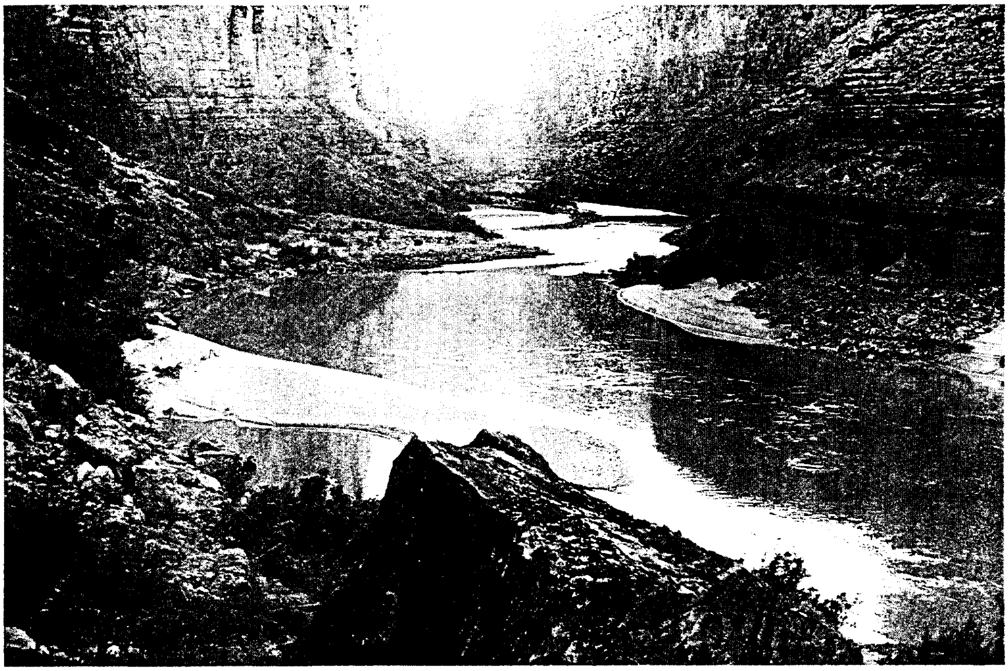

FIG. 12.—Reattachment bar at Eminence Break Camp, October 12, 1985. Discharge is about 85 m^3/s. Flow in main channel is away from viewer. Note slipface on upstream side of bar.

two-thirds of each bar is deposited by upstream and onshore currents within the recirculation zone. The high-elevation, downstream parts of these bars typically are entirely composed of structures indicating upstream bedform migration.

Most sedimentary structures found within these bars are ripple-drift cross-laminations confirming that deposition occurs in a low-velocity environment (Rubin et al. 1990). Another common sedimentary structure is planar foresets formed by upstream-migration of the bar's slipface within the recirculation zone. Geophysical studies have been unsuccessful in determining the contact between existing reattachment bars and underlying bedrock or talus. However, comparison of air photographs and bathymetry at Badger Creek Rapids where sand bars were entirely eroded by high flows in 1983 shows that these bars were 4–5 m thick in 1973 (fig. 4*B*).

Separation bars mantle debris fans and may extend downstream beyond the limits of the fan. At their downstream end is the primary eddy return current channel. Average thickness of separation bars is typically less than 4 m, and they thin in upstream and upslope directions. Characteristic sedimentary structures of separation bars are ripple-drift cross-laminations and low-angle planar foresets. The former structures reflect deposition in a low-velocity environment, and the latter reflect reworking by waves that typically occur at these bars.

Sediment Size.—Sediment that comprises reattachment bars is coarser than that which comprises separation bars (fig. 2). Reattachment bar sediment is similar in size distribution to the suspended load, while sediment that forms separation bars is the finer fraction of the suspended load. Climbing-ripple structures are finer-grained than are planar foreset structures in all bars, but, when differentiated by the structure of each sediment sample, reattachment bars are also coarser than separation bars. Sediment in both types of bars is moderately well sorted, and is better sorted than is suspended or bed load of the Colorado River.

Spatial Distribution.—Separation and reattachment bars are common throughout Grand Canyon; both types are more common in wider reaches. Within a 197-km reach downstream from Lees Ferry, 399 recirculation zones were identified on aerial photographs (Schmidt and Graf 1990). Of these zones, 47% had separation bars, and 71% reattachment bars. Debris fans with steep, high slopes do not typically have separation bars because there is no place for secondary eddies to develop at high discharge. In narrow reaches (width-to-depth ratio less than 11.5 and average channel top width less than 75 m), reattachment bars occurred in 31% of all recirculation zones. In wider reaches, they occurred in 40% of all recirculation zones. The occurrence of separation bars in narrow and wide reaches was 22 and 24%, respectively (Schmidt and Graf 1990).

DISCUSSION

Flow Pattern, Sedimentation, and Stability.—Many of the characteristics of separation and reattachment bars are related to general flow patterns. Reattachment bars occur beneath the primary eddy; these bars are bounded by the primary eddy return current, the eddy fence, and the main current beyond the reattachment point. Separation bars only form upstream from the primary eddy return current. Comparison of mapping of surface current directions at discharges preceding bar emergence and migration directions inferred from sedimentary structures at numerous bars shows close agreement, indicating that both types of bars are active features when inundated. Rubin et al. (1990) and Schmidt and Graf (1990, their figs. 12, 13) show this agreement at a reattachment bar and a separation bar, respectively.

Reattachment bar sediments deposited by high flows in 1983 and 1984 are of a size distribution similar to the main-channel suspended load. Separation bar sediments are finer than the suspended load and finer than reattachment bars. These relations are consistent with observations that the upstream limb of concave-bank benches is composed of finer sediment and more abundant organic detritus than other parts of these deposits (Page and Nanson 1982). Flow patterns and climbing-ripple migration directions indicate that suspended load enters recirculation zones through the downstream part of the eddy fence. The distribution of sediment sizes indicates that some of the suspended load is deposited on the reattachment bar, and only finer fractions are transported upstream to the separation bar. Howard and Dolan (1981)

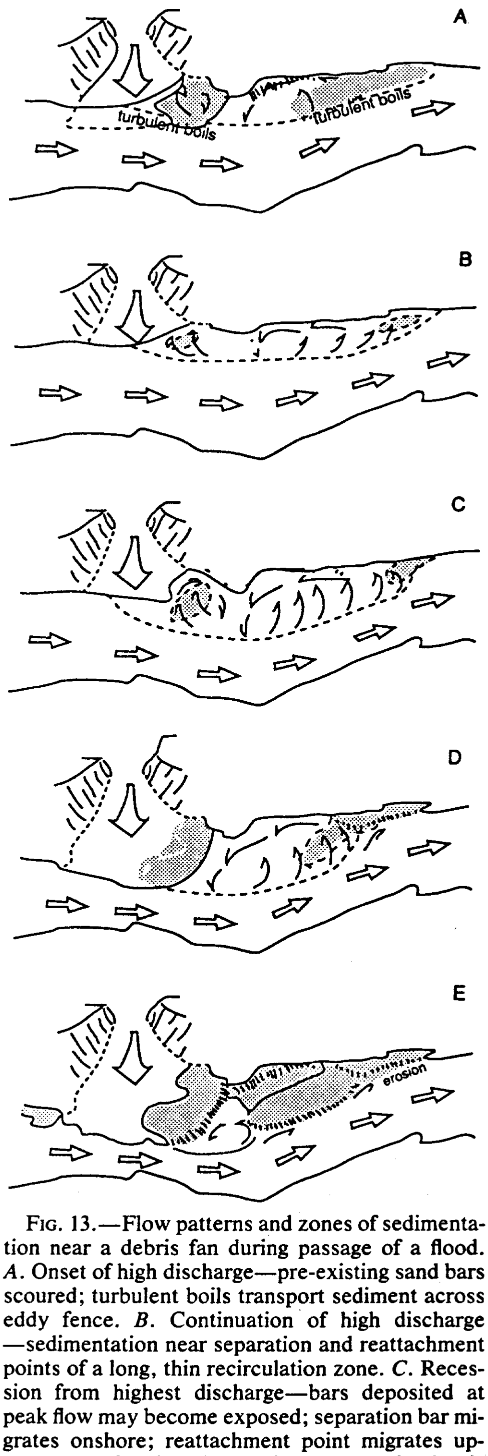

FIG. 13.—Flow patterns and zones of sedimentation near a debris fan during passage of a flood. *A*. Onset of high discharge—pre-existing sand bars scoured; turbulent boils transport sediment across eddy fence. *B*. Continuation of high discharge—sedimentation near separation and reattachment points of a long, thin recirculation zone. *C*. Recession from highest discharge—bars deposited at peak flow may become exposed; separation bar migrates onshore; reattachment point migrates upstream. *D*. Continued recession—separation bar is exposed; part of reattachment bar is exposed; erosion of upper surface of reattachment bar and redistribution of sand within recirculation zone. *E*. Lowest discharge—reattachment point located on reattachment bar; primary eddy return channel is stagnant.

determined size distributions of bar sediment but did not identify any of these trends because bar sediments had been reworked by over 10 yr of daily fluctuating flows.

Response of Recirculation-Zone Deposits to Passage of a Flood.—Figure 13 summarizes the behavior of a recirculation zone and related sand bars during passage of a flood, generalized from mapping at many field sites at different discharges. With initial onset of high discharge, bars are entrained by turbulent boils. Sand is redistributed within the recirculation zone and exchanged with the main current. As high discharge persists, sand is deposited in the vicinity of the new locations of the separation and reattachment points and may also be deposited shoreward from the eddy fence. Recirculation zones have higher length-to-width ratios at higher discharges which may result in proportionally higher primary-eddy return-current velocities (Allen 1984, fig. 3–10). Such a situation would restrict the tendency of bars to migrate onshore.

When high flow recedes, the separation and reattachment points migrate downstream and upstream, respectively. At low discharge, sedimentation occurs at different locations than at higher discharges and previously-deposited sediments may be reworked. Observations during river trips in 1989 and 1990 indicate that the remaining high-discharge parts of reattachment bars were deposited upstream from the high-discharge reattachment point. Areas deposited downstream from the reattachment point have been eroded by lower flows of the period 1987–89. Eroded sediments downstream from the reattachment point become available for main-channel transport, while eroded sediments upstream from the reattachment point can be transported within the recirculation zone. In this way, the lower parts of separation and reattachment bars may be constructed from sediments eroded from high-discharge parts of the reattachment bar. At lowest discharge, the entire surface of reattachment bars may be exposed.

Migration of the separation point during flood recession typically eliminates secondary eddies and low-velocity areas as flow ceases to cover the debris fan. The area of potential separation-bar deposition is reduced or eliminated. Downstream flow is thereafter adjacent to the emergent debris fan and near-shore parts of separation bars are typically eroded until coarse sediments of the underlying debris fan are exposed. Such armoring can lead to perched separation bars.

Because bars in bedrock gorges form near stagnation points, prediction of the location of these points at various discharges can improve understanding of long-term bar stability. Where there are large shifts in stagnation-point location with changing discharge, and where high-velocity flow is located just beyond the stagnation-point area, high discharge bars may be unstable after flood recession. Conversely, where stagnation points do not change location with discharge, or where nearby downstream flow is of low velocity, bars are more likely to be stable.

CONCLUSION

In Grand Canyon, channel expansions are wider than average channel conditions. Downstream-directed flow issuing from a constricted channel fills most of the expansion but recirculating currents occur in near-bank areas. The longest recirculation zones are caused by narrow, deep constricted flows. The dominant hydraulic feature of recirculating currents in Grand Canyon is a one-celled eddy that fills the entire zone at low discharges and comprises the central and downstream parts of the zone at higher discharge. At higher discharge on submerged parts of debris fans, one or more secondary eddies and areas of low-velocity unorganized flow exist upstream from the primary eddy. These changes in recirculating-flow pattern are associated with enlargement of the recirculating-current zone by upstream migration of the separation point and downstream migration of the reattachment point.

Bars may form beneath these recirculating currents. Where they occur, reattachment bars fill the central and downstream parts of recirculation zones and separation bars mantle adjacent upstream debris fans. Reattachment bars form beneath primary eddies and separation bars form beneath secondary eddies and low-velocity areas. Reattachment bars are bounded by the primary-eddy return current, the eddy fence, the main-current flow downstream from the reattachment point and are comprised of sediments similar in size to the suspended load. Separation bars, located upstream but downcurrent from reattachment bars, are composed of finer sediments. This spatial distribution is consistent with flow patterns indicating that sediment moves from the main channel to reattachment bars and then to separation bars.

Wherever recirculating currents exist, stagnation zones near the separation and reattachment points provide the opportunity for deposition of main-channel transported sediment. Changing discharge causes changes in the location of these potential deposition sites, however. Separation points may migrate downstream a sufficient distance to eliminate the secondary eddies or low-velocity areas necessary for separation-bar formation. Upstream migration of the reattachment point also decreases the area of potential deposition. Stagnation-point migration also leads to redistribution of previously-deposited sediment to the main channel and within the primary eddy. The planform shape of both types of bars reflects these changes.

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