

Flume Simulation of Recirculating Flow and Sedimentation

JOHN C. SCHMIDT

Department of Geography and Earth Resources, Watershed Science Unit, Utah State University, Logan

DAVID M. RUBIN

U.S. Geological Survey, Menlo Park, California

HIROSHI IKEDA

Environmental Research Center, University of Tsukuba, Ibaraki, Japan

Experiments were conducted in a 4-m-wide flume to simulate recirculating flow and sedimentation in a lateral eddy within a channel expansion. The percentage of main stem sediment that was captured by the eddy decreased from 37% (when the eddy was empty) to 24% (when sand filled approximately 32% of the eddy volume). The reattachment bar within the eddy grew in an upstream direction, and the finest size sediment was deposited in the lee of the obstruction; both observations are consistent with field observations. Measurements of reattachment length during sediment transport (0.5–1.0 kg/s) at constant discharge (0.60 m³/s) show that reattachment length depends not only on characteristics of the expanding jet, but also on the topography of the channel bed downstream; reattachment length decreased when part of the channel expansion was filled by an aggrading midchannel bar. Comparison of these results with measurements in the Colorado River in Grand Canyon suggests that downstream channel irregularities play a large role in controlling the length of eddies in natural rivers.

INTRODUCTION

Recirculating currents, or eddies, develop in rivers wherever the orientation of downstream flow and the channel banks are sufficiently divergent, such as at sharp meander bends [Leeder and Bridges, 1975] and downstream from channel confluences [Best, 1986]. These currents also develop where constricted flow enters a wider reach, such as in the lee of debris fans or bedrock that partly obstructs downstream flow. Recirculating flows are weaker than adjacent downstream flow, which causes sediment to accumulate in recirculation zones; sediment storage in recirculation zones may comprise a high proportion of total sediment storage in some bedrock canyons. Bars deposited at high discharge in recirculating currents (and subsequently emergent) may become substrate for riparian vegetation or be used as campsites. In canyons affected by upstream dams, recirculating current bars may be eroded [Schmidt and Graf, 1990], and future restoration management strategies may include high-discharge, regulated releases intended to reconstruct these bars.

Flow separation and associated recirculation are long-studied phenomena in the laboratory [Eaton and Johnston, 1981; Simpson, 1989] and coastal settings [Signell and Geyer, 1991; Wolanski et al., 1984], but have received less attention in rivers. The general hydraulic and sedimentologic characteristics of recirculation zones and associated bars have been described in Grand Canyon [Rubin et al., 1990; Schmidt, 1990; Schmidt and Graf, 1990], but few field observations have been made of the rate and style of bar development and hydraulic conditions in river eddies. There

have also been few physical model experiments which measured recirculating flow conditions during bar aggradation. This paper summarizes the results of experiments intended to simulate flow and sedimentation in a bedrock canyon; these experiments were undertaken in the 4-m-wide flume at the Environmental Research Center, University of Tsukuba. We describe (1) flow patterns, velocities, and changes in reattachment length in a large recirculation zone, (2) evolution of bar topography and bed forms, (3) areal sorting of sediments, and (4) efficiency of this zone in capturing sediment. The experimental results are related to field studies.

LITERATURE REVIEW

We have observed large recirculation zones and associated sand bars along the Colorado River in Grand Canyon, Arizona, and Cataract Canyon, Utah; along the Snake River in Hells Canyon, Idaho and Oregon; along the River of No Return reach of the Salmon River, Idaho; along the Green River in Lodore and Desolation Canyons, Utah; and on smaller streams in the western United States and New England. Accounts of river runners indicate that such zones occur in bedrock canyons throughout the world, and recirculating current sedimentation has been described in paleoflood studies throughout the western United States [Baker, 1984]. In the Colorado River in Grand Canyon, recirculation zones are large and persistent, typically occupying one third to one half of the channel width downstream from constricting debris fans. In the upstream 195 km of Grand Canyon, about 400 large eddies exist at most discharges [Schmidt and Graf, 1990].

Experiments show that wakes with simple recirculating flow develop in the lee of cylinders at Reynolds numbers greater than about 4 [Chang, 1966]. At Reynolds numbers

Copyright 1993 by the American Geophysical Union.

Paper number 93WR00770.
0043-1397/93/93WR-00770\$05.00

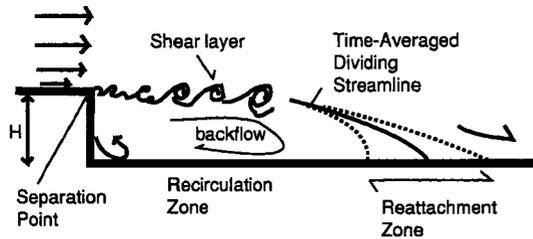


Fig. 1. Plan view of flow features at a backward facing step adapted from *Driver et al.* [1985]. H is step height.

greater than 40, flow within the wake becomes unsteady, and vortices develop along the shear zone between the main flow and the wake. Two flow zones develop: a near wake of closed recirculation and a far wake within which shed vortices move downstream. In open-channel flow, the near wake is referred to as the separation bubble or recirculation zone.

The simplest reattaching flow occurs at the backward facing step at the boundary of an otherwise semi-infinite or uniform flow field (Figure 1). The point of flow separation, which *Simpson* [1989] has shown to be a zone of varying detachment conditions, is generally considered fixed in space where the step corner is sharp, although *Eaton and Johnston* [1981] have documented unsteadiness of the separation point even at this geometry. Near the separation point, the detached boundary layer forms a free shear layer which is initially thin and parallel to the orientation of the constricted flow. Further downstream, the separated shear layer curves sharply toward the wall. Simplified drawings of experimental conditions typically show a time-averaged mean streamline impinging the wall at the time-averaged reattachment point, which is located within a zone through which the instantaneous reattachment point fluctuates. Reattachment point fluctuation has been related to the migration of large turbulent structures along the shear layer, and the length of the reattachment zone is of the order of 4 step heights. *Simpson* [1989] also reported that the maximum backflow velocity is typically greater than 20% of the free stream velocity. Experiments and numerical modeling have demonstrated that reattachment length is highly sensitive to the longitudinal pressure gradient and to bottom friction [*Eaton and Johnston*, 1981; *Yeh et al.*, 1988].

Schmidt and Graf [1990] measured great variability in reattachment length in Grand Canyon, and found that recirculation zones lengthen with increasing discharge until discharge becomes so great that the constricting debris fan is overtopped and the surface expression of the recirculation zone appears to become washed out. Flow in recirculation zones is organized into a simple one-cell primary eddy rotating such that upstream flow occurs along the river bank. At higher discharges, primary eddies lengthen downstream and secondary eddies develop upstream from the primary eddy on flooded parts of the constricting debris fan. *Schmidt* [1990] showed that there is a maximum length to which each recirculation zone can extend, controlled at the upstream end by the constriction itself and at the downstream end by irregularities in channel geometry. *Schmidt* [1990] found that narrow and deep constrictions create longer recirculation zones than do wider, shallower constrictions.

Baker [1984] distinguished and described four major bar

types that occur in narrow, deep bedrock stream channels, including the expansion bars and eddy bars that are the subject of this paper. The category of eddy bars, formed beneath recirculating currents, was subdivided by *Schmidt* [1990], based on observations in Grand Canyon (Figure 2). Reattachment bars form in the reattachment zone and beneath the primary eddy. Separation bars mantle the constricting debris fan and are formed at higher discharges by secondary eddies that submerge parts of these fans [*Schmidt*, 1990]. Sorting occurs within recirculation zones [*Page and Nanson*, 1982]. In Grand Canyon, those separation bars formed by high annual peak discharges in 1983–1985 were composed of finer sediment than were reattachment bars formed by the same flows, presumably because sorting processes caused the coarser sediment to be deposited in the area where sediment first entered recirculation zones, the reattachment zone [*Schmidt*, 1990]. Bed load transport directions beneath the primary eddy, inferred from



Fig. 2. Photograph, looking downstream, of the Colorado River in Grand Canyon about 1 km upstream from Blacktail Canyon. Three reattachment bars on river right exist at this discharge; one is at the bottom, one in the middle, and one near the top of the photograph. Each reattachment bar occurs in association with a flow separation inducing debris fan. A small rapid in the center of the photograph has been formed by a debris fan on river right; a small patch of sand on top of this debris fan is a separation bar. Note that reattachment bars are highest in elevation on their downstream and shoreward side, and that each reattachment bar has a small remnant channel separating the low-elevation part of the bar from the talus bank. This channel is maintained by backflow at higher discharges.

TABLE 1. Experimental Conditions

	Experiment	
	Empty Flume	Bed Aggradation
Flow rate, m^3/s	0.15–0.61	0.60
Total run time, hours	22	30
Number of runs	13	4
Sediment feed rate, k/s	0	0.5–1
Sediment feed characteristics:		
mean, mm	...	1.3
standard deviation, phi units	...	0.96

Number of runs indicates number of times flume was drained and bed observations were made.

bed form orientations and sedimentary structures, mimic surface flow patterns and indicate rotary motion [Rubin *et al.*, 1990]. The only large area of structures indicating downstream transport is in the downstream part of the reattachment zone. Typical sedimentary structures found within reattachment and separation bars are foresets deposited by the bar as it migrates onshore and foresets deposited by ripples and dunes migrating in a rotary pattern. Symmetrical straight-crested ripples are common in the reattachment zone [Rubin *et al.*, 1990]. Separation bar development has been described by Schmidt and Graf [1990, Figure 13], who documented upstream migration of a separation bar within a secondary eddy during a regulated flood in Grand Canyon.

Field studies of topographic changes and sedimentologic characteristics of selected bars in Grand Canyon are the basis of conceptual models of bar building within recirculating currents proposed by Rubin *et al.* [1990] and Schmidt [1990]. These models predict that reattachment bars build in an upstream direction from the reattachment zone and that sediment deposited at high discharge is reworked during upstream retreat of the reattachment zone during flood recession. Separation bars are formed at high discharges and are reworked during flood recession to a lesser extent than are reattachment bars.

METHODS

These experiments were conducted in the 160-m-long, 4-m-wide, 2-m-deep flume at the University of Tsukuba; details of the Tsukuba facility are provided by Ikeda [1983]. Water surface slope was controlled by a tailgate at the downstream end of the flume. Bed topography and bed forms were examined and measured during experiments by raising the tailgate, ponding the flow, and then slowly draining the flume. After measurements were made, flow was reintroduced and experiments resumed. Flow velocities were measured with a two-dimensional electromagnetic current meter and from time-lapse photography of surface floats. Electromagnetic current meter measurements at 16 sites were made 0.1 m beneath the water surface every 0.75 s for a duration of 5 min. Because flow depth increased in the downstream direction, the position of the measuring point relative to the bed differed longitudinally. Resultant horizontal flow vectors and rose diagrams of the relative amount (duration times velocity) of flow in different directions were computed. The vertical component of the flow field was not determined, although Nelson [1991] has shown that the vertical component is an important part of the flow field near the shear layer. Locations in the flume are referenced to distance downstream from the headgate where water and sediment were supplied; for example, station 120 is located 120 m downstream from the headgate. All references to left or right side of the flume are made as if the viewer were facing downstream.

We report the results of two experiments in this paper (Table 1). In both, a semicircular obstruction (constructed with sand bags and covered by large plastic sheets) constricted flow width to about 1.5 m (Figure 3). This obstruction was located between stations 90 and 95. For purposes of comparison with laboratory studies of backward facing step flow, the step height during our experiments is taken as the distance from the right wall to the obstruction apex, 2.5 m. In order to simulate the increased elevation of the bed that occurs at constrictions in Grand Canyon [Kieffer, 1988], a 0.1-m cinder block step was placed at the constriction during

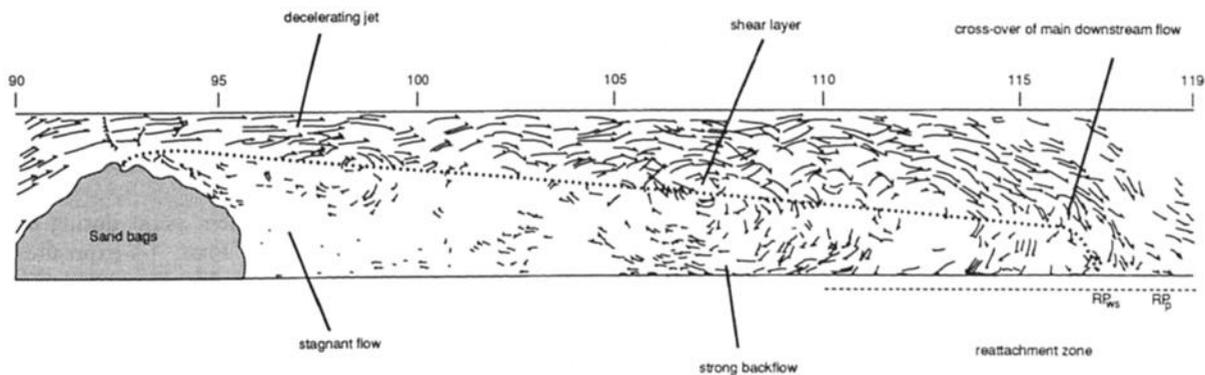


Fig. 3. Path lines of surface floats during run 13 (discharge $0.30 m^3/s$). Length of individual paths are for 1 s duration. Some path lines intersect one another because field of view for each photograph was about 5 m and fields of view overlapped. Dashed line through path lines shows average location of dividing streamline for purposes of measurement of A_d . RP_{ws} is location of the instantaneous reattachment point determined from water surface measurements, and RP_p is location of the instantaneous reattachment point determined from photographs. Dashed curve near reattachment points is the full range of the reattachment zone during this run. Values along the left side of the flume are station locations.

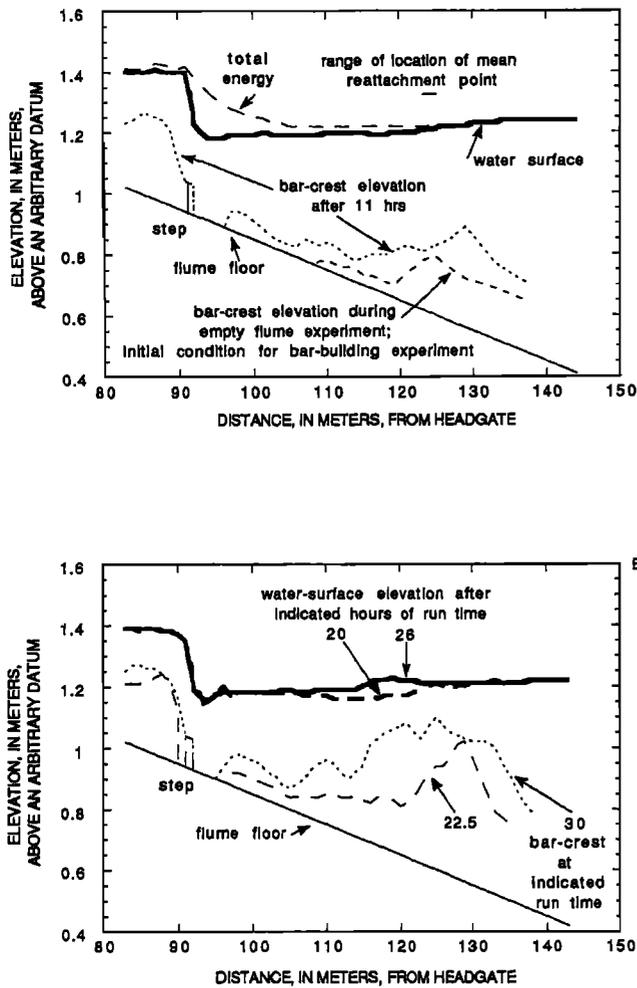


Fig. 4. Longitudinal profile of water surface elevation and maximum bed elevation during bar-building experiment for different durations. (a) Water surface elevation and total energy grade line after 14 hours and bed conditions at start of experiment and after 11 hours. Total energy grade line calculated from v_d , using (1) from text. (b) Water surface elevation after 20 and 26 hours and bed elevation after 22.5 and 30 hours.

the second experiment and for some of the runs of the first experiment (Figure 4). Downstream from the obstruction, a zone of recirculating current extended to within about 20 m from the tailgate. Bed slope was 0.01 for the first experiment and was variable due to bed aggradation during the second experiment. Water surface slope was always less than the bed slope, and water depth increased greatly downstream.

This physical model is an analogue of some of the conditions in large rivers that flow within bedrock canyons. In these canyons, the longitudinal profile consists of steps (debris fans) and pools (channel expansions) [Leopold, 1964]. Debris fans function as natural tailgates, often acting as local controls upstream to the base of the preceding step [Kieffer, 1985]. Recirculation in bedrock gorges occurs within the channel and is not restricted to overbank settings investigated by Tamai *et al.* [1986].

The size of the experimental channel expansion was greater than the mean size of expansions in Grand Canyon. In the experiments, the flow width constriction ratio (downstream flow width divided by constricted flow width) of 0.38

was narrower than the mean flow width constriction ratio in Grand Canyon which Kieffer [1985] found to be 0.5, but the experimental range was within the range of all measured field sites. The flow-width expansion ratio was 2.7 in all runs because the flume walls were never altered; Schmidt [1990] found that the mean flow-width expansion ratio in Grand Canyon is 2.9. The flow area expansion ratio (downstream flow area at station 130 divided by constricted flow area at station 92) during the experiments varied between 3.4 and 14.2 and greatly exceeded the flow width expansion ratio (Table 2). Because flow depth increased longitudinally, the flow area expansion ratio was even greater at points downstream from station 130. Some expansions in Grand Canyon are as large as those in the experiments because depths of individual scour holes are as much as 9 times the depth of the constricted channel. These experiments are therefore representative of some of the field conditions observed in Grand Canyon; however, these experiments may not be representative of sites where the downstream increase in flow area is small. In the latter case, deceleration of streamwise flow due to increasing flow area is smaller, and the relative importance to deceleration of lateral diffusion of momentum across the shear zone is greater.

In the first experiment, changes in recirculating flow characteristics were measured for different clear water discharges and tailgate elevations. During this experiment, sediment formed a linear bar with maximum relief of 0.18 m in the center of the flume downstream from station 120. In the second experiment, a heterogeneous sand mixture was added to a $0.60 \text{ m}^3/\text{s}$ flow at a rate between 0.5 and 1.0 kg/s , and the rate and style of bar aggradation was measured 5 times during 30 hours.

Water surface elevations were measured from a movable platform above the flume. Mean downstream velocity was computed using the following equation:

$$v_d = Q/A_d \quad (1)$$

where v_d is the mean downstream velocity, Q is discharge, and A_d is the cross-sectional area of downstream flow based on estimates of the location of the time-averaged mean separation surface that divides downstream and recirculating flow. Estimates of v_d are only a general approximation because the straight line defining the mean dividing streamline can only be an approximate representation of a highly unsteady three-dimensional surface (Figure 3). Froude numbers were calculated based on v_d and depths measured 0.5 m from the left wall. Hydraulic jumps occurred at the constriction where the Froude number of constricted flow was as small as 0.8 because v_d is less than maximum velocity in the constriction.

The location of the reattachment point during each run was determined in three ways. First, 1-s-exposure photographs of surface floats were used to identify the instantaneous reattachment point at the time when the photograph was taken. Second, digitized longitudinal traces of the water surface 0.5 m from the right wall were used to identify the reattachment point by determining the most downstream extent of adverse (upstream) water surface slope at the time of the water surface measurements. The time of these measurements was generally within 15 min from the time of the photography. Third, visual observations of the time-averaged location of the reattachment point were made.

Bed topography was determined by repeatedly surveying

TABLE 2. Hydraulic Conditions During Empty Flume and Bar-Building Experiments

Run	Discharge, m ³ /s	Total Range in Reattachment Length, Step Heights	Station Location of Reattachment Point by Indicated Method				Visual Observation (Long-Time Average)	Water Surface Slope ^b	Froude No.		Reynolds No., St. 85	Constriction Water Elevation, Meters Above Datum	Downstream Water Elevation, Meters Above Datum	Gate Height, Meters Above Arbitrary Point	Flow Area Expansion Ratio ^c
			Photographs	Right Wall Elevation ^a	Froude No.										
					St. 85	St. 92.3									
1	0.15	6.6-11.8	NA	>120	109-122 (114)	0.00028	<i>Empty Flume Experiment</i>		25,000	1.1	1.11	0.800	7.6		
2	0.16	13-13.4	NA	126	125	0.0028	0.3	0.4	26,000	0.9	0.99	0.650	8.5		
3	0.15	2	97.5	NA	97.5	0.0047	0.6	3.1 ^d	25,000	0.9	0.91	0.600	6.9		
4	0.30	2	NA	NA	97.5	0.0067	0.5	2.9 ^d	49,000	0.8	0.93	0.595	4.9		
5	0.60	15	130	NA	130	NA	0.3	NA	NA	NA	NA	0.660	NA		
6	0.61	13.4-13.8	126	127	NA	0.0036	0.1	2.2 ^d	100,000	1.1	1.20	0.800	4.9		
7	0.60	9.4-9.8	116	117	NA	0.0022	0.3	0.9 ^d	99,000	1.2	1.25	0.850	4.9		
8	0.30	7.4-9.4	111	116	NA	0.0056	0.2	0.4	49,000	1.2	1.22	0.880	5.6		
9	0.30	10.2	118	118	NA	0.0011	0.3	0.5	49,000	1.2	1.18	0.840	5.8		
10 ^e	0.32	6.2-11.4	121	120	108-120 (118)	0.0031	0.2	1.3	53,000	1.1	1.14	0.800	8.9		
11 ^e	0.30	8.2-11	120	115	113-120	0.0022	0.2	0.9	51,000	1.1	1.18	0.840	14.2		
12 ^e	0.30	7-10.6	110	119	NA	0.0011	0.2	0.5	50,000	1.2	1.22	0.880	11.7		
13 ^e	0.30	6.2-11	118	108, 117	110-120	0.0014	0.2	0.5	4,900	1.2	1.21	0.863	11.8		
14 ^e	0.60	13-16.6	NA	134	125	0.0053	0.3	0.8	98,000	1.2	1.23	0.800	4.9		
15 ^e	0.60	13-13.8	NA	127	125	0.0047	0.1	0.9	180,000	1.2	1.21	0.800	4.3		
16 ^e	0.60	10.2-13.8	NA	127	118-125	0.0047	0.4	0.9	99,000	1.2	1.21	0.800	3.9		
17 ^e	0.60	9-10.6	NA	119	115-118	0.0046	0.6	0.9	240,000	1.2	1.21	0.800	3.4		

NA, not available.

^aLocation of highest water surface along right wall.

^bWater surface elevation at station 89 minus water surface elevation at station 125.

^cFlow area at station 130 divided by flow area at station 92.

^dLocation of highest Froude number was between stations 93 and 94.

^eA 0.1-m step at constriction.

Bar-Building Experiment

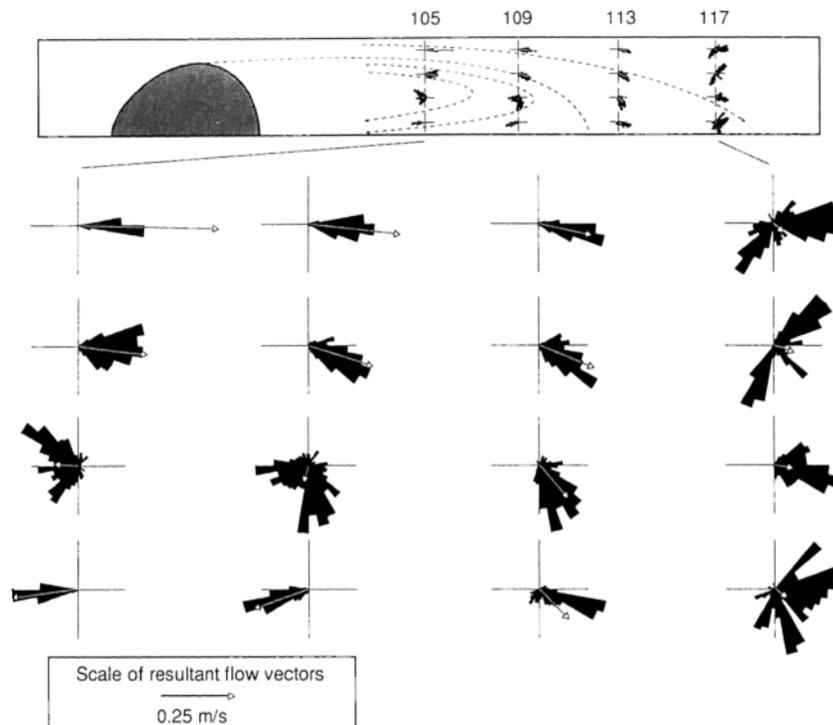


Fig. 5. Rose diagrams showing resultant flow vectors and amount of flow (speed times duration) toward each indicated direction during run 7.

cross sections located at 2-m intervals between stations 89 and 125 and at 4-m intervals elsewhere. Measurements at each cross section were taken at 0.2-m intervals and are accurate to within 0.1 cm. Volume calculations were made using surface and volume modeling software, and mass transport rates were calculated assuming that the specific gravity of the sediment was 2.65 and the porosity of the sediment deposits was 35%. Samples of bed sediment were collected when the flume was drained and were later sieved.

Sediment transport rates past the recirculation zone could not be determined from the sediment feed rate because the deposition rate upstream from the constriction was variable. We determined the transport rate through the constriction by measuring the total volume of sediment aggraded in the flume downstream from the constriction during each run. The resulting transport rates are accurate because no sediment washed out of the flume; in fact, little aggradation occurred in the most downstream 20 m of the flume. Aggradation rates in different parts of the flume were used to determine the efficiency of the eddy in capturing sediment transported by the main downstream current. These rates were calculated by determining the difference in sediment volume between successive measurements for five areas, each of constant dimension. This procedure eliminated bias in estimating the dimensions of the recirculation zone during each measurement period but may slightly overestimate the proportion of sediment deposited in the eddy during the final period because the recirculation zone decreased in size.

RESULTS

Flow Patterns and Velocity

The flow field downstream from the constriction can be subdivided into (1) the decelerating jet, (2) the shear layer

where vortices increase in diameter in the downstream direction, (3) nearly stagnant flow in the lee of the obstruction and extending 1–1.5 channel widths downstream, and (4) strong backflow in an area immediately downstream from the stagnant flow area (Figure 3). Vortices eventually increased in diameter such that they extended across the entire flume. The recirculation zone typically was truncated where the high-velocity core of downstream current crossed to the right side of the flume. The location of the reattachment point fluctuated over distances as great as 5 times the step height, similar to fluctuation ranges reported by *Simpson* [1989] (Table 2).

Although the flow field can be described by average flow conditions, instantaneous vectors were widely variable, especially in the shear layer. Figure 5 shows rose diagrams of instantaneous velocity at selected locations using the two-dimensional current meter. In the upstream part of the expanding jet, downstream velocities were so much greater than the rotary flow of the vortices that the instantaneous flow directions of the combined flow remained within 45 degrees of directly downstream. In the center of the recirculation zone, mean velocities were weaker and flow directions were more variable. Farther downstream where the jet slowed and combined with the vortices, instantaneous vectors varied over 360 degrees. Instantaneous velocities in the reattachment zone were bidirectional, and upstream-downstream flow reversals occurred. Along the wall, flow direction was restricted, but speeds varied greatly. Backflow along the wall was typically about half of v_d , but instantaneous speeds ranged from a minimum of nearly zero to a maximum that approached the mean speed of the downstream current. Upstream velocity was between 0.00 and 0.10 m/s in the lee of the constriction. Backflow speeds greatly exceeded values reported by *Simpson* [1989] and

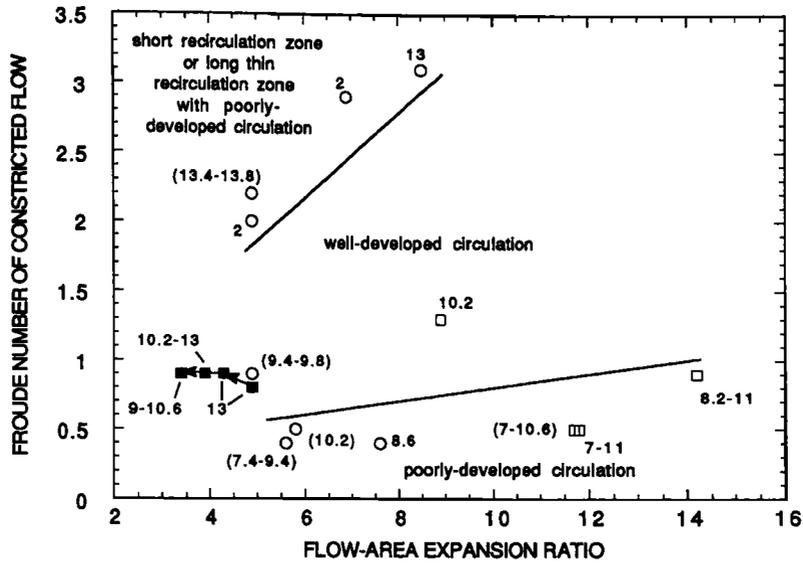


Fig. 6. Recirculation zone length at different experimental conditions. Numbers are time-averaged reattachment length divided by step height. Numbers in parentheses are the range of instantaneous reattachment length where time-averaged values are not available. Squares are runs with 0.1 m step at constriction. Solid squares are bar-building experiment.

exceeded the values (0.2–0.4 times v_d) measured by Schmidt [1990] at three sites in Grand Canyon.

Reattachment Point Migration and Fluctuation During Clear Water Experiment

Over the range of conditions of the runs of the first experiment, reattachment lengths were bimodal: either very short or were much longer; intermediate conditions did not exist (Table 2). The very short reattachment lengths (less than 2 step heights) were associated with shooting flow through the constriction, a hydraulic jump located about 1

channel width downstream from the constriction, a Froude number of constricted flow exceeding 2, and a flow area expansion ratio less than 8 (Figure 6). Very slight changes in these conditions resulted in narrow recirculation zones with reattachment lengths 13 times the step height (Figure 7). At Froude numbers less than 1.5, reattachment lengths were between 9 and 16.6 times step height. At these conditions, a recirculation zone similar to that shown in Figure 3 developed; this condition best represented field conditions observed in Grand Canyon. At Froude numbers typically less than 0.5, poorly developed recirculation existed and time-

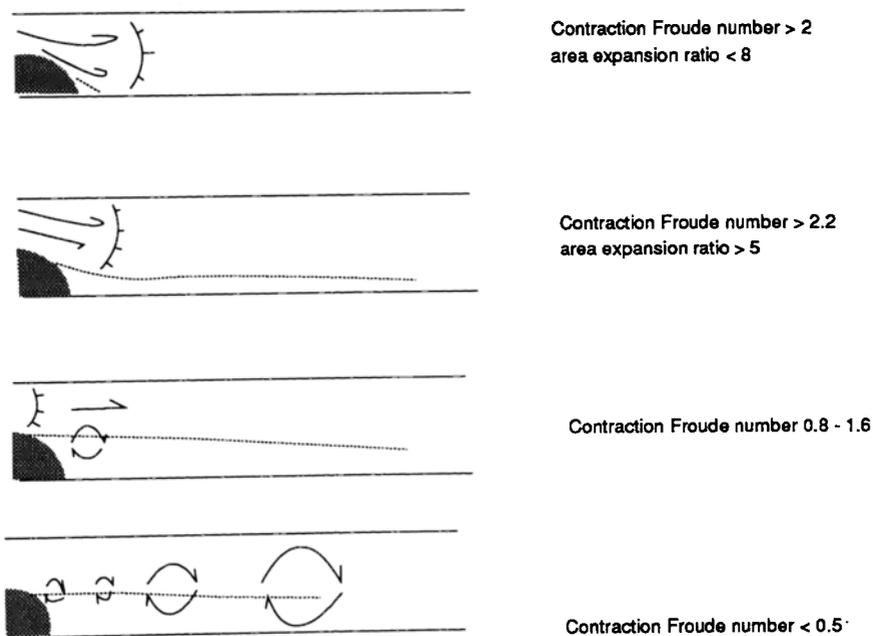


Fig. 7. Schematic diagram of flow patterns and recirculation zone length at different flow conditions. Hatched line is location of hydraulic jump and dashed line is average shear surface.

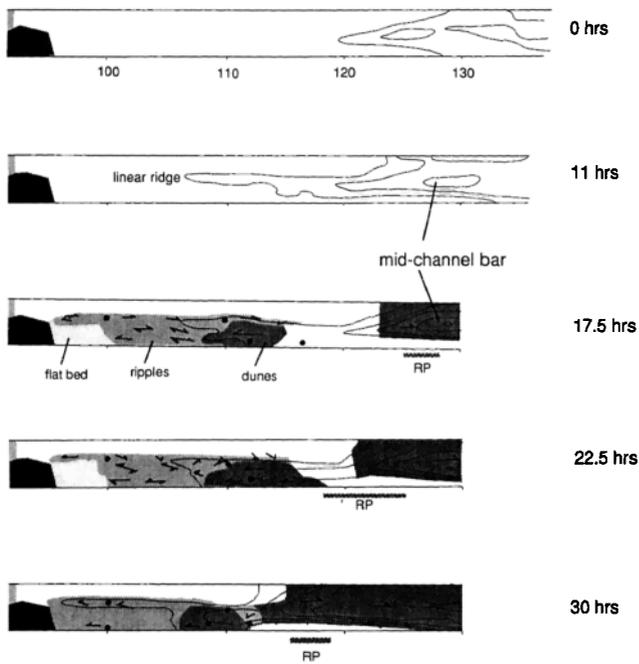


Fig. 8. Bed topography and distribution of bed forms during bar-building experiment. Contour interval is 10 mm. Dark patterned areas were covered with dunes migrating in the directions indicated by the arrows. Intermediate pattern areas are rippled areas, and lightest patterned area are flat bed areas. Zone over which reattachment point oscillated during experiments also shown. Cumulative run time indicated at right.

averaged reattachment length was between 7 and 11 times step height; vortices migrated slowly downstream, and recirculation was poorly developed. We never observed instantaneous reattachment lengths between 2 and 6.2 times step height, and only rarely were reattachment lengths less than 8.2 times step height. Variation in the instantaneous location of the reattachment point during runs where constricted flow Froude numbers were less than 2 was nearly of the same order as variation in time-averaged location among all these runs. The large variation in instantaneous reattachment length in the first experiment (Figure 6, open circles and squares) masked any relation between reattachment length and the flow area expansion ratio [Eaton and Johnston, 1981].

Topography and Bed Forms During Bar-Building Experiment

During the second experiment, sediment was deposited (1) in the pool upstream from the constriction, (2) in and near the recirculation zone, and (3) downstream from the recirculation zone. Downstream from the constriction, sediment was first deposited beneath the shear zone as a linear ridge, near the right wall near station 120, and as a midchannel bar near station 130 (Figure 8).

The highest vertical aggradation rates in the entire flume occurred at the midchannel expansion bar downstream from the recirculation zone (Figure 9). These rates were as high as 5 cm/h and occurred over a larger area than the area of recirculation zone aggradation. With time, the midchannel bar became attached to the left wall and may have steered downstream flow from the left to the right wall. Vertical

aggradation rates within the recirculation zone were always less than 2 cm/h. The highest rates occurred in the downstream part of the recirculation zone, and these rates were between 2 and 3 times as great as rates that occurred at the linear ridge. Deposition within the recirculation zone did not occur at the reattachment zone, but instead always occurred well upstream.

Although the linear ridge was a persistent feature, its volume increased at a slower rate than that of downstream parts of the recirculation zone. The location of the ridge changed with time as parts of the ridge were scoured while other parts aggraded.

Bed forms that developed on the ridge and platform during the bar-building experiment are also mapped on Figure 8. Within the recirculation zone, upstream-migrating dunes existed near the reattachment point, and upstream-migrating ripples developed elsewhere. With time, dunes migrated into areas previously covered by ripples, so that a vertical sequence exposed in the bar would have passed upward from ripples to dunes. Areas of highest recirculation zone aggradation were areas covered by dunes. Symmetrical ripples (Figure 10) oriented with crests transverse to the long axis of the flume existed near the center of the eddy. Evidently, lateral shifts in the location of the eddy center subject this region to flow that reverses in direction.

Sediment Sorting and Capture Rates

Aggraded sediments within the eddy were finer than the sediment feed. Within the eddy, the coarsest sediments were deposited near the reattachment point and the finest sediments collected in the lee of the obstruction near the separation point (Figure 11). Sorting within the recirculation zone was similar to that reported for flood deposits in Grand Canyon [Schmidt, 1990] and for other recirculation zone deposits [Page and Nanson, 1982].

The rate of deposition within the recirculation zone was roughly proportional to the transport rate through the constriction (Figure 12). The relation in Figure 12 (which is not temporally ordered) could be expected to depend in part on the extent to which the eddy was filled at the time of each measurement. Based on stratigraphic evidence in bars in Grand Canyon [Rubin *et al.*, 1990], we suspected that the

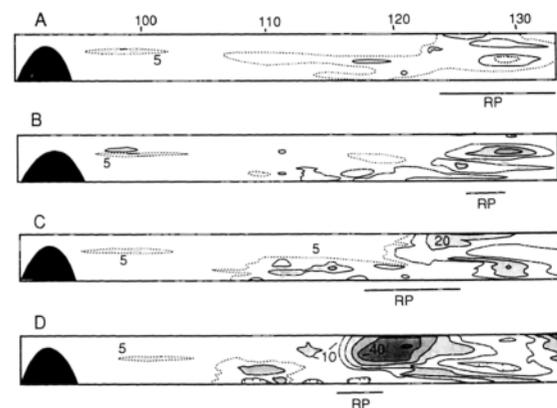


Fig. 9. Aggradation rates during runs, determined by subtracting previous bed topography from resultant bed topography. Contour interval 10 mm/h, with supplemental 5 mm/h dashed contours. (a) Zero to eleven hours; (b) 11–17.5 hours; (c) 17.5–22.5 hours; (d) 22.5–30 hours.



Fig. 10. Photograph of symmetrical ripples that developed beneath the center of the eddy.

capture rates would be greatest when the eddy was empty and would decrease as the eddy became filled. To evaluate the effect of such filling on the capture rate, the data were plotted in temporal order in Figure 13, which shows that the cumulative percentage of sediment captured by the eddy decreased through time. The percentage of main stem sediment that was captured by the eddy between observations (Table 3, column 10) decreased from 37% (when the eddy was empty) to 24% (when sand filled approximately 32% of the eddy volume). We hypothesize that if the experiment had continued long enough, the mean capture rate would have approached zero as the eddy filled to such an extent that circulating currents and sediment input were restricted or eliminated.

Changes in Reattachment Length and Downstream Changes in Mean Velocity During Bar-Building Experiment

During the bar-building experiment, reattachment length decreased and velocity increased as deposition occurred. During the initial part of this experiment, the reattachment length was 13 to 16.6 times step height; after 17.5 hours the reattachment length decreased to 10.2 to 13.8 times step height, and at the end of the experiment the reattachment length was 9 to 10.6 times step height (Figure 8). The location of the reattachment zone was compared to the longitudinal pattern of deceleration of streamwise flow. Mean downstream velocity in the channel expansion was

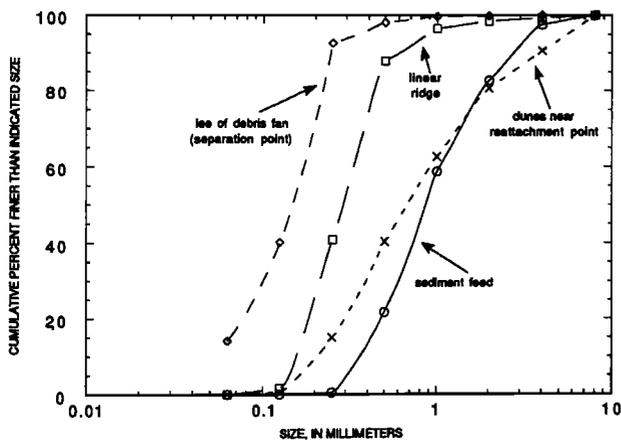


Fig. 11. Size distribution of composite samples of sediment collected during different runs at indicated locations.

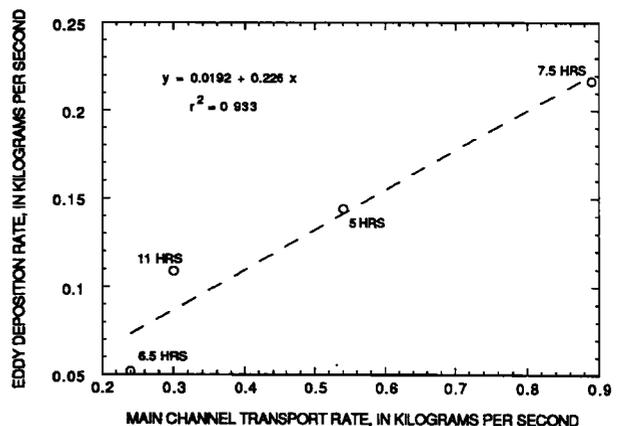


Fig. 12. Eddy deposition rate and main channel transport rate for bar-building experiment. Measurement period, in cumulative run time, is shown for each value.

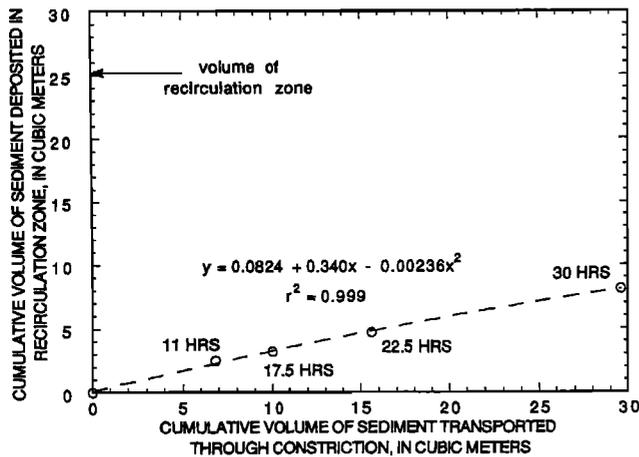


Fig. 13. Cumulative volume of recirculation zone filled with sediment in relation to cumulative sediment transported through constriction during bar-building experiment, both divided by the volume of the empty original recirculation zone. The total volume of the original recirculation zone was 25.2 m^3 ($28 \text{ m length} \times 2 \text{ m width} \times 0.45 \text{ m average water depth}$ between stations 97 and 125). Cumulative run time for each measurement is shown.

calculated from (1) by calculating A_d from measurements of bed topography and water surface elevation and estimating the location of the dividing streamline between streamwise and recirculating flow. The longitudinal pattern of very high velocity at the constriction and steady decrease downstream shown in Figure 14 exists because conservation of mass dictates that flow accelerate through the constriction and decelerate as flow cross-sectional area increases downstream; after 4 hours cumulative run time, v_d decreased continuously downstream. Velocity increased with time between stations 120 and 130 because bed aggradation decreased A_d ; following the initial measurement period, v_d decreased to a minimum but increased further downstream between stations 120 and 130. The magnitude and location of the cross section of minimum streamwise velocity increased and migrated upstream. Reattachment occurred where mean downstream velocity was about 0.3 m/s (4 hours), 0.4 m/s (14 hours), 0.5 m/s (20 hours), and 0.55 m/s (26 hours), respectively. The location of the reattachment zone was between the cross section of minimum downstream velocity and the cross section where accelerated flow reached its maximum value at the two intermediate measurements periods (14 and 20 hours), and was located upstream from the location of the minimum value in the last (26 hours) measurement period.

FIELD ESTIMATES OF AGGRADATION

Available estimates of deposition rates in recirculation zones in Grand Canyon provide minimum values of the percentage of sediment trapped in eddies that are at least one order of magnitude less than those measured in these experiments. Schmidt [1987] estimated an aggradation rate at a reattachment bar along the Colorado River 1.5 km downstream from the Paria River (see Schmidt and Graf [1990] for locations). At this site, topographic surveys and recovered scour chains showed that 0.18 m of brown silty sand aggraded between October 1985 and January 1986. During this period, only one discharge event occurred in the Paria River (October 10, 1985, peak discharge $41 \text{ m}^3/\text{s}$), the only up-

stream tributary source of sediment. Schmidt [1987] concluded, based on textural characteristics, that all deposition had occurred during this one Paria flood event. He used a locally developed stage-to-discharge relation at the reattachment bar to estimate the duration of inundation of the bar and estimated the mass of aggraded sediment from surveying and trenching. Based on these measurements and assumptions, Schmidt [1987] estimated an aggradation rate of 4.2–7.5 kg/s (vertical aggradation rate of 0.6–0.9 cm/h) during 4.5–8.5 hours of inundation.

Schmidt [1987] estimated a capture rate by the recirculating current by comparing his estimate of the mass of sediment delivered by the Paria with the estimate of the mass of sediment deposited in the recirculation zone. The mass of delivered sediment was estimated by using the average sediment transport relation for the Paria River gage [Randle and Pemberton, 1987], the 25% value suggested by Randle and Pemberton [1987] for the proportion of transported sediment within the sand size fraction (0.0625–2 mm), and hourly water discharge values. Based on the estimated rate of sediment delivery to the Colorado River, the maximum suspended sediment concentration of the Colorado River immediately downstream from the Paria was 55,000 mg/L, and concentrations exceeded 10,000 mg/L for the entire period of bar aggradation. The total delivered sand load to the river was between 5.0×10^7 and 10.0×10^7 kg. The mass of sediment aggraded at the reattachment bar, 1.2×10^5 kg, was at least 0.1 and 0.2% of the total estimated sand load delivered by the Paria River flood, and at least 0.03 to 0.06% of the total suspended load. The average aggradation rate for the entire bar of 4.2–7.5 kg/s was not less than two to three orders of magnitude less than the estimated sediment discharge rate of the Colorado River. These estimates are only minimum values of eddy capture rate because (1) the proportion of the delivered sediment deposited on the channel bed upstream from the measurement site is unknown and (2) the actual delivered sediment load and its size distribution is unknown.

Schmidt and Graf [1990] estimated an aggradation rate of 0.3 kg/s (vertical aggradation rate of 0.04 cm/h) during a 33-day period of inundation of a separation bar at Eighteen Mile Wash in Grand Canyon. Using the sand transport relation for the Colorado River at Lees Ferry, located 30 km upstream from this site [Randle and Pemberton, 1987], the average water discharge during the period of inundation, and the local aggradation rate, this site accumulated at least 0.04% of the total main stem transported sand.

DISCUSSION

Bar Construction and Bed Forms

There is general similarity between the topographic form of reattachment bars in Grand Canyon and the bar that developed during the bar-building experiment. In both cases, the highest part of the bar exists in the downstream part of the recirculation zone, although in Grand Canyon, there is great variability in the degree to which these bars fill the upstream parts of recirculation zones. Field evidence is consistent with the progression of bar construction during the experiments. Sediment transport directions interpreted from the orientation of bed forms and the progression of topographic change in the flume shows that the bar built in

TABLE 3. Aggradation Rates During Bar-Building Experiment

Elapsed Run Time, hours	Change in Volume of Sediment (m ³) Between Indicated Stations					Total Eddy Deposition, ^a m ³	Eddy Deposition Rate, kg/s	Proportion of Eddy Capture per Hour ^c	Cumulative Proportion of Eddy Capture	Cumulative Proportion Eddy Capture per Hour ^d	Main Channel Sediment Transport Rate, kg/s
	69-97	97-115	115-125 (Right Half)	115-125 (Left Half)	125-157						
11	7.2	1.3	1.2	0.5	3.8	2.5	0.109	0.033	0.37	0.033	0.30
17.5	2.7	0.5	0.2	-0.1	2.6	0.7	0.052	0.034	0.32	0.018	0.24
22.5	4.6	0.8	0.7	0.9	3.2	1.5	0.144	0.054	0.30	0.013	0.54
30	0.9	1.6	1.8	5.2	5.4	3.4	0.217	0.032	0.27	0.009	0.89

^aComputed as sum of third and fourth columns from the left.

^bComputed as quotient of eighth and seventh columns from the left.

^cComputed as quotient of tenth and first columns from left.

^dComputed as quotient of twelfth and first columns from left.

an upstream direction. Upstream migration of the reattachment zone also caused scour of the farthest downstream areas deposited within the initially longer recirculation zone.

There is inconsistency between field and flume in aggradation patterns in the reattachment zone, however. In the field, we have observed the results of reattachment zone aggradation in the form of thick sequences of climbing ripple structures with migration directions consistent with reattachment zone flow [Rubin *et al.*, 1990]. In the flume, deposition did not occur in the reattachment zone adjacent to the wall; in fact, this zone was an area of local scour.

This discrepancy may be related to the experimental channel geometry. First, in these experiments there were only small differences between the streamwise and upstream velocity in the vicinity of the reattachment zone because of the large magnitude of streamwise deceleration upstream from the reattachment zone (Figure 14). In Grand Canyon, these differences are much greater [Schmidt, 1990, Table 2 and Figure 11], such that more sediment-laden water is delivered to reattachment zones in the field. Second, there may be differences between flume and field in the relative position of main channel scour hole and the reattachment zone leading to differences in the location of shoaling of streamwise flow. Third, the area of low velocity surrounding the instantaneous reattachment point was much smaller in the flume than is observed in the field. This is because the rough sloping bank of the river slows the flow more than does the smooth vertical wall of the flume. In the field, the area of low velocity is larger and the average velocity of the reattachment zone may be lower than in the flume. Scour in downstream parts of the reattachment zone in the flume could occur if high velocity downstream flow occasionally exists in the reattachment zone when the instantaneous reattachment point is at the upstream end of the zone.

Characteristics of Recirculating Flow

The course of floating objects reflects the sum of all the instantaneous flow directions over the object's path. Observations of these path lines are consistent with bed form migration directions interpreted from analysis of sedimentary structures [Rubin *et al.*, 1990]. However, both field and experimental results indicate that there is great variation in the instantaneous velocity field, especially near the center of the recirculation zone and near the reattachment point. These instantaneous variations are great enough to even cause symmetrical ripples to develop beneath areas where there is net onshore flow.

Some flow pattern characteristics of these experiments were influenced by the strong streamwise deepening and are consistent with experiments concerning jets debouching into still water. A high rate of deceleration leads to relatively rapid decrease in the velocity head (Figure 4), increase in water surface elevation downstream, and existence of an adverse pressure gradient. First, current meter measurements showed that instantaneous backflow velocities were about 0.5 times v_d , values much greater than typically observed in the field. The high ratio of backflow to downstream velocity may simply be due to fact that deceleration of v_d was so great. Second, unusual crossover of streamwise flow from left to right wall occurred in some runs, such as is depicted near station 119 in Figure 3. Vortices advected from upstream developed where velocity and cross-stream shear

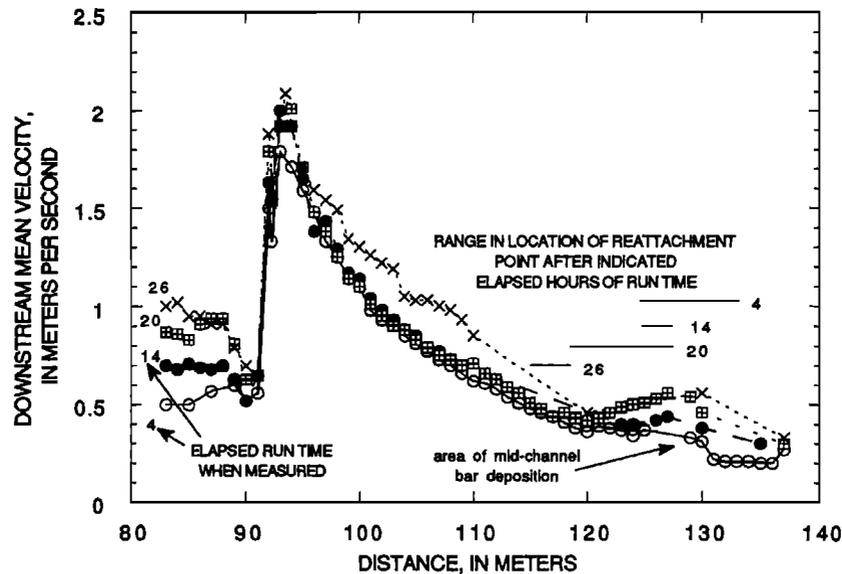


Fig. 14. Mean section velocity during different runs of bar-building experiment. Range of location of reattachment point also shown. Values of v_d determined by estimating area of downstream flow.

was high, and these vortices may have been strong enough to produce upstream flow along the left wall. Third, reattachment lengths were very long for the experimental flow width expansion geometry.

Controls on Reattachment Length

Our laboratory experiments and field observations have documented both shorter and longer recirculation zones than would be predicted using published relations between step height and reattachment length. Relative to the relations of *Abbott and Kline* [1960] for clear water flow at a single backward step (Figure 15, line c), the reattachment lengths in our empty flume experiments are too long. Reattachment lengths in the bar-building experiments are shorter and tend to be similar to those of published relations; field reattachment lengths typically are too short (Figure 15). As will be discussed below, these deviations result from topography that influences the pressure gradient. In flows with obstacles downstream (such as the bar that was deposited in our flume experiments or cobble bars in Grand Canyon) the flow accelerates, resulting in a diminished adverse pressure gradient and a shorter reattachment length. In contrast, where downstream flow is a deep pool (as in our empty flume experiment and in very deep pools in rivers), flow decelerates, resulting in an increased adverse pressure gradient and longer reattachment length.

Seven runs were conducted at different discharges but at the same tailgate elevation (Table 2, thirteenth column) and therefore simulate changing flow conditions in an expansion whose water surface elevation is set by a downstream control. The experimental results of these runs (1, 6, 10, 14–17) are consistent with field data that show that time-averaged reattachment length increases with discharge. Although instantaneous fluctuations in the location of the reattachment point varied greatly in these runs, the time-averaged reattachment length was greatest at highest discharge (Figure 16). Lengthening at higher discharge was associated with higher Froude numbers of constricted flows

and more adverse pressure gradients. In these runs, Froude number was higher at higher discharges (Table 2, ninth column) because water depth through the constriction did not change (Table 2, eleventh column). The magnitude of the adverse pressure gradient was higher at higher discharges because the elevation of the water surface downstream (Table 2, twelfth column) increased with increasing discharge.

At constant discharge and nearly constant flow conditions in the constriction during the bar-building experiment (Table 2, ninth column), reattachment length decreased as the magnitude of streamwise deceleration decreased (Figure 14). The decrease in the rate of deceleration was due to the decrease in flow area expansion ratio (Figure 6, solid squares; Figure 16, solid squares); there was no change in the magnitude of the adverse water slope (Table 2, runs 15–17, eleventh to twelfth columns).

Reattachment length shortening was also related to the fact that streamwise velocity (v_d) near the initially very long reattachment zone nearly doubled due to midchannel bar deposition. At the beginning of the bar-building experiment, streamwise velocity was about 0.3 m/s opposite the reattachment zone (Figure 14, station 130, 4 hours). At the time of the last measurement, v_d was more than 0.5 m/s at this same site. As the channel filled with sediment and velocity necessarily increased, areas that had formerly been of low streamwise velocity or stagnant became areas of higher streamwise velocity. The midchannel bar essentially filled areas that had been part of the reattachment zone.

These results suggest that there should be wide variation in reattachment lengths in natural rivers, due in part to presence or absence of downstream bars and narrowing of downstream walls which would also accelerate flow. Figure 15 shows Grand Canyon reattachment length data, reattachment lengths during the bar-building experiment, and other experimental data plotted in relation to step height. Data from specific field sites are shown as separate lines extending over the range of different measured reattachment lengths and

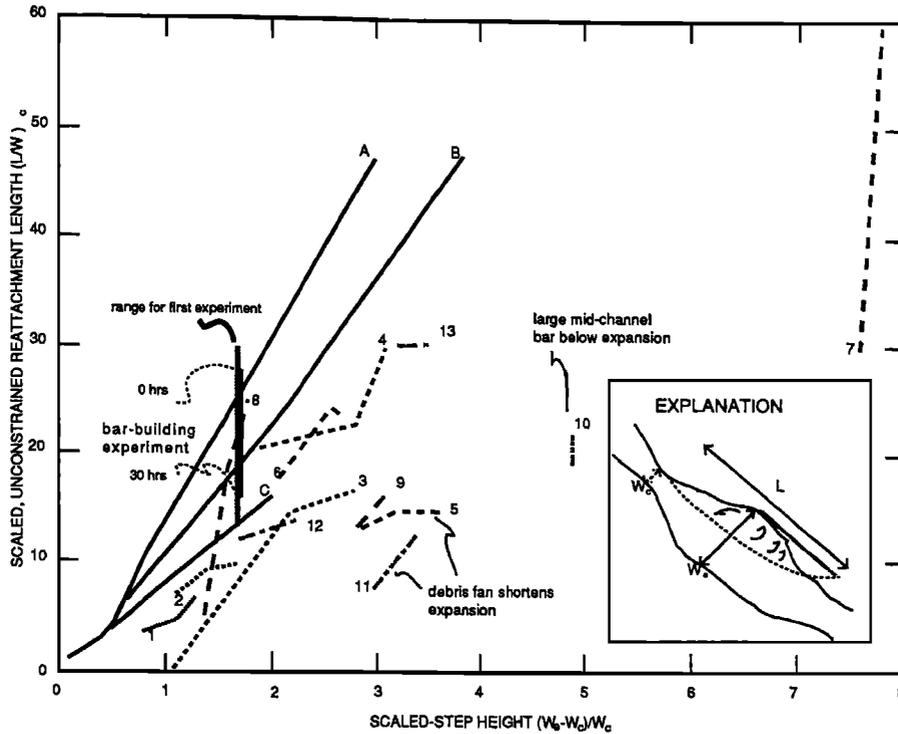


Fig. 15. Change in recirculation zone length in relation to change in channel expansion geometry showing that field sites have shorter scaled recirculation zones than in flume experiments. Lines A, B, and C are for flume studies of double-backward steps (maximum observed values), double-backward steps (minimum observed values), and single-backward steps, respectively, from *Abbott and Kline* [1962]. Solid vertical lines above abscissa value of 1.7 are range in reattachment lengths for first experiment (longer line) and range in recirculation zone length for bar-building experiment (shorter line) after indicated run time. Inset diagram shows how field measurements were made. Number of each field site refers to *Schmidt* [1990, Table 1]. Scaled-step height changes in field with changing discharge because w_c is held constant at value for lowest observed discharge.

geometric conditions. Reattachment lengths were determined by mapping recirculation zone flow patterns at different discharges onto 1:5000 scale air photos and then estimating the unconstrained reattachment length [*Schmidt*,

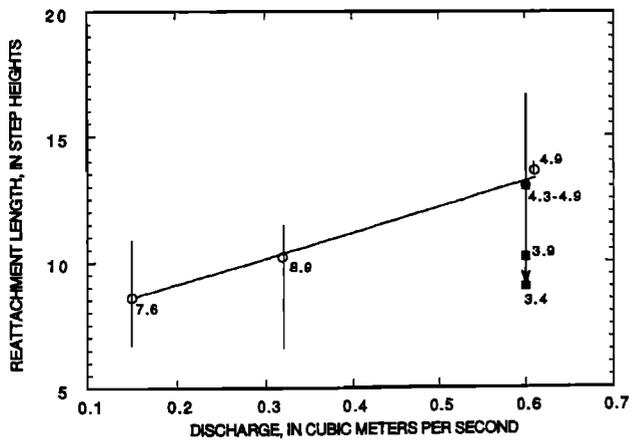


Fig. 16. Time-averaged reattachment length for the same downstream gate height (0.800 m above an arbitrary point, see Table 2, thirteenth column). Error bars indicate total range in instantaneous reattachment length, in step heights. Numbers adjacent to circles are flow-area expansion ratio for each run. Open circles are for clear water, empty flume experiment, and solid squares are for bar-building experiment. Arrow indicates the progress of the second experiment.

1990, Table 1]. The parameter unconstrained reattachment length was proposed to permit comparison of reattachment length in channel expansions of different curvature and shape. These data show that unconstrained reattachment length increases as step height increases. There is great variability in the rate of lengthening at each field site, but all reattachment lengths are shorter than those reported by *Abbott and Kline* [1962] for double backward facing steps (Figure 15, A and B) and are typically shorter than for single backward facing steps (Figure 15, C).

What field conditions might explain the shorter reattachment lengths in Grand Canyon? In Grand Canyon, midchannel cobble and gravel bars are common downstream from many constrictions, especially rapids with the steepest gradients [*Webb et al.*, 1988]. These bars are analogous to the expansion bars described by *Baker* [1984] and analogous to the midchannel bar that developed in the second experiment. In other field cases, a downstream debris fan or talus cone narrows the channel and shortens the length of the channel expansion. Of the field sites plotted on Figure 15, the channel expansions at sites 5, 10, and 11 are strongly influenced by a midchannel bar (site 10, Granite Rapids) or a debris fan (site 5, Eighteen Mile Wash, and site 11, One Hundred Twentytwo Mile Creek). These three sites plot the furthest from the experimental values of *Abbott and Kline* [1962], suggesting that downstream channel irregularities do constrain these reattachment lengths.

Midchannel bars not only shorten the length of recircula-

tion zones at high discharges by necessitating acceleration over them, but at low discharges reattachment length may be shortened because bars are emergent. Schmidt [1990] implied that recirculation zone length is controlled by the chance intersection of the shear zone and irregularly oriented downstream channel banks. These experiments show that acceleration caused by narrowing of the channel, shoaling over midchannel bars, and associated decrease in flow area expansion ratio also influences the point where flow reattaches. In rivers where midchannel bars are larger and more numerous, reattachment lengths should be even shorter than those measured in Grand Canyon. The results also indicate that successful modeling of reattachment length in rivers will depend on prediction of flow conditions in the constriction, identification of the downstream channel control, prediction of the water surface elevation upstream from that control into the expansion in question, and prediction of main channel bed behavior during the modeled flows.

Implications for Restoration of Eddy Bars in Regulated Rivers

These experiments show that deposition rates within recirculation zones increase as main channel transport increases due to increased sediment concentration at constant discharge. Aggradation rates within the recirculation zone were highly correlated with main current sediment transport rates and indicate, within the range of these experimental conditions, that about 20% of main channel transport was deposited within the recirculation zone. We only conducted our bar-building experiment at one constant flow, and we have no data to suggest whether the percent of sediment trapped in an eddy increases at higher main channel transport rates caused by (1) further increases in sediment concentration at constant discharge or (2) increased water discharge and increased sediment concentration, such as indicated by the calculations of Andrews [1991].

Although we found a direct correlation between cumulative transport through the constriction and degree of filling of the recirculation zone, our experiment only continued until the recirculation zone was filled to about 40% of its original volume. These data suggest that this relation decreases in slope; such a relation should exist because as the recirculation zone fills it can be expected that circulation within the eddy and delivery of sediment into the eddy would both decrease. This idea is consistent with stratigraphic sequences observed in Grand Canyon reattachment bars. In these sequences, grain size decreases as reattachment zones fill and sedimentary structures change from those indicating vigorous circulation (dunes and erosional flutes filled with coarse sand deposited from turbulent suspension) to those indicating weak circulation (ripples and mud drapes). An important unresolved question concerns how the proportion of captured sediment varies as a function of the strength of recirculating flow, which is not only a function of the extent to which the recirculation zone is filled but is also a function of the spatial structure of the decelerating jet. Flume and field measurements of eddy capture rates likely differ by at least one order of magnitude; however, available field measurements are subject to substantial error.

While these data show that the rate of eddy deposition depends on the rate of main channel transport, the extent to which a recirculation zone fills depends on the duration of

the sediment-transporting event. In the planning of any regulated flood intended to reconstruct eroded reattachment and separation bars, one must be sure that there is sufficient sediment supply available to maintain high main stem transport rates for durations sufficient to result in net deposition.

Field evidence shows that some recirculating current bars are scoured during rise of a regulated flood [Schmidt, 1990; Schmidt and Graf, 1990]. These observations, if representative, imply that reattachment bars are either a primary source of sediment for the main stem or a relatively quickly mobilized source. The bars can not begin to rebuild until sediment concentration in the main stem exceeds that in the eddy. To achieve net aggradation, any flow designed to reconstruct bars must first rebuild bars to the level that existed prior to initial scour, then continue to add sediment.

The role of sediment availability in the design of bar reconstruction floods places great importance on accurate accounting of sediment sources prior to design of such floods. If it turns out that most sediment in bedrock gorges is stored in recirculation zones, rather than in main channel pools, than it may be impossible to sustain necessary sediment transport rates for sufficient durations without augmenting naturally available supplies. Otherwise, net erosion of recirculation zones in upstream sediment-deficient reaches will result. Planning of bar reconstruction floods must be based on predicting eddy deposition rates, predicting the duration of high main channel sediment transport, and accounting for the wide variation in channel and recirculation zone geometry that exists in natural rivers.

CONCLUSIONS

During a 30-hour experiment when a mixed size distribution of sediment was added to the flow at a rate of 0.5–1.0 kg/s, a bar formed within the zone of recirculating current downstream from a channel constriction. The general topographic form of this bar was that of a linear ridge widening downstream into a broad platform. Within the recirculation zone, the highest deposition rates occurred near the downstream end, but these rates were always less than rates on a midchannel bar that formed just downstream from the reattachment zone. These results are consistent with field investigations of the sedimentology of reattachment bars in Grand Canyon which show that deposition occurs in the vicinity of the reattachment zone and fills the primary eddy in an upstream direction.

Bed forms on the surface of the ridge and platform and repetitive topographic surveys show that the entire bar aggraded in an onshore and upstream direction during the experiment. Sorting of sediment within the recirculation zone is sufficient to form a deposit that is generally finer than the size distribution in transport by the main channel; the finest sizes are deposited in the lee of the debris fan. This areal distribution is similar to that described in Grand Canyon for separation and reattachment bars, and the progression of bar deposition is consistent with the model of Grand Canyon bar deposition developed from interpretation of sedimentary structures and sequential field topographic surveys. The percentage of main stem sediment that was captured by the eddy during the bar-building experiment decreased from 37% (when the eddy was empty) to 24% (when sand filled approximately 32% of the eddy volume).

The reattachment point occurs where expanding vortices

impinge on the flume wall, and this point fluctuated over a range of about 5 times the step height. Some parts of the recirculation zone had instantaneous velocities that varied over an entire 360-degree range. Resulting bed forms that developed near the center of the eddy resembled oscillatory ripples. Oscillatory ripples that in the field are formed by reattachment point fluctuation did not develop during our experiments. In fact, deposition did not occur near the wall in the reattachment zone.

Recirculation lengths were similar within broad ranges of hydraulic conditions. Where constricted flow was highly supercritical, the length of the recirculation zone was about two step heights, but where Froude numbers were less than about 2, the zone of recirculating current was of similar size over a range of area expansion ratios. To some extent, reattachment lengths were longer, and recirculation flow patterns better developed, at intermediate Froude numbers between 0.8 and 1.6. As aggradation of a midchannel bar proceeded and the bar migrated upstream, reattachment length decreased and the recirculation zone shortened. These processes were linked because flow accelerated over the midchannel bar, which prevented stagnation along the wall in areas previously of adverse water slope. As the midchannel bar retreated upstream, acceleration occurred where deceleration had previously been the case.

Sedimentation can occur in bedrock gorges where flow separation and flow stagnation exist [Baker, 1984]. The areal extent and magnitude of deposition depend on the areal extent of the stagnated flow, the areal extent of the zone over which reattachment point oscillation occurs, the flow structure of the remainder of the recirculation zone, the rate of main channel sediment transport, and the duration of the transporting event. In regulated rivers where degradation of reattachment and separation bars has occurred, the task in planning bar reconstruction floods is to predict the location of stagnation points, the size of the zone over which these stagnation points oscillate, the nature and stability of the general recirculating flow field, the rate of sediment delivery from main channel to recirculation zone, and the duration during which that delivery from main channel to recirculation zone will occur.

Acknowledgments. Field work was supported by the Glen Canyon Environmental Studies program of the U.S. Bureau of Reclamation. Travel funds were provided by the Middlebury College Faculty Development Fund (J.C.S.) and the U.S. Geological Survey G. K. Gilbert Fellowship (D.M.R.). T. O. Manley, Department of Geology, Middlebury College, conducted the surface and volume modeling calculations. Assistance during the experiments was provided by Y. Kodama and H. Iijima. We thank J. G. Bennett, J. M. Nelson, and T. L. Vallier for careful review of the manuscript and suggestions for improvements.

REFERENCES

- Abbott, D. E., and Kline, S. J., Experimental investigation of subsonic turbulent flow over single and double backward facing steps. *J. Basic Eng.*, 84, 317-325, 1962.
- Andrews, E. D., Deposition rate of sand in lateral separation zones, Colorado River (abstract), *Eos Trans. AGU*, 72, 219, 1991.
- Baker, V. R., Flood sedimentation in bedrock fluvial systems, in *Sedimentology of Gravels and Conglomerates*, edited by E. H. Koster and R. J. Steel, pp. 87-98, The Canadian Society of Petroleum Geologists, Calgary, Alta., 1984.
- Best, J. L., The morphology of river channel confluences, *Prog. Phys. Geog.*, 10, 157-174, 1986.
- Chang, P. K., *Separation of Flow*, Pergamon, New York, 1966.
- Driver, D. M., and H. L. Seegmiller, Features of a reattaching turbulent shear layer in divergent channel flow, *AIAA J.*, 23, 163-171, 1985.
- Eaton, J. K., and J. P. Johnston, A review of research on subsonic turbulent flow reattachment, *AIAA J.*, 19, 1093-1100, 1981.
- Ikeda, H., Experiments on bedload transport, bed forms, and sedimentary structures using fine gravel in the 4-meter-wide flume, *Univ. of Tsukuba Environ. Res. Cent. Pap.* 2, Ibaraki, Japan, 1983.
- Kieffer, S. W., The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon, *J. Geol.*, 93, 385-406, 1985.
- Kieffer, S. W., Hydraulic maps of major rapids, Grand Canyon, Arizona, *U.S. Geol. Surv. Geophys. Invest., Map, I-1897*, 1988.
- Leeder, M. R., and P. H. Bridges, Flow separation in meander bends, *Nature*, 253, 338-339, 1975.
- Leopold, L. B., The rapids and the pools—Grand Canyon, *U.S. Geol. Surv. Prof. Pap.*, 669-D, 1964.
- Nelson, J. M., Experimental and theoretical investigation of lateral separation eddies (abstract), *Eos Trans. AGU*, 72, 218-219, 1991.
- Page, K., and G. Nanson, Concave-bank benches and associated floodplain formation, *Earth Surf. Processes Landforms*, 7, 529-543, 1982.
- Randle, T. J., and E. L. Pemberton, Results and analysis of STARS modeling efforts on the Colorado River in Grand Canyon, *Glen Canyon Environ. Study GCES-38*, U.S. Bur. of Reclam., Salt Lake City, Utah, 1987.
- Rubin, D. M., J. C. Schmidt, and J. N. Moore, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona, *J. Sediment. Petrol.*, 60, 982-991, 1990.
- Schmidt, J. C., Geomorphology of alluvial-sand deposits, Colorado River, Grand Canyon National Park, Arizona, Ph.D. dissertation, Johns Hopkins Univ., Baltimore, Md., 1987.
- Schmidt, J. C., Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona, *J. Geol.*, 98, 709-724, 1990.
- Schmidt, J. C., and J. B. Graf, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona, *U.S. Geol. Surv. Prof. Pap.*, 1493, 1990.
- Signell, R. P., and W. R. Geyer, Transient eddy formation around headlands, *J. Geophys. Res.*, 96, 2561-2575, 1991.
- Simpson, R. L., Turbulent boundary-layer separation, *Annu. Rev. Fluid Mech.*, 21, 205-234, 1989.
- Tamai, N., T. Asaeda, and H. Ikeda, Study on generation of periodical large surface eddies in a composite channel flow, *Water Resour. Res.*, 22, 1129-1138, 1986.
- Webb, R. H., P. T. Pringle, S. L. Reneau, and G. R. Rink, Monument Creek debris flow, 1984: Implications for formation of rapids on the Colorado River in Grand Canyon National Park, *Geology*, 16, 50-54, 1988.
- Wolanski, E., J. Imberger, and M. L. Heron, Island wakes in shallow coastal waters, *J. Geophys. Res.*, 89, 10553-10569, 1984.
- Yeh, H. H., W. Chu, and O. Dahlberg, Numerical modeling of separation eddies in shallow water, *Water Resour. Res.*, 24, 607-614, 1988.
- H. Ikeda, Environmental Research Center, University of Tsukuba, Ibaraki, 305 Japan.
- D. M. Rubin, U.S. Geological Survey, MS 999, 345 Middlefield Road, Menlo Park, CA 94025.
- J. C. Schmidt, Department of Geography and Earth Resources, Watershed Science Unit, College of Natural Resources, Utah State University, Logan, UT 84322.

(Received October 28, 1992;
revised March 1, 1993;
accepted March 16, 1993.)