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SAND DEPOSITION IN SHORELINE EDDIES ALONG FIVE WILD AND SCENIC RIVERS, IDAHO†

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ABSTRACT

Sand bars deposited along the lateral margin of a river channel are frequently a focus of recreational activities. Sand bars are appealing sites on which to camp, picnic, fish and relax because they are relatively flat, soft, non-cohesive sand, free of vegetation and near the water's edge. The lack of vegetation and cohesion make sand bars easily erodible. Without appreciable deposition of new material, number and size of bars through a given reach of river will decline substantially over a period of years. We studied 63 beaches and their associated eddies located throughout 10 selected reaches within the designated Wild and Scenic River sections of the Lochsa, Selway, Middle Fork Clearwater, Middle Fork Salmon and Salmon Rivers in Idaho to determine the relation of beaches to the frequency and magnitude of streamflows that deposit appreciable quantities of sand. At present, these rivers have been altered little, if at all, by flow regulation, and only the Salmon River has substantial diversion upstream of a study reach. The river reaches studied have an abundance of sand bar beaches of appreciable size, in spite of suspended sand concentrations that rarely exceeded a few hundred milligrams per litre even during the largest floods.

Calculated mean annual rates of deposition in an eddy vary from 5.8 to more than 100 cm depending primarily on: (1) the duration of streamflows that inundate the eddy sand bar depositions; (2) the rate of the flow exchange between the channel and an eddy and (3) the concentrations of suspended sand in the primary channel. The annual thickness of sand deposition in an eddy varies greatly from year to year depending on the duration of relatively large streamflows. Maximum annual sand depositions in an eddy are three to nine times the estimated long-term mean values. Relatively large, sustained floods deposit an appreciable portion of total deposition over a period of years. For the period of record, 1930–2002, the seven largest annual depositions, which represent more than 40% of all material deposited over the Lochsa River 21.9 km eddy, occurred in the years with the seven largest instantaneous annual peak floods. Beach area and volume for most beaches, however, are less variable year-to-year than the variation in annual deposition would indicate. Accumulative 10-year weighed deposition rate was computed to estimate the effective variability of beach deposition. Although less variable than the annual deposition, the cumulative 10-year deposition calculated for the longest hydrologic records, 71 years, existing on the Idaho Wild and Scenic Rivers varied by more than an order of magnitude from less than 20 cm to more than 220 cm. Published in 2006 by John Wiley & Sons, Ltd.

KEY WORDS: river mechanics; suspended sediment transport; whitewater recreation; Wild and Scenic Rivers

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INTRODUCTION

River recreation has grown substantially over the past several decades. Both established activities, such as fishing, and relatively new activities, such as whitewater boating, have become increasingly popular. The social and economic values of these recreational activities now challenge many traditional uses of water resources. For example, when Congress authorized the construction of Glen Canyon Dam on 11 April 1956, less than 500 people had navigated the Colorado River through Grand Canyon by boat since J. W. Powell made the first trip in 1869. The popularity of whitewater boating increased dramatically during the following two decades. In the early 1970s, the National Park Service imposed a limit on the number of river runners of about 22 000 per year. Today, the economic value contributed by whitewater boating in Grand Canyon is about equal to and may exceed the value of electric power generated by Glen Canyon Dam (Bishop *et al.*, 1987).

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Sand bars deposited along the lateral margin of a river channel, commonly called beaches, are frequently a focus of recreational activities. Because they are relatively flat, soft, free of thick vegetation and near the water's edge, sand bars are appealing sites on which to camp, picnic, fish and relax.

Lateral sand bars are deposited in eddies, zones of separated, recirculating flow, which commonly develop downstream of abrupt changes in channel width or a large flow obstruction on the river banks (Schmidt, 1990; Schmidt and Graf, 1990). Eddies have less intense turbulence than the primary downstream flow. Thus, when sediment-laden water from the centre of the river is exchanged into an eddy, the sand particles settle to the bottom of the eddy and accumulate. The relatively weak circulation of an eddy, however, is sufficient to redistribute sand throughout the eddy all the way to the water edge (Wiele *et al.*, 1999). So long as an eddy exists, a fresh supply of sand is contributed to the eddy, except at the lowest river flows when the suspension of sand is negligible. During periods of relatively high flows, substantial quantities of sand may accumulate in an eddy, because of the much larger concentration of sand carried by the river. In addition to this increased rate of sand accumulation at relatively high flows, sand is deposited higher on the river bank where it becomes exposed and available for recreational activities when the river stage falls (Andrews *et al.*, 1999).

The very attributes that make lateral sand bars appealing for recreation, soft non-cohesive sand free of vegetation, however, make sand bars easily erodible. Variations in river stage, changes in the geometry and intensity of eddy circulation, wind and human traffic can lead to the relatively rapid erosion of lateral sand bars. Kearsley *et al.* (1994, 1999) and Hazel *et al.* (1999) found the area of sand bar campsites along the Colorado River through Grand Canyon decreased by nearly half in approximately 20 years following significant deposition under certain flow conditions. Sand bar erosion rates, however, varied greatly from one deposit to another.

Investigations to date of lateral sand bars have focused primarily on reaches downstream of large dams principally the Colorado River below Glen Canyon Dam, (Howard and Dolan, 1979; Webb *et al.*, 1999), the Green River below Flaming Gorge Dam (Grams and Schmidt, 1999) and the Snake River through Hells Canyon (Schmidt *et al.*, 1995). Flow and sand transport in each of these rivers have been substantially altered from the natural conditions by flow depletion, flow regulation and trapping of upstream sand supply. In each of these reaches, which are very popular sites for recreational whitewater boating, the number and size of sand bars available for camping have decreased substantially since the construction of upstream dams. Hypothesized causes for the loss of sand bars include large daily fluctuations in flow associated with hydropower generation, substantially reduced annual maximum flow and greatly diminished sand concentrations over a range of flows (Andrews and Pizzi, 2000).

An investigation of the nature of beaches and the accumulation of sand in eddies was undertaken on the five Wild and Scenic Rivers in Idaho with appreciable recreation activity: the Selway, Lochsa, Middle Fork Clearwater, Middle Fork Salmon and Main Salmon Rivers, see Figure 1. Three of the rivers, the Selway, Middle Fork Salmon and Main Salmon, are among the most popular and sought after whitewater rivers in North America. The U.S. Forest Service, which manages the Wild and Scenic reaches, has developed a lottery system to allocate a limited number of launches during the most popular periods for whitewater recreation each year. The availability of campsites is one of the primary factors considered to determine the appropriate number of daily launches. The specific objectives of the study were to quantify the range of streamflows in each Wild and Scenic River reach that has constructed and maintained the beaches under the existing hydrologic regime. The study considered three specific questions:

1. What is the relation between river stage and vertical extent of beach deposits?
2. How does the rate of sand deposition in an eddy vary with discharge?
3. What are the magnitude and frequency of streamflows that deposit sand in an eddy?

HYDROLOGIC AND GEOMORPHIC OBSERVATIONS

In order to address these questions, 10 study reaches were identified within the 5 Wild and Scenic River reaches. Several beaches within each study reach were selected for investigation and analysis. The 10 study reaches are listed in Table I. The number and location of the study reaches were determined by the availability of sufficient information to determine the local river discharge at the time a given beach was surveyed. In most instances, this

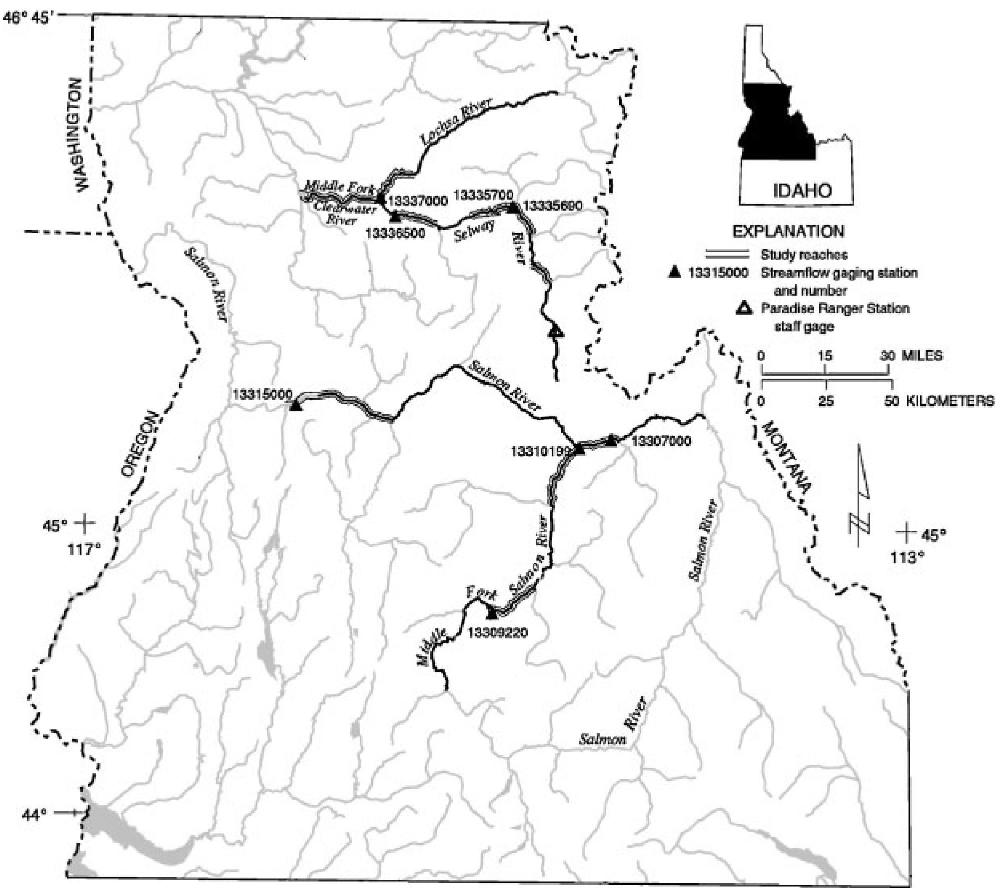

Figure 1. Location of the five Wild and Scenic Rivers in Idaho with appreciable recreation use. The extent of the Wild and Scenic reaches are represented by the bold river courses

information was provided by a U.S. Geological Survey stream gauge, or, in two instances, the sum of flows recorded at two gauges. Each stream gauge consists of a cross-section with a measured stage–discharge relation and a nearby continuous record of river stage. Three of the study reaches had a rated cross-section, that is a stage–discharge relation, but lacked an operating stage recorder. At these reaches, river stage was recorded manually when beaches in the reach were being surveyed. Two of these reaches without an operating stage recorder at the time of this study, the Salmon River near Shoup and the Salmon River near French Creek, are located near discontinued USGS stream gauges. The available period of record at the operating and discontinued stream gauges is shown in Table I. The Selway River near Paradise Ranger Station has a rated cross-section and stage plate, but no systematic record of river stage.

The longitudinal extent of a study reach was defined by the location of tributary streams of sufficient size to appreciably change the river discharge. Thus, each study reach extends upstream and downstream from the rated cross-section to the first appreciable ungauged tributary. The relative significance of ungauged tributaries was determined by comparing drainage of tributaries to the reach area to the drainage area at the rated cross-section. The drainage area of tributaries to the study reaches averaged 4.7% and ranged from less than 1% to almost 10% of the mainstem drainage area.

The first survey of beaches in the 10 study reaches was made in June 1998 during the snowmelt runoff. All beaches within a study reach larger than a few tens of square meters of exposed sand and readily accessible were surveyed and included in the study. No beach was excluded for any other reason. A majority of the beaches of an appreciable size in all study reaches were surveyed. Several factors affected the accessibility of beaches. Four of the

Table I. Summary of study reaches and streamflow records

Wild and Scenic River	Study reach location in river kilometres[a]	Gauging Station or Rated Cross-Section	Period of daily streamflow records water years	Reach averaged beach sand size, in mm		
				d_{84}	d_{50}	d_{16}
Lochsa	(1) 21.9–0.0	Lochsa River near Lowell, USGS# 13337000	1930-Current	0.422	0.308	0.197
Selway	(1) 264.4–253.1	Paradise Ranger Station Boat Ramp Staff Gauge	No streamflow record	0.318	0.236	0.176
	(2) 238.5–218.2	Selway River above Moose Creek near Moose Creek Station USGS# 13335690	1995–2001	0.454	0.344	0.258
	(3) 218.2–210.2	Selway River above Moose Creek near Moose Creek Station USGS# 13335690 Moose Creek at mouth near Moose Creek Ranger Station USGS# 13335700	1995–2001	0.429	0.269	0.188
	(4) 186.4–168.8	Selway River near Lowell USGS# 13336500	1930-Current	0.344	0.257	0.192
Middle Fork Clearwater	(1) 157.2–120.2	Lochsa River near Lowell USGS# 13337000 Selway River near Lowell USGS# 13335690	1930-Current	0.307	0.221	0.167
Middle Fork Salmon	(1) 101.2–73.4	Middle Fork Salmon River at Middle Fork Lodge near Yellow Pine USGS# 13309220	1973–1982	0.375	0.254	0.176
	(2) 29.0–0.0	Middle Fork Salmon River at mouth near Shoup USGS# 13310199	1994-Current	0.384	0.274	0.191
Salmon	(1) 338.1–319.8	USFS Staff Gauge at Cove Creek Boat Ramp near site of discontinued Salmon River near Shoup USGS# 13307000	1944–1982	0.315	0.245	0.174
	(2) 215.6–168.7	Salmon River near French Creek USGS# 13315000	1945–1956	0.436	0.306	0.209

[a]Study reach location was determined from the 7.5 min USGS Quadrangle Series Maps which delineate river length upstream from river mouth in miles. Reach number is given in parenthesis.

study reaches, the Lochsa, Middle Fork Clearwater, Selway reach 4 and Salmon reach 1, have a road along one side. Except for Selway reach 4, only those beaches in these reaches accessible from the road were studied. The six roadless study reaches and Selway reach 4 were approached by whitewater raft. Some of the beaches were occupied by campers when the surveying party floated past the site. These established camps were not disturbed.

All of the 63 beaches considered in this study are used for recreational purposes, camping, picnicking, swimming, fishing etc. All of the beaches located in Middle Fork Salmon River reaches 1 and 2, Salmon River reach 2 and Selway River reaches 1, 2 and 3 are identified campsites for river runners. Six of the 11 beaches along the Lochsa and Middle Fork Clearwater River are immediately adjacent to a designated campground or picnic area. The remaining beaches were near highway turnouts and had fire rings and other evidence of recreational use. The study beaches in Salmon River reach 1 and Selway River reach 4 were near road turns, established trails led from roadside to beach, fire rings and/or other evidence of recreational use.

During the initial visit to a study beach, a local benchmark was established and a sample of beach sand was collected for particle size analysis. A brief description of the beach location and evidence of recreational use were recorded. Where possible, a GPS location was determined. On the initial visit and each subsequent visit, the water surface elevation relative to the local benchmark was surveyed. The discharge corresponding to the surveyed water surface was determined by correlating the time of survey with the discharge recorded or observed at the previously determined stage–discharge relation within the study reach.

The water surface elevation at all study beaches was resurveyed at an intermediate flow in July 1998, and again at low flow in late July and August 1998. During the low flow visit, the beach profile from hillside to water's edge was surveyed and a tape and compass map of the beach was sketched.

The Lochsa, Selway, Middle Fork Clearwater and Salmon River reach 1 beaches were resurveyed in June 1999, and all beaches, except those in Salmon River reach 1, were surveyed in May and June 2000.

A line(s) of debris, consisting primarily of conifer needles, cones, bits of wood and leaves, stranded at the peak stage of recent flood(s) was present on most beaches. Floating debris in a river tends to accumulate in the recirculating, low-velocity environment of an eddy. Thick rafts of debris form along the shore of the eddy during periods of high flows and become stranded when river stage falls. During the initial beach surveys, debris lines marking the peak stage of both the 1997 and 1998 floods were present on most, though not all, beaches. When present on a beach, the elevation of a debris strand line(s) was surveyed relative to the local benchmark. The 1997 peak flood stages were unusually high in all of the five rivers, where as the 1998 peak stages were relatively common and lower. In all of the study reaches, the 1997 and 1998 maximum discharges were recorded at the active river gauges or could be determined from flood mark at the established rated cross-section. Thus, the discharge associated with a strand line on a given beach could be determined.

The composite sample of sand collected from each beach was sieved and the distribution of particle sizes determined. The reach-averaged values for d_{16}, d_{50} and d_{84} are summarized in Table I. Across a broad range of eddy size, geomorphic setting and circulation intensity, the median size and sorting of sand beach is remarkably similar. The reach-averaged median size of beach sand varied from 0.22 to 0.31 mm. The degree of sorting represented by d_{84}/d_{16}, that is, the ratio of the particle sizes one standard deviation greater than the median to the particle size one standard deviation smaller than the median in a lognormal distribution, varies from 1.76 to 2.28 with a mean of 1.97. The beach sands are well-sorted and similar to the sorting observed in beaches deposited in the shoreline eddies of other rivers, for example Schmidt and Graf (1990). As will be described below, relatively little material coarser than 0.50 mm enters an eddy and relatively little material finer than 0.12 mm remains in an eddy long enough to settle through the water column.

Suspended and bedload sediment transport have been sampled over a range of relatively large discharges at six of the gauging stations listed in Table I. Concentrations of suspended sediment were determined by collecting a discharge-weighted sample of the flow using standard equipment and techniques (Edwards and Glysson, 1988). For those sand particles that are most abundant in the beach deposits, typically = 0.50 mm in diameter, see Table II, suspension is the predominant mode of transport. Suspended sand transport accounts for more than 95% of all sand transported over the period of record at each of the six gauging stations analysed in this study. Suspended sand concentrations were sampled primarily at relatively large discharges in May and June during the period of snowmelt runoff. The variation of suspended sand transport with river discharge was determined by fitting a linear relation to the log-transformed values. The six sand transport relations are compared in Figure 2. Values of R^2 determined for the six relations vary from 0.69 to 0.95. The range of river discharges over which the concentration of suspended sand has been sampled is indicated by the length of the fitted relations. Suspended sand concentrations in the five Idaho Wild and Scenic Rivers are relatively low, generally less than 100 mg/L even at relatively large discharges.

The variation of suspended sand concentration with river discharge determined at two Colorado River gauging stations in Grand Canyon, Arizona, is also shown in Figure 2. The Colorado River sand concentrations versus river discharge relation are included for comparison because of the very extensive and on-going investigations of river beach deposits in Grand Canyon National Park and the effect of river discharge and sediment transport on them (Howard and Dolan, 1979; Schmidt and Rubin, 1995; Webb *et al.*, 1999). The Colorado River through Grand

Table II. Comparison of eddy exchange coefficients, mean residence time and beach sand size determined in nine study eddies, two additional Selway River eddies and one Colorado River eddy in Grand Canyon, AZ

River reach and eddy	Eddy exchange coefficient, in (sec^{-1})	Mean residence time[a] in seconds (sec)	Beach sand size, in mm		
			d_{16}	d_{50}	d_{84}
Lochsa near Lowell					
RKm 11.3	0.00231	300	0.19	0.24	0.33
RKm 20.9	0.00284	244	0.22	0.29	0.38
Selway near Lowell					
RKm 186.2	0.00742	93.4	0.21	0.30	0.43
Bait Creek	0.00334	207			
Race Creek	0.00883	78			
Middle Fork Clearwater near Lowell					
RKm 143.7	0.00602	115	0.15	0.22	0.30
Salmon River near Shoup					
RKm 336.7	0.00311	223	0.20	0.29	0.40
RKm 332.3	0.00745	93	0.14	0.20	0.27
Salmon River near French Creek					
RKm 201.8	0.00364	190	0.16	0.22	0.29
RKm 209.8	0.00328	211	0.23	0.31	0.44
Middle Fork Salmon River at mouth near Shoup					
RKm 10.3	0.00205	338	0.16	0.24	0.33
Colorado River					
RKm 85.9	0.0039	178		0.22	

[a]The mean residence time in seconds is equal to (ln 0.5/$-\lambda$), where λ is the eddy exchange coefficient.

Canyon is regulated by Glen Canyon Dam, located 100 km upstream of the above Little Colorado River gauge and 160 km upstream of the Grand Canyon gauge, Glen Canyon Dam traps all of the sand supplied to it and the only sand transported downstream of the dam is the material supplied by tributaries (Andrews, 1991). The greater concentration of sand transported at the Grand Canyon gauge is primarily due to the contribution of sand by the Little Colorado River. Since the completion of Glen Canyon Dam in 1963, the total number and size of beaches has decreased substantially throughout the Grand Canyon reach. In addition to decreasing concentrations of suspended sand by approximately an order of magnitude, operation of Glen Canyon Dam has substantially reduced the annual range of river flow. The mean annual peak discharge has decreased from 2420 m^3/s, 1922–1957, to 920 m^3/s, 1965–present. The comparison of suspended sand concentrations shown in Figure 2 indicates the importance of a wide annual range of river discharges to the deposition of shoreline sand bars. Shoreline sand bars of substantial size are currently numerous in the Idaho Wild and Scenic River rivers. These sand bars have been deposited by river flows with relatively low suspended sand concentrations.

A local stage–discharge relation was determined for each of the 63 study beaches using the surveyed water surface elevation and flood debris strand lines. The stage–discharge relation for the Selway River beach at river kilometre 210.1, commonly known as Trapper's Camp, is typical and shown in Figure 3. Specific surveyed points are represented by a diamond symbol. The corresponding discharge, in cubic meters per second, is given next to each symbol. The water discharge scale is shown on the top margin of Figure 3. A smooth curve has been fit to the surveyed values. Also, shown on Figure 3 is the surveyed profile of the Trapper's Camp beach. The sand and gravel portions of the beach are identified. The horizontal dimension of the beach is shown on the bottom margin of the figure. The exposed width of the beach at a given discharge is the profile length above the corresponding stage.

The beach profile was surveyed over the full extent of the exposed beach at a discharge of 30 m^3/s on 28 July 1998. Thus, the beach may extend below 28.2 m; however, the upper limit of the beach was at an elevation of 31.8 m

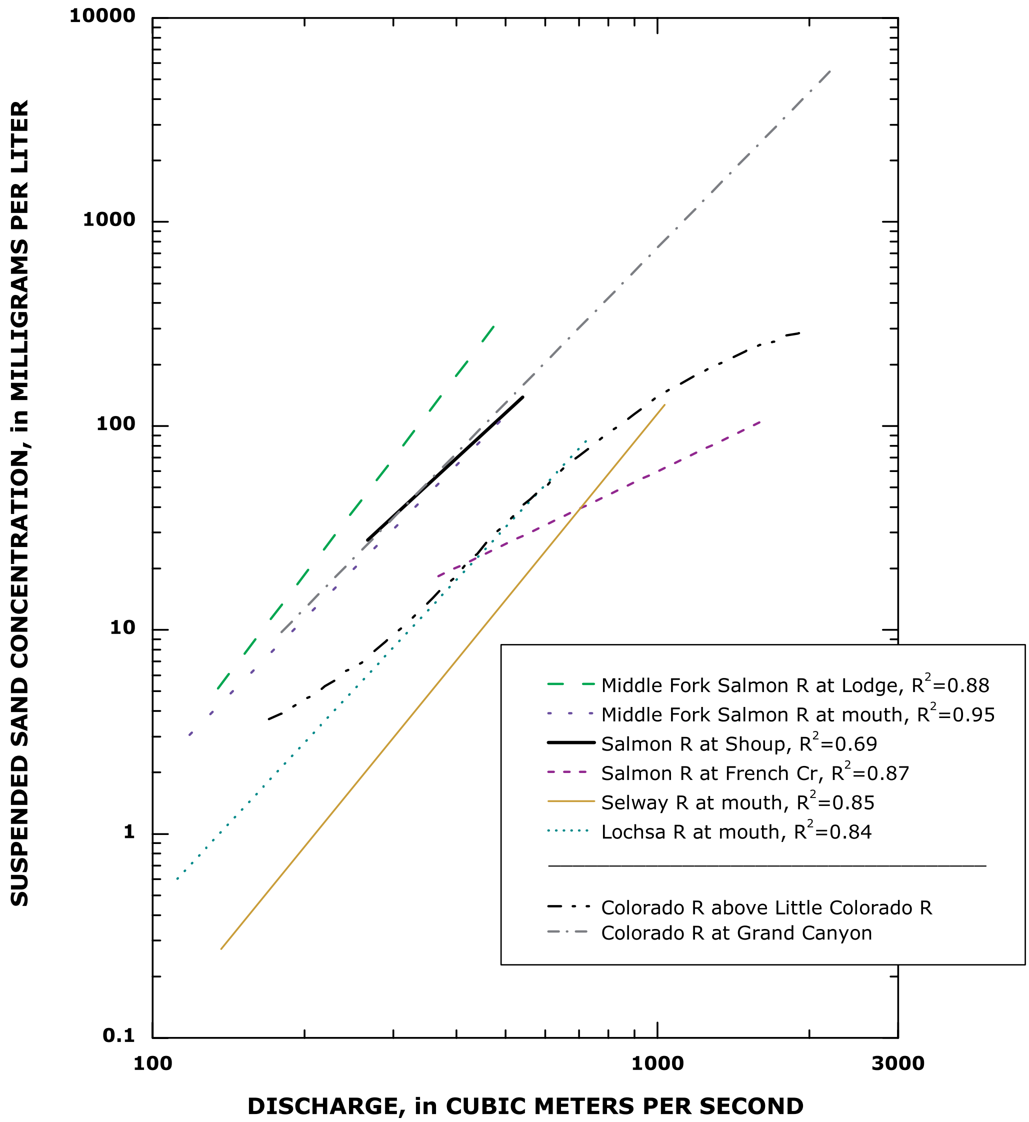

Figure 2. Variation in suspended sand concentration with river discharge in six Idaho Wild and Scenic River study reaches and two Colorado River Reaches in Grand Canyon, AZ. This figure is available in colour online at www.interscience.wiley.com/journal/rra

where a forested hillside with a developed soil borders the beach. Recently deposited sand was present on the bank up to the maximum stage of the 1997 flood, as was typical throughout the five Wild and Scenic Rivers. The 1997 maximum stage was identified on 49 of the 63 beaches studied. On those 49 beaches, recently deposited sand was present on the riverbank up to, but not above, the 1997 maximum stage on 36 beaches. On the remaining 13 beaches, the top of the beach was within 0.25 m above the 1997 maximum stage on 7 beaches and within 0.70 m below the 1997 maximum stage on 6 beaches. The 1997 maximum stage was the highest stage recorded since 1974 at the Lochsa River near Lowell and the Selway River near Lowell, the only two gauges with a continuous record over the period.

CALCULATIONS OF SAND DEPOSITION IN EDDIES

As noted above, water is exchanged between relatively high velocity, high turbulence primary flow and the relatively low velocity, and low turbulence recirculating flow of an eddy. During the exchange, sand suspended in

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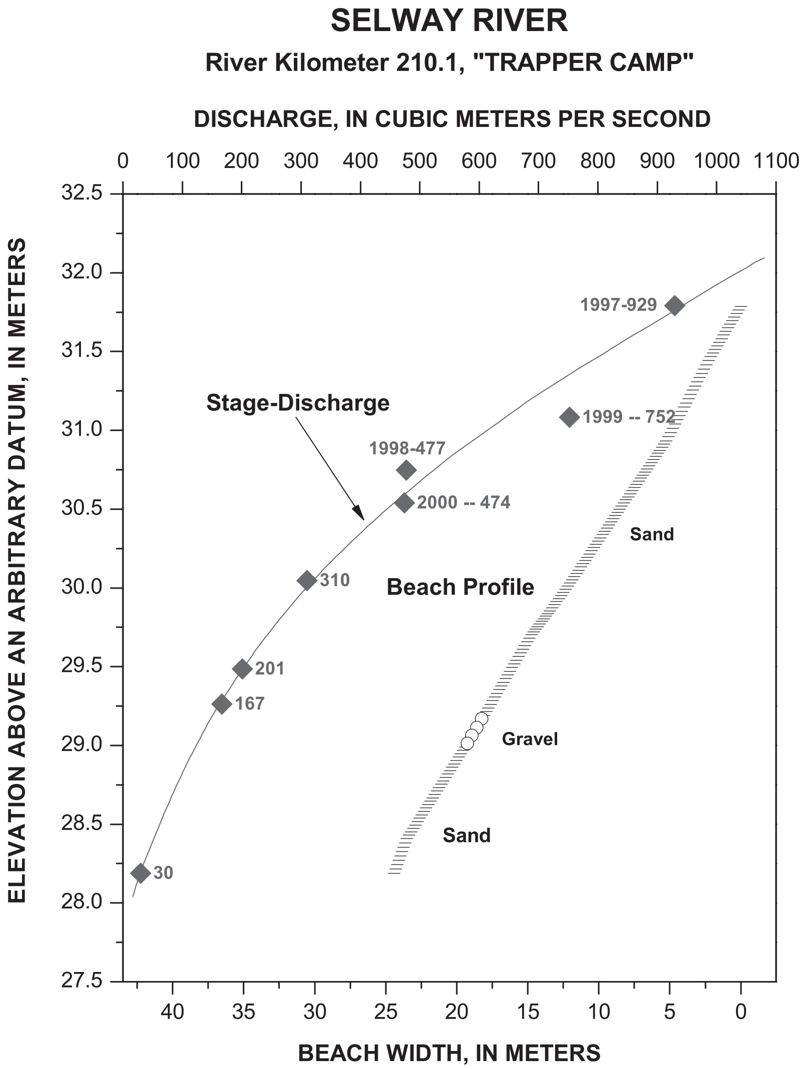

Figure 3. Local stage–discharge relation and beach profile determined for the Selway River, RKm 210.8 eddy

the primary flow is carried into an eddy where the turbulent intensity is insufficient to maintain the suspension of sand particles coarser than about 0.01 mm in diameter and they settle to the bottom of the eddy. The rate of sand deposition in an eddy at given river discharge, S_d, can be calculated where the rate of flow exchange between the primary flow and the eddy, the geometry of the eddy and the concentration of sand in the primary flow are known.

The boundary between the primary flow and the eddy is a zone of intense shear and a line of advected vortices. Instantaneous flow across the boundary fluctuates strongly into and out of the eddy as each vortice is transported passed a given point. When averaged over the entire channel-eddy boundary and periods of a few tens to hundreds of seconds; however, net flow into and out of the eddy is zero. Sand will accumulate in the eddy when the flow into the eddy has a large concentration of suspended sand than flow out of the eddy. The following approach to estimate sand deposition in eddies treats the exchange of water and suspended sand between the primary channel and the eddy as a steady-state process over a time scale in which a sand grain will settle through the eddy water column. The exchange of water and suspended sand as well as the settling of suspended sand are characterized by spatially and temporally average rates. Furthermore, the dissipation of turbulence in fluid entering the eddy is assumed to be rapid compared to the time required for a sand grain to settle through the eddy water column.

The flux of river water into an eddy, q, is

$$q = \lambda V_e \tag{1}$$

where V_e is the volume of the eddy and λ is the eddy exchange coefficient, that is the fraction of the eddy volume exchanged per second. The flux of suspended sand into an eddy is

$$qC_s(i) = \lambda V_e C_s(i) \tag{2}$$

where $C_s(i)$ is the mean concentration of suspended sand in the ith size fraction in the river. Depending on the water depth in the eddy, the settling velocity of the sand particles and the time a parcel of water resides in the eddy, a portion of the suspended sand may be exchanged out of the eddy before settling to the bottom. At steady state, the volume of water in an eddy is constant and the flux of water into and out of an eddy is equal. The flux of suspended sand out of an eddy is

$$qC_o(i) = \lambda V_e C_o(i) \tag{3}$$

where $C_o(i)$ is the volumetric mean concentration of suspended sand in the ith size fraction in flow out of the eddy. The rate of sand deposition for a given particle fraction, $S_d(i)$, per unit area of eddy bottom is

$$S_d(i) = w_s(i) C_e(i) \tag{4}$$

where $w_s(i)$ is the settling velocity of sand particles in the ith fraction and $C_e(i)$ is the volumetric mean concentration of suspended sand in the ith size fraction in the eddy. The flux of suspended sand into an eddy equals the flux out of the eddy plus the deposition of sand on the eddy bottom. Hence,

$$\lambda V_e C_s(i) = \lambda V_e C_o(i) + w_s(i) C_e(i) A_e \tag{5}$$

where A_e is the area of the eddy in square meters. At steady state, the linear approximation of $C_e(i)$ is

$$C_e(i) = \frac{C_s(i) + C_o(i)}{2} \tag{6}$$

The ratio of the eddy volume to the eddy area is the mean depth, $\overline{h_e}$, of the eddy

$$\overline{h_e} = \frac{V_e}{A_e} \tag{7}$$

hence, the rate of sand deposition is

$$S_d(i) = \frac{\lambda \overline{h_e} w_s(i)}{\lambda \overline{h_e} + \frac{w_s(i)}{2}} C_s(i) \tag{8}$$

The rate of fluid exchange between the primary flow and an eddy can be measured directly by mixing a chemical tracer into an eddy and sampling the decreasing concentration of tracer in the eddy over a period of time as it is diluted by water from the primary flow which has no tracer concentration. Eddy exchange rates were measured at nine study beaches in the Wild and Scenic River reaches at relatively high flow during the period of snowmelt runoff. The measured eddy exchange coefficients are summarized in Table II. Eddy exchange coefficients measured in two Selway River eddies, which are not within one of the study reaches and a Colorado River eddy in Grand Canyon, AZ, are included in Table II for comparison. All of the eddies listed in Table II have a surface area of a few thousand to ten thousand square meters at relatively high flows and are associated with an identified camping beach. Measured eddy exchange coefficients, λ, the fraction of the eddy volume exchanged per second vary from 0.00205 to 0.00883. The mean residence time, that is, the time over which half of the water in an eddy is exchanged, can be calculated directly from the eddy exchange coefficient. The mean residence times varied from 78 to 338 s. While measuring the dilution of tracer in an eddy, the eddy rotation period was estimated from the movement of the leading edge of the dye tracer and floats. Subsequently, it was observed that the rotation period of an eddy is approximately the mean residence time. Thus, approximately half of the eddy volume is exchanged with the river

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flow with each complete rotation of the eddy. For a given eddy volume, eddies with relatively rapid circulation exchange water with the river more rapidly than do eddies with relatively slow circulation.

The mean eddy depth at a given discharge can be estimated from the eddy stage–discharge relation. The gross quantity of sand of a given size deposited per unit area of eddy bottom during a day is $86\,400 \times S_d(i)$. For the nine eddies where exchange coefficient was measured, the daily gross deposition of sand in each of four particle size fractions, 0.0625–0.125, 0.125–0.250, 0.250–0.500 and 0.500–1.0 mm, can be calculated using Equation (8) for the period of recorded streamflows. The total daily sand deposition is calculated by summing over all size fractions.

MAGNITUDE AND FREQUENCY OF SAND BAR DEPOSITION

The rate of sand deposition in all eddies increases rapidly with increasing river discharge because of the larger concentration of suspended sand in the primary flow which can be exchanged into an eddy. The sand deposition rate in centimetres per day varies with river discharge to approximately the 4th power. Thus, a doubling of the river discharge increases the rate of sand deposition in an eddy by a factor of about 16-fold. Consequently, the quantity of

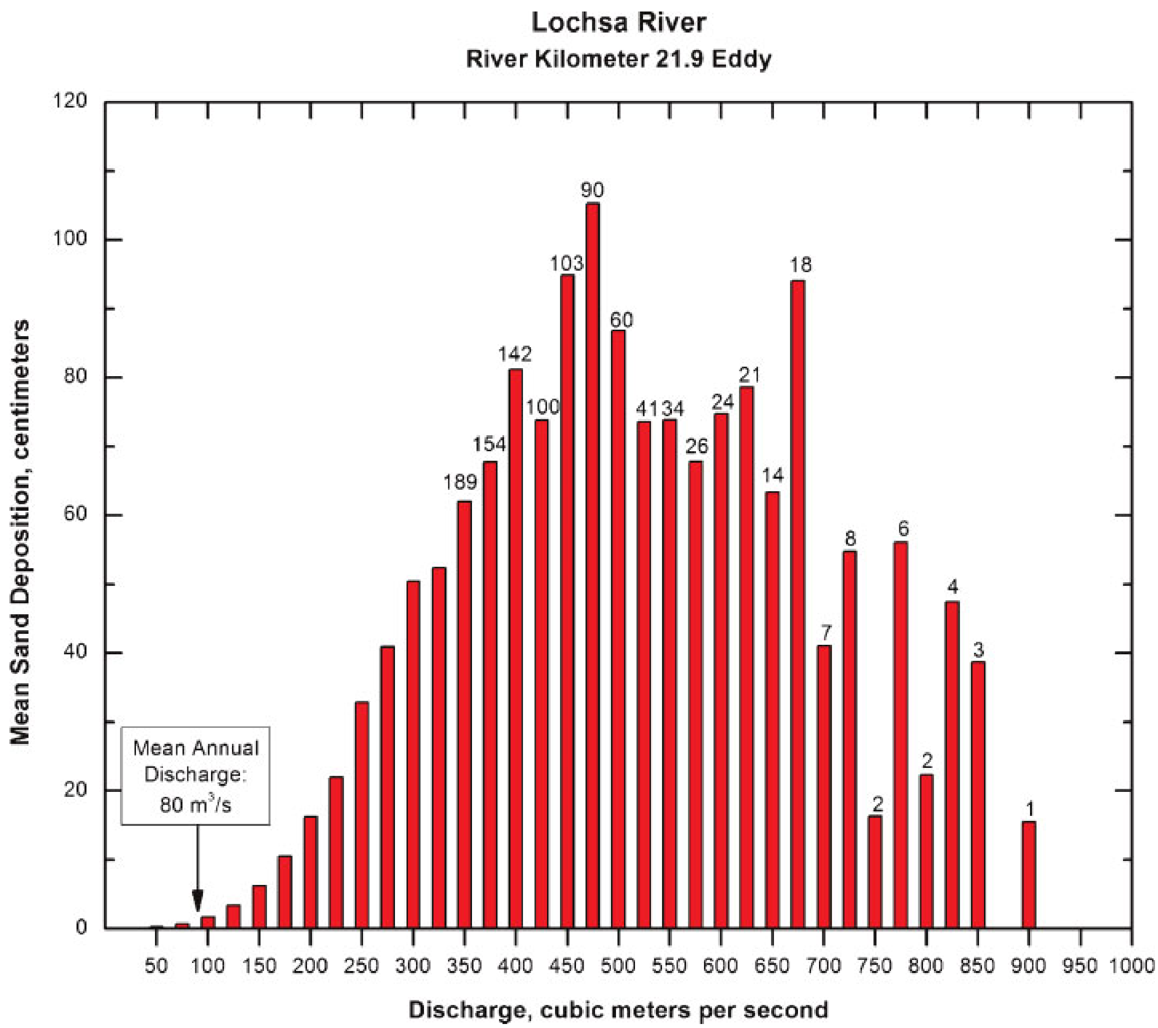

Figure 4. Thickness of sand deposition by increment of discharge at the Lochsa River, RKm 20.9 eddy over the period of record, 1929–2000. The number of days a discharge within a given increment has occurred is shown above the symbol bar for the daily mean discharge equalled or exceeded less than 4% of the time

sand deposited by relatively large, infrequent streamflows is much greater than relatively small, common streamflows over a period of years. The calculated total thickness of sand deposited in the Lochsa River 20.9 km eddy by increments of discharge over the entire period of record, water years 1929–2000, is shown in Figure 4. For those discharges equalled or exceeded less than 4% of the time, 14.6 days per year on average, the number of days a discharge within a given increment has occurred is shown above the bar. Daily mean discharges between 475 and 500 m^3/s have occurred on 90 days over the period of record and deposited a total of 105 cm of sand. Daily mean discharges equal to 475 m^3/s or greater have occurred only 1.4% of the time, an average of 5.1 days per year, and have contributed more than 56% of the total sand deposition over the period of record. Ninety percent of all sand deposited in the Lochsa River 20.9 km eddy occurred at discharges equalled or exceeded 6.6% of the time or 24 days per year on average. Discharges equalled to the mean annual discharge, 80 m^3/s or less, have deposited an insignificant fraction of the total sand deposition in the 13.0 mile eddy. A majority of the total quantity of sand deposited in an eddy occurs during the few to several days per year with the largest streamflows.

The duration of streamflows which accounted for 90% of the total sand deposition in the nine eddies analysed are shown in Table III. In these eddies, 90% of all sand deposition occurred when streamflow equalled or exceeded between 1.9% and 8.2% of the time or 6.9 to 30 days per year over the various periods of record.

The calculated minimum, mean and maximum annual sand deposition, expressed as centimetres are shown in Table III for the observed streamflows for the period of record. Calculated deposition rates for all selected eddies are quite consistent. Mean annual deposition rates within a particular eddy varies from 5.8 to over 100 cm per year. Maximum annual deposition rates vary from slightly less than three to nine times the mean annual deposition ratio. The calculated maximum annual depositions, as large as 3 m, are comparable to the observed deposition in Grand Canyon eddies during the 1996 experimental Colorado River flood, Andrews *et al.* (1999). As noted above, beaches located in the Salmon River near French Creek study reach were typically much larger than those in any other reaches. Calculated annual deposition rates for the two Salmon River near French Creek eddies are considerably larger, as one would expect, than those calculated for the generally smaller eddies in the other reaches.

The computed annual thickness of sand deposition in the Lochsa River, 20.9 km eddy are shown in Figure 5 for the period of record, WYR 1930–2001. The mean annual deposition is 22.9 cm/year, however, there is considerable variation about the mean. During 7 of the 71 years, annual deposition was less than 2.0 cm, whereas annual

Table III. Sand deposition characteristics in selected eddies over the period of streamflow records

Study reach and eddy	Streamflow duration to contribute 90% of sand deposition (%)	Annual sand deposition in centimetres		
		Percent of record		
		Minimum	Mean	Maximum
Lochsa near Lowell				
RKm 11.3	2.8	0	8.7	70
RKm 20.9	6.6	0.03	22.9	145
Selway near Lowell				
RKm 186.2	6.6	1.5	45.7	235
Middle Fork Clearwater near Lowell				
RKm 143.7	3.4	0	15.2	113
Salmon River near Shoup				
RKm 336.7	6.0	0	8.5	36.6
RKm 332.3	1.9	0	5.8	39.6
Salmon River near French Creek				
RKm 201.8	8.2	14.0	104	294
RKm 209.8	6.3	3.7	57.0	193
Middle Fork Salmon River at mouth near Shoup				
RKm 10.3	7.2	0.6	33.5	91.4

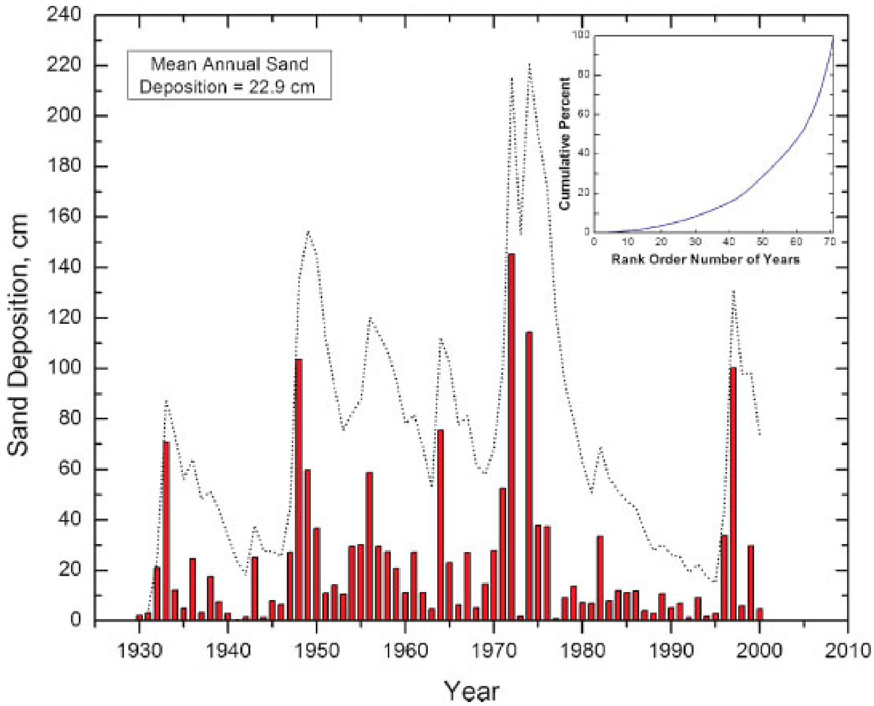

Figure 5. Annual thickness of sand deposition at the Lochsa River, RKm 20.9 mile over the period of record, 1929–2000. This figure is available in colour online at www.interscience.wiley.com/journal/rra

deposition exceeded 100 cm during the 4 years. A majority of the total deposition over the period of record has occurred in a relatively few years. The inset graph in Figure 5 shows the accumulative deposition in percent versus the rank order annual deposition from smallest to largest. Slightly more than 50% of the total deposition over the period of record occurred during just 10 years, while 9% of the total deposition occurred during a single year, 1973.

The annual deposition depends on both the magnitude and duration of the maximum discharges that occur in a year. The vast majority of the annual peak floods recorded at the Lochsa River near Lowell, ID, 68 of 71 have been a direct result of Spring snowmelt. Accordingly, the magnitude and duration of the relatively large streamflow each year are not independent. The seven largest annual depositions shown in Figure 5, which represent 41% of the total deposition during the period of record, occurred in the years with the seven largest annual peak floods. Among the largest annual peak floods, however, differences in duration of the largest streamflows in a given year are substantial. The largest annual deposition, 145.3 cm in 1972, occurred during the 5th largest annual peak flood, whereas only 75.5 cm of deposition occurred in 1964 during the largest annual peak flood.

As was noted in the Introduction, investigations of eddy sand bars along the Colorado River through the Grand Canyon have found that they tend to be eroded relatively fast during periods when streamflows are insufficient to deposit additional material on the bar. The loss of bar area and mass during such periods varies greatly from eddy to eddy depending on their specific geomorphic setting. Eddy sand bars may lose a substantial portion of their mass and area each year when there is no replenishment. Given the rapid loss of material, the size of a typical sand bar will depend primarily on the quantity of sand deposited in a given year and to a progressively diminishing degree the proceeding years. Sand deposited a decade or more in the past will not be especially significant. An estimate of the cumulative weighted deposition, D_W, over the previous 10-year period can be calculated for this period of record by

$$D_W = \sum_{n=1}^{10} D_n (1 - E_s)^{n-1} \tag{9}$$

where E_s is the gross annual fractional loss of material from a sand bar and D_n is the gross annual deposition on a sand bar during the nth year. Repeated surveys of eddy sand bar volume indicates that annual erosion is highly variable year-to-year and from one eddy to another. For the purpose of estimating a cumulative weighted deposition, the gross annual fractional erosion, E_s, is assumed to be 0.30. The cumulative weighted 10-year deposition for the Lochsa River 20.9 km eddy over the period of record is shown in Figure 5 by the thick dashed curve. The cumulative weighted 10-year deposition varies by more than a factor of 10 from less than 20 cm to more than 220 cm. Equation 9 discounts the significance of sand deposited in an eddy years ago relative to the quantity deposited in the current and immediately proceeding years. This result is consistent with the common observation that the size of eddy sand bars tend to vary substantially over a period of a few to several years.

SUMMARY AND CONCLUSIONS

We studied 63 beaches and their associated eddies located throughout 10 selected reaches within the designated Wild and Scenic River sections of the Lochsa, Selway, Middle Fork Clearwater, Middle Fork Salmon and Salmon Rivers in Idaho to determine the relation of the beaches to the frequency of various magnitudes of streamflow. All of the 63 beaches studied were frequently used for camping, picnicking, fishing etc. and are an important recreational resource within the Wild and Scenic Rivers.

A local stage–discharge relation was developed for each beach by surveying the stage at known water discharges. Comparison of surveyed beach profiles with the local stage-discharge demonstrated that, at most eddies, sand is deposited up to the maximum river stage. Throughout central Idaho, the 1997 annual maximum flood was the largest in more than 20 years. For a majority (36) of the 49 beaches where the 1997 maximum stage was identified, the beach top was within a few centimetres of the flood crest. The top of an additional six beaches was below the 1997 maximum stage, although by less than 0.70 m. The top of only seven beaches exceeded the 1997 maximum stage. At these beaches, sand deposited by even greater floods more than 30 years ago remained. Accordingly, we concluded that the upper extent of most beaches was determined by the maximum stage which has occurred within the most recent 5–20 years. For more than 80% of the eddies, an appreciable quantity of the sand deposited on a beach is not retained beyond a decade or two.

The rivers considered in this investigation transport relatively low concentrations of suspended sand. Suspended sand concentrations rarely exceeded a few hundred milligrams per liter even during the largest floods. The abundance of sand bar beaches of appreciable size, in spite of relatively low concentrations of suspended sand, underscores (1) the highly efficient sand trapping characteristics of the channel margin eddies and (2) the importance of the largest streamflow that occur, on average, a few to several days per year.

The rate of water exchanged between the primary channel and an eddy at relatively high flow were measured at 11 sites. The mean residence time of water in an eddy varied from 78 to 338 s. The mean residence time is only somewhat longer than the time required for typical beach sand grain, d_{50}~0.20–0.30 mm, to settle to the bottom of an eddy. A parcel of relatively sediment-free water, however, does not remain in an eddy very long before it is exchanged out of the eddy for primary current water carrying a much higher concentration of suspended sediment. A model calculation of channel-eddy exchange indicates that 60–90% of the suspended sand that enters an eddy settles to the bottom.

Calculated mean annual rates of deposition in an eddy vary from 5.8 to more than 100 cm depending primarily on: (1) the duration of streamflows that inundate the eddy sand bar depositions; (2) the rate of the flow exchange between the channel and an eddy and (3) the concentration of suspended sand in the primary channel. The annual thickness of sand deposition in an eddy varies greatly from year to year depending on the duration of relatively large streamflows. Maximum annual sand depositions in an eddy are three to nine times the estimated long-term mean values. Relatively large, sustained floods deposit a substantial portion of total deposition over a period of years. For the period of record, 1930–2002, the seven largest annual depositions, which represent more than 40% of all material deposited over the Lochsa River 20.9 km eddy, occurred in the years with the seven largest instantaneous annual peak floods. Observations of eddy beach area and/or volume along western rivers, both regulated and unregulated, have shown that the large quantity of sand deposited on a beach during a large flood is eroded over a period of a few to several years. Consequently, beach area and volume for most beaches is less variable year-to-year than the variation in annual deposition would indicate. A cumulative 10-year weighted deposition rate was computed to estimate the effective variability of beach deposition. Although less variable than the annual deposition, the cumulative 10-year weighted deposition calculated for the longest hydrologic records, 71 years, existing on the Idaho Wild and Scenic Rivers varied by more than an order of magnitude from less than 20 cm to more than 220 cm.

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