Sand Bar Erosion and Deposition on the Snake River in Hells Canyon Between 1990 and 1998

FINAL REPORT

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SUMMARY

Although the Snake River in Hells Canyon is incised in a narrow and deep bedrock gorge, alluvial sand bars and terraces are important components of the river landscape. The bars and terraces provide substrate for riparian vegetation, are often sites of cultural significance, and provide camping areas for recreationists. This study included an inventory of sand bars along the Snake River between Hells Canyon Dam and the Salmon River confluence and topographic surveys of four study sites where sand bars and alluvial terraces are both present. The bar inventory and the surveys at three of the sites are compared with similar data collected by the authors in 1990.

The sand bar inventory indicates that there were approximately the same number of bars along the river in 1998 as there were in 1990 and 1982. This indicates that sand bar erosion rates have declined dramatically since the 1964-1973 period. However, repeat topographic surveys and repeat photography show erosion of the sand bars and terraces at three detailed study sites. Thus, while the number of bars is no longer rapidly decreasing, the sand in the remaining bars is being eroded.

The area and volume of erosion exceeded the area and volume of deposition at each of the three sites. Areas of sand deposition did, however, occur at two of the sites. The greatest amount of erosion occurred at Salt Creek Bar where the area of the bar that is armored by gravel also increased substantially. Erosion of the high alluvial terraces also occurred at each of the sites and the rates of this erosion varied greatly. As much as 4 m of cutbank retreat occurred at Salt Creek Bar. At some locations the rate of bank retreat between 1990 and 1998 was lower than occurred previously and at other locations the rate increased.

These findings indicate that continued large floods, in the absence of sediment inputs to the system, have caused continued erosion of the sand resources in Hells Canyon. While local areas of deposition occur, there was a net decrease in the volume of sand at all of the monitoring sites. The rate of sand bar erosion has declined substantially since the initial period of rapid erosion between 1964 and 1973. This decline has likely occurred because (1) there is less sand remaining, (2) many areas are now armored with gravel, and (3) the remaining sites are the most efficient sediment traps in the system.

INTRODUCTION

The Snake River in Hells Canyon is a narrow, incised gorge dominated by bedrock cliffs, talus slopes, and bouldery debris fans. Alluvial landforms are, however, also abundant and include sand bars, gravel bars, and fine-grained terraces. In addition to providing the substrate for aquatic and riparian biota, sand bars and terraces are the preferred camping locations for boaters. The alluvial terraces also contain significant cultural artifacts that are of historic and prehistoric interest and are protected by federal law. Concern exists about the effect of operations of upstream dams on the alluvial landforms in Hells Canyon. These effects have only been quantified by studies utilizing historical aerial photographs (Grams, 1991); no previous studies have directly measured erosion or deposition of sand bars or terraces.

Eddies are a primary storage location of fine-grained sediment in many canyon-bound rivers (Schmidt and Rubin, 1995; Schmidt and others, 1995; Grams and Schmidt, 1999). These are areas where streamflow velocities are low allowing for high deposition rates in an otherwise high-gradient and high-energy system (Schmidt, 1990). Because eddies typically form downstream from stable channel features such as bedrock outcrops and tributary debris fans, they are persistent locations of fine-grained sediment storage (Schmidt and others, 1995).

Many upstream dams and diversions regulate Streamflow on the Snake River. The most significant of these are the three dams in the upstream end of Hells Canyon, collectively called the Hells Canyon Complex (Figure 1). Brownlee Dam is the largest of these facilities and was completed in 1958. Oxbow Dam and Hells Canyon Dam are downstream from Brownlee Dam and regulate streamflow for hydroelectric power generation. These dams were completed in 1962 and 1968, respectively. Because the ratio of surface runoff to reservoir storage on the Snake River is large (Hirsh, 1990), these dams do not significantly affect the magnitude of peak flows, although they do affect duration of low flows and cause diurnal flow fluctuations. The dams of the Hells Canyon Complex also block all sediment from all upstream sources. No large tributaries enter the Snake River between Hells Canyon Dam and the Imnaha and Salmon River confluences. The combination of recurring large floods and lack of sediment resupply have resulted in erosion of fine-grained deposits in Hells Canyon (Grams, 1991).

Widespread erosion of channel-side sand bars and bank retreat of alluvial terraces occurred during the first 20 yr of dam operations in the reach between Hells Canyon Dam and the Salmon River confluence (Grams, 1991). Grams (1991) showed that the number of sand bars and the total area of exposed sand decreased significantly between 1955 and 1990, based on analysis of aerial photography and a field inventory. The greatest erosion occurred upstream from the Salmon River confluence where more than 110 sand bars were present in 1955 and 1964 in the 44 km reach between Pittsburg Landing and the Salmon River confluence (Grams, 1991). By 1973, only 70 of these sand bars remained. The rate of erosion decreased after 1973 and by 1990 only 40 of the sand bars were still present. Grams (1991) also demonstrated that alluvial terraces had eroded at a similar rate during the same period. For example, the terrace at Salt Creek Bar receded over 50 m at some locations between 1955 and 1990. The greatest rates of sand bar and terrace erosion occurred between 1964 and 1973, a period during which several large-magnitude floods occurred. Although large floods also occurred between 1973 and 1990, the rate of erosion decreased during this period. Grams (1991) hypothesized that the remaining bars were more resistant to erosion and that lack of tributary resupply of sediment precluded recovery of the sites that had eroded. The consistent erosional trend documented by Grams (1991) indicates that the post-dam supply of sand is insufficient to rebuild sand bars and that sand persists only at sites resistant to erosion.

The objective of this report is to describe changes that have occurred between 1990 and 1998 in the alluvial sand bars and terraces along the Snake River between Hells Canyon Dam and the Salmon River confluence. We will compare measurements made during this study with measurements made in 1990 by Grams (1991).

Research efforts will focus on the role of floods in affecting depositional and erosional patterns. Our findings will be placed in context with studies of the effects of floods conducted on other large regulated and unregulated rivers including the Colorado River in Grand Canyon, the Green River in Dinosaur National Monument, and the Salmon River upstream from Riggins, Idaho. Because each of these rivers has different streamflow and sediment supply characteristics but similar alluvial depositional environments, it is possible to compare how floods uniquely affect each system. Through this comparison the relative importance of sediment supply and floods can be evaluated.

HYDROLOGY

Streamflow for the study reach is currently measured at the US Geological Survey gage, Snake River at Hells Canyon Dam (station number 13290450), which has been in operation since 1965. Between 1923 and 1971, streamflow was measured at two other locations: Snake River at Oxbow, Oregon (13290000) and Snake River below Pine Creek near Oxbow, Oregon (13290200). These gages were located approximately 35 km upstream from Hells Canyon Dam. Grams (1991) analyzed the historic streamflow data and extended the record for the Hells Canyon Dam gage back to 1923 by correlation between the Hells Canyon and Oxbow gages for the six-year period of overlap. The 75-yr record of annual peak discharges shows a period of low-magnitude floods in the early 1960's during the filling of Brownlee Reservoir and another period of low-magnitude floods in the late 1980's and early 1990's (Figure 2). The magnitude of the mean annual flood is 1,332 m^3/s and is the same for the pre- and post-Brownlee periods (Figure 3). The magnitudes of floods greater than a 10-yr recurrence interval are slightly larger in the post-dam period than in the pre-dam period (Figure 3).

The interval between the 1990 and 1998 sand bar measurements included both some of the lowest and the highest discharges for the entire period of record (Figure 4). Peak flows were less than the mean annual flood except for in 1996, 1997, and 1998. These years all had extreme floods and the January 1997 flood of 2,917 m^3/s was the maximum for the period of record (Figure 2).

The magnitude of the most common and the rarest mean daily flows, those equaled or exceeded more than 50% of the time or less than 5% of the time, is unchanged for the period of record (Figure 4). There is an increase in the duration of time that mean daily flows are between 500 and 1,600 m^3/s (Figure 4). For example, the length of time that discharge equals or exceeds the magnitude of the mean annual flood has increased from 7 to 18 days per yr.

SEDIMENT TRANSPORT

Calculation of a sediment budget for the Hells Canyon reach of the Snake River is severely hindered by the scarcity of sediment transport data. The only locations in the Hells Canyon region with any sediment transport data are the Weiser, Idaho, and

Anatone, Washington, gages on the Snake River and the White Bird, Idaho gage on the Salmon River (Figure 1). The Weiser gage is approximately 100 km upstream from Hells Canyon and is upstream from the dams of the Hells Canyon Complex. The Anatone gage is downstream from Hells Canyon and downstream from the Imnaha, Grande Ronde, and Salmon River confluences. Although the Imnaha and Grande Ronde are major tributaries and likely contribute significant amounts of sediment, no transport measurements have been made on these streams. No major tributaries enter the Salmon River between the White Bird gage and the Snake River confluence.

No pre-dam era data are available for any of the gages and the measurements that are available are infrequent. At the Weiser gage, 85 suspended sediment measurements were made between 1977 and 1996. On the Salmon River at White Bird, 146 suspended sediment measurements were made between 1974 and 1994. An intensive study of suspended and bedload transport was conducted on the Snake River near Anatone between 1972 and 1979. During this period, 126 measurements of suspended load and 63 measurements of bedload were made by the US Geological Survey (Jones and Seitz, 1980). An additional 13 suspended load measurements were made between 1990 and 1997. The data analyzed in this report were obtained from the US Geological Survey, Water Resources Division, Boise, Idaho

Rating relations of discharge to suspended sand have large scatter that is typical of sediment transport data (Figure 5). The relations for Weiser and White Bird are significantly worse than for Anatone, which has a relatively good R^2 of 0.73. Measurements that did not include particle size data were not included in the transport relations because the sand component could not be separated from the total load. The relation for Anatone is shifted to the right relative to the other two gages, indicating that concentrations are typically lower at Anatone than at White Bird and Weiser, for any given discharge. Plots of sediment concentration hysteresis show changes in the sediment transport relation during the passage of individual annual floods (Figure 6). The hysteresis at Weiser and White Bird tends to be less pronounced, concentrations on the falling limb of the hydrograph are often only slightly lower than concentrations on the rising limb of the hydrograph. The "loops" that occur at the Anatone gage are indicative of a system that rapidly becomes depleted of sediment during a flood. However, the lack of such loops in the plots for the other gages may be a result of too few measurements during each year.

More sediment transport data are needed to calculate a sediment budget for the Hells Canyon reach. In particular, measurements or estimates of gaged and ungaged tributary contributions are essential.

METHODS

Sand Bar Inventory

The condition of sand bars in Hells Canyon prior to construction of the Hells Canyon Complex can only be determined by analysis of the photographic record. Aerial photograph series that cover all of Hells Canyon and that are of sufficient detail to show alluvial sand deposits were taken in 1955, 1964, 1970, 1973, 1977, and 1982. In his analysis, Grams (1991) identified and labeled all sand deposits visible on the 1964 aerial photographs. The same locations were analyzed for presence or absence of sand in the subsequent years of aerial photographs and during a field inventory in July 1990. The discharge of the Snake River at Hells Canyon Dam at the time the 1964 photographs were taken was greater than the discharge during the subsequent photographs (except 1982) and during the field inventories (Table 1). Thus erosion measured between 1964 and any of these subsequent dates is a minimum estimate because greater areas of sand would be exposed at the lower discharges if no change occurred. The sand bar indices and all photographs were used during the 1998 field work to identify all locations where sand bars are or had previously been present. The presence or absence of a bar at each site was noted.

Topographic Comparisons

Detailed topographic surveys were made at three study sites and compared with topographic maps made in 1990 (Figure 1). These sites were chosen in 1990 as representative of large, eddy-deposited sand bars located upstream from the Salmon River confluence. Large bars were selected because they were determined to be the deposits most likely to be present for continued monitoring. Eddy deposits were chosen because most of the large bars occur in eddies and because work elsewhere has indicated that eddies are the most stable depositional locations (Schmidt and Graf, 1990). Based on the 1990 sand bar inventory, there are a total of nine eddy deposits upstream from the Salmon River confluence that are of comparable size to the selected study sites, which are about 930 m^2 or larger. The three sites are sand bars deposited in eddies and each occurs downstream from a debris fans or bedrock constriction.

Topographic data in 1990 and in 1998 were collected by survey with an electronic total station. In 1990 the survey data were plotted in the field, and detailed topographic maps were drawn. Prior to field work in 1998, the data from the 1990 surveys were entered into topographic mapping software (SURFER®) in order to facilitate comparison between the 1990 and 1998 data. The data collected in 1998 were imported into the mapping software in the field. The topographic data were used to generate 1.0-m by 1.0-m elevation grids using a triangulation with linear interpolation algorithm. The computer-generated topographic contour maps compared well with the original field maps.

The benchmarks used in the 1990 surveys were relocated and the 1998 surveys were conducted in the same arbitrary coordinate systems established in 1990. Computer-generated topographic maps were made in the field and checked for accuracy. We also mapped significant geomorphic features including cutbanks and the areas covered by sand, gravel and debris fans. The current water surface elevation and high-water marks were also measured. High water marks that consisted of fresh driftwood, detritus, and grass wrapped around tree and bush branches were identified at each site. Where multiple high-water marks could be identified, all were surveyed and checked for consistency. The top of a prominent white stripe that occurs throughout Hell Canyon was also surveyed at each of the study sites. We believe that this stripe is caused by the high flows of the normal powerplant operating range, which is 850 m^3/s. River guides familiar with the stage fluctuations agreed that this line was likely associated with the 850 m^3/s discharge (Ric Bailey, personal communication).

Erosion and deposition between the two surveys was determined by calculating the difference between the 1990 and 1998 topographic surfaces. Because subtle variations in bar topography less than approximately 0.1 m were not surveyed, only changes in topography greater than 0.25 m are considered significant. Greater than 0.25 m of elevation decrease is considered significant erosion and greater than 0.25 m of elevation increase is considered significant deposition. The average thickness of significant erosion or deposition was calculated as the total volume of sand deposited or eroded in the area where deposition or erosion exceeded 0.25 m divided by the area of the respective polygon. Erosion along cutbanks was detected by these volume calculations and is also shown by mapped changes in cutbank position.

The position of the terrace cutbanks in 1990 and 1998 are compared with previous cutbank positions shown in aerial photographs. Grams (1991) determined the location of cutbanks at these sites between 1955 and 1982 using aerial photographs. The cutbank location along selected profiles was determined relative to stable features that could be identified both on the photographs and in the field. This method allowed integration of aerial photograph mapping and field mapping. Topographic profiles from the sand bar to the terrace edge were constructed from the 1990 and 1998 topographic maps at the same locations where cutbank position was determined from the aerial photographs.

RESULTS

Sand Bar Inventory

The results of the 1998 field inventory of sand bars are consistent with the previous inventories made by Grams (1991). The complete results of the inventory are included as Appendix A. In the reach between Pittsburg Landing and the Salmon River confluence, 12 sand bars were eroded and 11 bars were newly deposited resulting in a net loss of one sand bar (Figure 7). In the reach between Hells Canyon Dam and Pittsburg Landing, we inventoried slightly more sand bars in 1998 than were identified in the 1982 aerial photographs (Figure 7). This is likely due to the higher discharge at the time of the 1982 photographs compared to the discharge during the 1998 field trip (Table 1).

Because of this discharge difference, the number of sand bars inventoried in 1998 is a minimum estimate compared with the 1982 inventory.

The frequency of sand bars and the rates of sand bar erosion both vary with distance downstream from Hells Canyon Dam (Figure 7). In all years of aerial photography and during the field inventories, there were more bars in the downstream reaches. Between 1964 and 1973, the period of greatest erosion, the relative amount of erosion was highest in the reaches nearest to Hells Canyon Dam (Figure 7). The rate of erosion since 1973 has been much less in the upstream reaches and greater in the reaches downstream from Pittsburg Landing.

Detailed Study Sites

Pine Bar

Pine Bar is a large sand bar and popular river campsite located on the east side of the river at river mile (RM) 227.5. Locations in Hells Canyon are in relation to distance, in miles, upstream from the Columbia River confluence. The Pine Bar site consists of a large eddy sand bar and an alluvial terrace that are located downstream from a large bedrock outcrop. This outcrop creates the eddy in which sand is deposited at high discharge. Grams (1991) documented erosion of the sand bar between 1964 and 1982, based on analysis of aerial photographs. During the same period, the sediments comprising the bar surface coarsened from mostly sand to mostly gravel (Grams, 1991). Erosion of the terrace behind the sand bar also occurred between 1964 and 1982 and exposure of a buried tank in 1997 or 1998 demonstrates continuing erosion. We conducted a topographic survey of this site to provide a baseline for future monitoring.

No topographic measurements had been made at this site in 1990 and no detailed comparison with previous conditions could be made for this report.

Salt Creek Bar

Salt Creek Bar is a large sand bar that forms in an eddy downstream from the debris fan at the mouth of Salt Creek. The site is at RM 222.5, on the west bank of the river. The study site includes a bare sand bar that is emergent at discharges less than about 850 m^3/s and a fine-grained terrace that is inundated only by large floods of about 2,500 m^3/s (Figure 8). The low-elevation sand bar is usable as a campsite at low discharges, and the terrace is a popular campsite at all discharges because of the shade provided by hackberry trees. Grams (1991) showed that erosion of the high terrace at Salt Creek Bar occurred between 1964 and 1990. The greatest amount of erosion occurred between 1970 and 1973, and erosion continued at a decreased rate between 1973 and 1990 (Figure 9).

Measurements made in 1998 demonstrate continued erosion along most of the terrace cutbank (Figure 8). Along transect B at the downstream end of the bar, as much as 4 m of cutbank retreat occurred between 1990 and 1998 (Figure 10). Bank erosion in the vicinity of transect B is also shown by photographs taken from the same location on the terrace in 1990 and 1998 (Figure 11). Towards the upstream end of the bar where the bank is less steep, deflation occurred along the slope of the bank (Figure 10).

The discharge required to inundate the terrace was estimated by locating indicators of the 1998 peak discharge, which was 2,675 m^3/s. High-water marks consisted of piles of fresh driftwood and duff, often with grass wrapped around small trees (Figure 12). The peak discharge partially inundated the terrace at the upstream and downstream ends of the bar and was approximately even with the top of the active cutbank in the center of the bar where a high sand dune separates the terrace from the bar. Erosion of the terrace between 1990 and 1998 occurred up to and slightly above the elevation of the 1998 peak discharge. Erosion above this level likely occurred in January 1997 when the peak discharge was 2,917 m^3/s.

On the bare sand bar, erosion greatly exceeded deposition and the area of the bar armored by gravel increased. Significant erosion occurred over most of the area of bare sand (Figure 8), and an average thickness of 0.7 m was eroded (Table 2). Most of the erosion along transect A occurred in places that were sand in 1990 and armored by gravel in 1998. The increase in the area of the bar that is armored by gravel is shown in matched photographs taken of the bar in 1990 and 1998 (Figure 11). The sand bar is completely inundated by discharges of 850 m^3/s and higher.

Fish Trap Bar

Fish Trap Bar is a large eddy-deposited sand bar located at RM 216.4 on the west bank. The bar fills a channel expansion that is bounded on each end by debris fans. The bar features a deep eddy-return channel that slopes down in the upstream direction, indicating that it is formed by recirculating flow. The sand bar is adjacent to a high terrace that is vegetated with hackberry trees and upland vegetation. Grams (1991) documented erosion of this terrace between 1955 and 1990, although the rate of erosion at this site was less than at Salt Creek Bar.

Erosion of the high terrace continued between 1990 and 1998. The location of the top edge of the cutbank was stable at the upstream end of the bar but retreated as much as 5 m in the vicinity of transect C (Figure 13). This erosion represents a large increase in the rate of bank retreat because that area was stable between 1982 and 1990 (Figure 14). The average rate of bank retreat between 1964 and 1998 is 0.5 m/yr at transect C.

The repeat topographic surveys documented both erosion and deposition between 1990 and 1998. The area of significant erosion exceeded the area of significant deposition by about 82% (Table 2). The volume of erosion during this period also exceeded the volume of deposition, and the net volume of the bar decreased by nearly 500 m^3. Deposition occurred along the bar crest, and erosion occurred in the eddy return channel and along the bar face (Figure 15). Along the bar crest, the thickness of deposition averaged about 0.3 m and was as great as 1.0 m in some places. Erosion in the vicinity of transect A resulted in armoring of the bar (Figure 16).

The 850 m^3/s stage approximately divides the area of deposition and the area of erosion along the bar crest (Figure 13) indicating that deposition occurred during flows higher than this and that erosion along the bar face has occurred during flows at and below 850 m^3/s. Flows on the order of the 1997 and 1998 peaks completely inundate the bar. The water's edge at these flows was along the edge of the cutbank, partially inundating the high terrace at the upstream end of the bar (Figure 13). Thus, while flows higher than about 850 m^3/s likely caused erosion along the rear of the bar and along the terrace cutbank, they also resulted in deposition of sand on the bar crest.

China Bar

China Bar is an eddy-deposited sand bar located downstream from a debris-fan at RM 192.4 on the west bank. The bar extends downstream to a large bedrock outcrop (Figure 17). The area of the bare sand bar and the position of the cutbank have not changed substantially since 1955 according to aerial photographs (Grams, 1991).

Although this site is relatively stable and the net volume change between 1990 and 1998 was small (Table 2), both erosion and deposition did occur. Deposition occurred only along the bar crest and erosion occurred along most of the bar margin (Figure 17). Erosion at the upstream end of the bar resulted in exposure of additional rocks on the debris fan and decrease in the total area of the sand bar (Figure 18). Erosion of the high terrace along the cutbank also occurred (Figure 19). Erosion of the cutbank has occurred along approximately 20 m of the terrace margin at the rear of the bar and has receded from 1.5 to 2.5 m (Figure 17). Erosion of this terrace had not been detected in Grams' (1991) aerial photograph analysis and is likely a recent occurrence associated with the 1997-98 floods.

CONCLUSIONS

The results of Grams (1991) are supported by the field inventory of sand bars and by the measurements of terrace erosion. Together, the inventories of 1990 and 1998 show no significant change in the total number of sand bars between 1982 and 1998. This suggests that the rate of sand bar erosion has decreased from high initial rates and that more detailed measurements are required to detect this change. The sand bar and terrace surveys made in 1990, and monumented by permanent benchmarks provided the means to make the necessary detailed measurements of change.

Repeat topographic measurements at three sites show (1) reworking of the sand bars during floods, (2) net decrease in the volume of sand in the bars, and (3) erosion of the high terraces along active cutbanks. The detailed measurements were made at sites where large sand bars were present in 1990 and in 1998 and are sites where the bar inventory indicated no change had occurred (Appendix A). However, each of these sites experienced significant depths of aggradation and/or degradation on the bar surface. Erosion of the sand bar exceeded deposition at each of the study sites and was greatest at Salt Creek Bar. Erosion of sand greatly increased the area of the bar armored by gravel at Salt Creek Bar and Fish Trap Bar and slightly increased the armored area at China Bar.

Cutbanks actively eroding into the terrace occur at each of the study sites. The rates of erosion are not uniform between the sites or along the same bank at a single site. The greatest amount of terrace erosion occurred at Salt Creek bar, where the cutbank retreated as much as 4 m at the downstream end of the bar. The erosion of the sand bars is limited by the presence of armor gravels and mitigated by periodic deposition. The terraces, however, do not receive significant amounts of deposition and, in some locations, are steadily eroding.

Most of the measured changes in the sand bars and terraces likely occurred at discharges of 850 m^3/s and greater. The 850 m^3/s stage partially inundates the sand bars and does not reach the base of the terrace cutbank. Thus, only low-elevation parts of the bars could experience erosion or deposition at that discharge. Discharges of about 2,675 m^3/s completely inundate the sand bars and are approximately level with the tops of the terrace cutbanks. The average annual peak discharge, which is 1430 m^3/s, likely inundates the entire bare sand bar and probably extends partially up the terrace cutbanks. Measurements that bracket specific flood events and additional stage-discharge information are needed to determine more precisely the discharges that cause terrace erosion and sand bar reworking.

The spatial distribution of areas of erosion and deposition measured at sand bars in Hells Canyon is similar to that measured on other rivers with eddy-deposited sand bars. The pattern of near-shore deposition and off-shore erosion was observed on the Colorado River in Grand Canyon during the 1996 experimental flood (Schmidt and others, 1999; Hazel and others, 1999). This pattern was also observed on the Salmon River upstream from Riggins, Idaho (J.C. Schmidt, unpublished data), and on the Green River in Dinosaur National Monument (Martin and others, 1998). The most significant difference between the results of this study and the response of eddy sand bars to floods on other rivers is in the height of the deposits. In Grand Canyon (Hazel and others, 1999) and on the Snake River (J.C. Schmidt, unpublished data), sand bars tended to aggrade to near the water surface elevation of the peak discharge. This resulted in bare sand bars exposed high above the baseflow water surface. At Salt Creek Bar, the site in Hells Canyon with the most deposition, the crest of the bar was at least 3 m below the elevation of the 1997 peak discharge. The absence of high-elevation deposition suggests that sediment concentrations during and following the flood peaks are too low to provide for large areas of deposition.

The pattern of hysteresis in the suspended sand transport relation that occurs at the Anatone gage is also consistent with rapid sediment depletion during a flood. The dramatic shifts in the transport relation that occur during each annual flood indicate high sensitivity to sediment availability and clearly show that even downstream from the Salmon River confluence, the Snake River is supply limited with respect to sand. Estimates of sediment input from gaged and ungaged tributaries are needed to calculate a sediment budget for Hells Canyon.

These findings indicate that continued large floods, in the absence of sediment inputs to the system, have caused continued erosion of the sand resources in Hells Canyon. While local areas of deposition occur, there was a net decrease in the volume of sand at all of the monitoring sites. These conclusions are, however, based on only three monitoring sites. Additional sites are needed to better quantify the system-wide trends of sand storage in Hells Canyon. The rate of sand bar erosion has declined substantially since the initial period of rapid erosion between 1964 and 1973. This decline is likely because (1) there is simply less sand remaining, (2) many areas are now armored with gravel, and (3) the remaining sites are the most efficient sediment traps in the system. The rates of terrace erosion are not uniform and have decreased at some locations and have increased at other locations.

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Table 1. Dates of photography and field work and corresponding discharges of the Snake River at Hells Canyon Dam.

Date*	Scale of Photos	Discharge# (m^3/s)	Discharge variability** (m^3/s)
1955	1:20000	306 - 314	14
1964	1:12000	292 - 311	
1970	1:14000	292 - 337	6
1973 (Mar 25)	1:12000	218	steady
1977 (Sep 9)	1:12000	150	4
1982 (Aug 19)	1:12000	399	
1990	field work	187 - 241	
1998	field work	269	steady

* The 1955 photographs were taken on August 20-21 and September 3-4, 1955. The 1964 photographs were taken on August 17-18, and 24, 1964. The 1970 photographs were taken on July 31 and August 10, 1970. The 1990 field work was conducted in the period July 7-25, 1990. The 1998 field work was conducted in the period October 18-23, 1998.

Mean daily discharge of the Snake River at Hells Canyon Dam for the date indicated or the range for the period indicated.

** Average discharge variability during the indicated period.

Table 2. Areas and volumes of significant erosion and deposition.

		Study Site		
		Salt Creek Bar	Fish Trap Bar	China Bar
Area measured (m^2)		16680	9890	5240
Erosion	area (m^2)	3470	1820	740
	volume (m^3)	2560	1050	380
	average depth (m)	0.7	0.6	0.5
Deposition	area (m^2)	20	1000	340
	volume (m^3)	10	550	130
	average depth (m)	0.3	0.6	0.4
Net Change	volume (m^3)	-2550	-490	-250
	average depth (m)	-0.7	-0.2	-0.2

* Areas of significant erosion and deposition are areas where more than 0.25 m of change occurred, respectively.

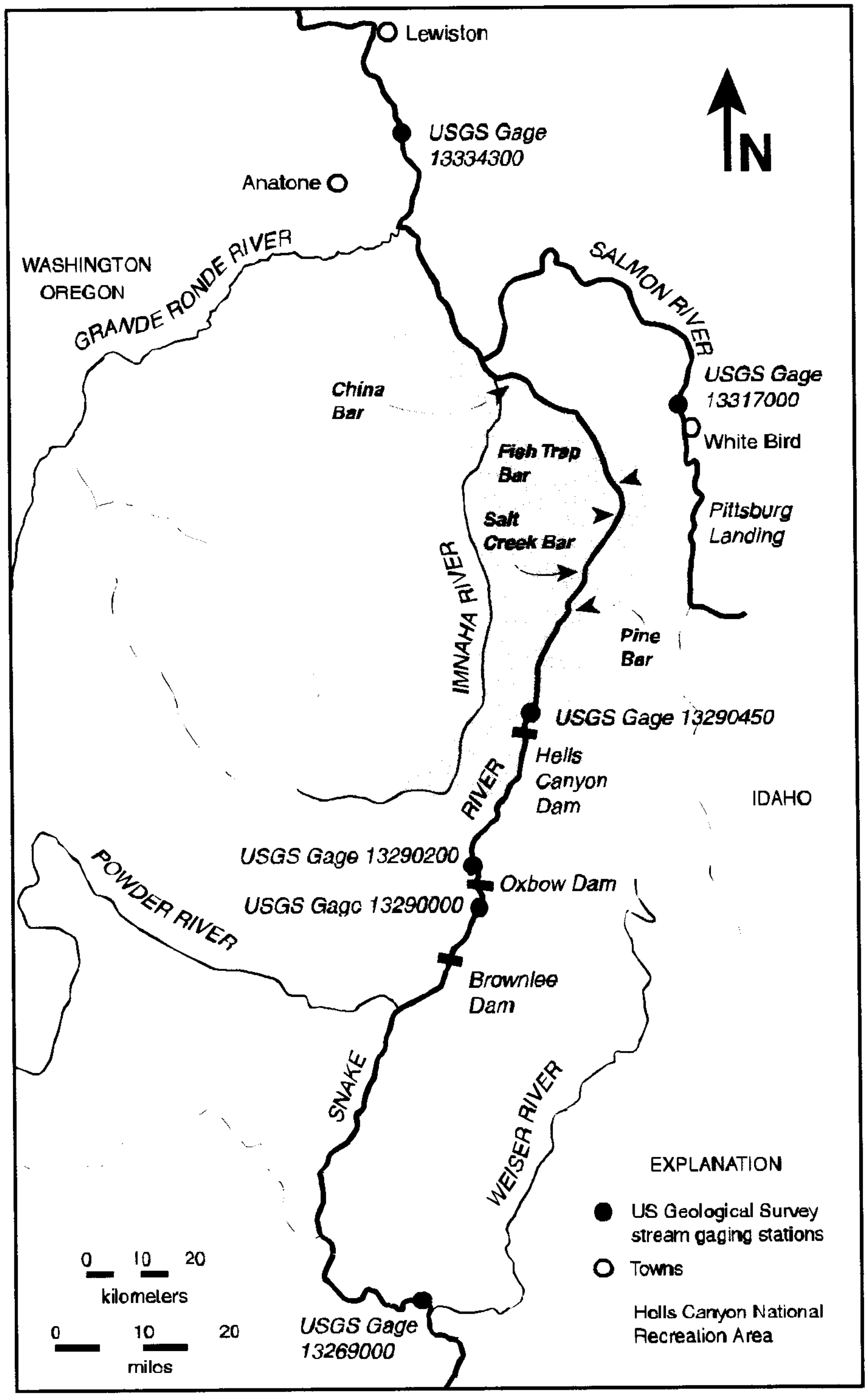


Figure 1. Map of the study area showing locations of study sites, stream gaging stations, and major tributaries to the Snake River.

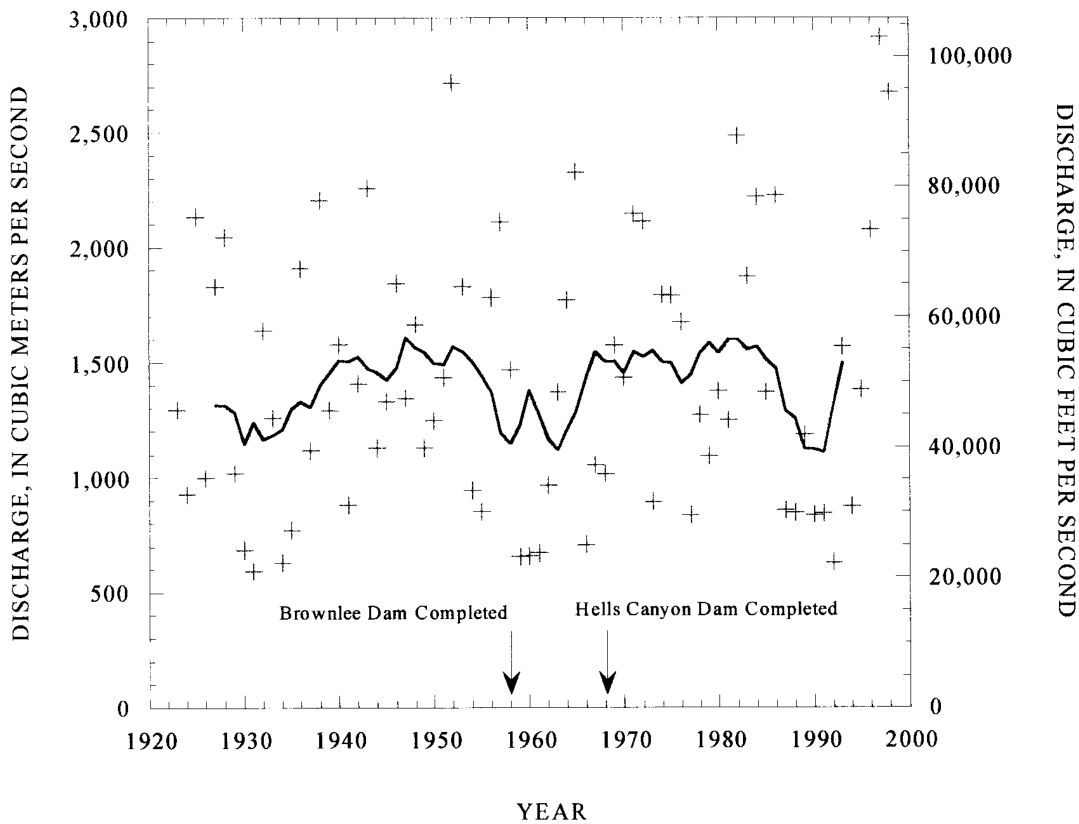


Figure 2. Annual maximum instantaneous discharge of the Snake River at Hells Canyon Dam, 1923 to 1998. Streamflow has been measured at Hells Canyon dam since 1965. The values for 1923 to 1964 were determined by correlation with upstream gages (Grams, 1991). The solid line shows the 10-yr moving average of the annual peaks.

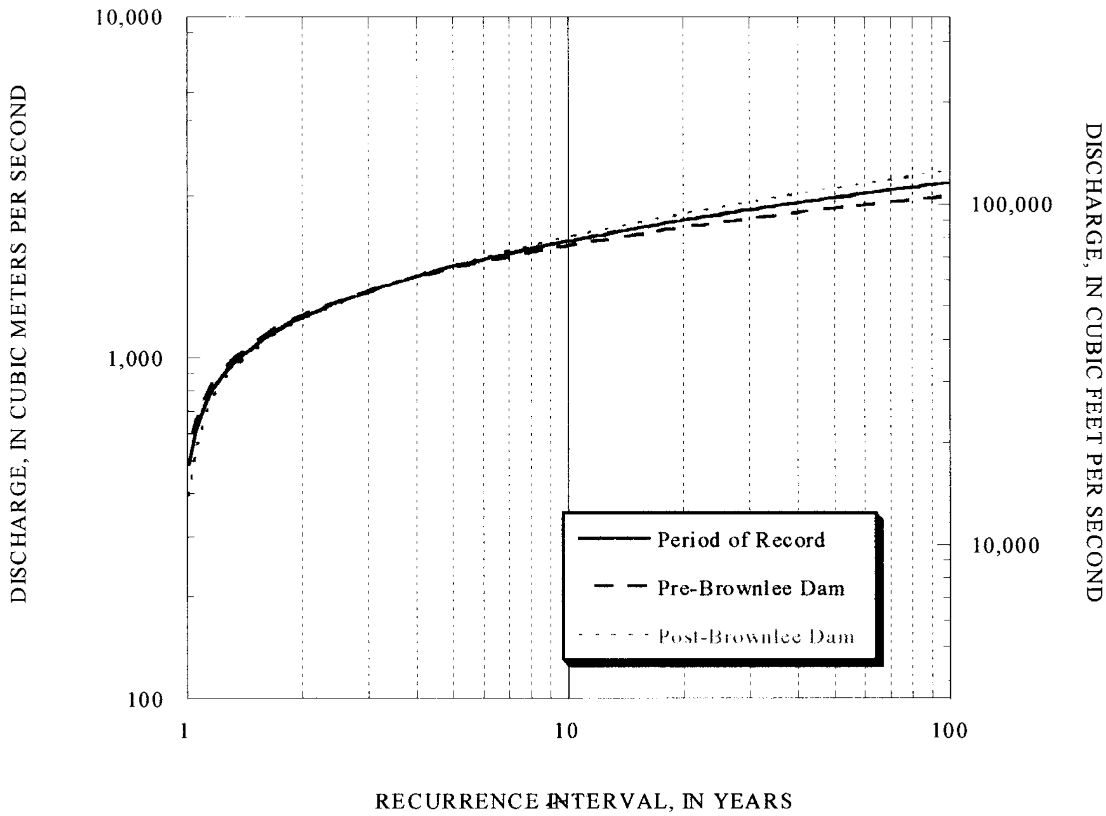


Figure 3. Recurrence interval of annual peak discharges for the Snake River at Hells Canyon Dam, 1923 to 1998.

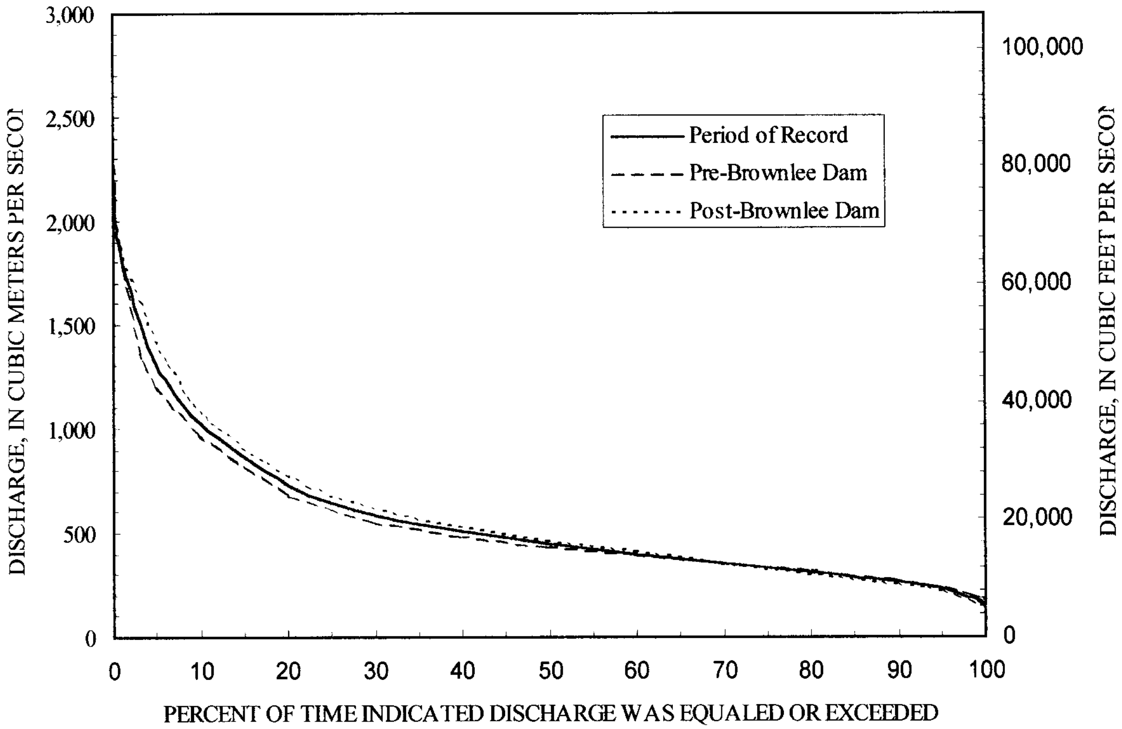


Figure 4a. Duration of mean daily discharges for the indicated time periods.

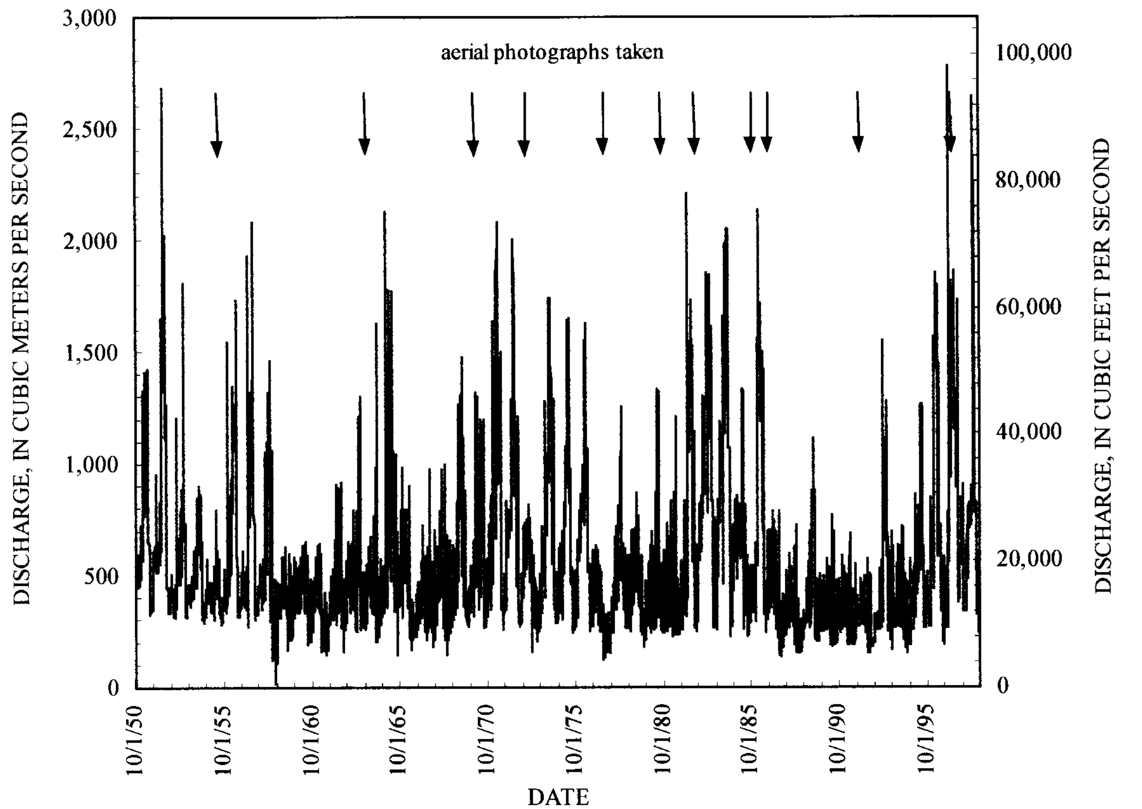


Figure 4b. Mean daily discharge of the Snake River at Hells Canyon Dam between 1950 and?present. The times of aerial photographs are indicated by arrows.

Figure 5a.

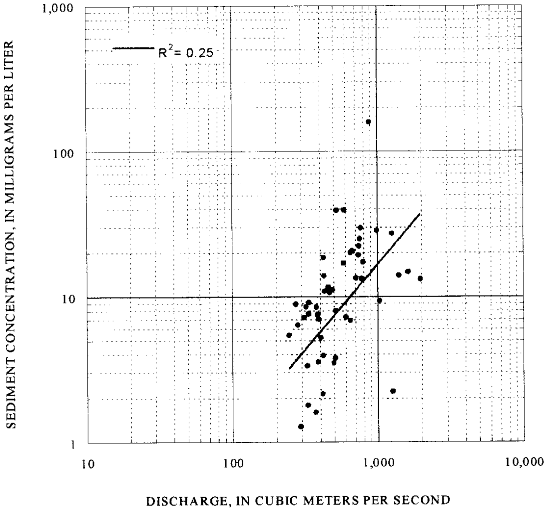
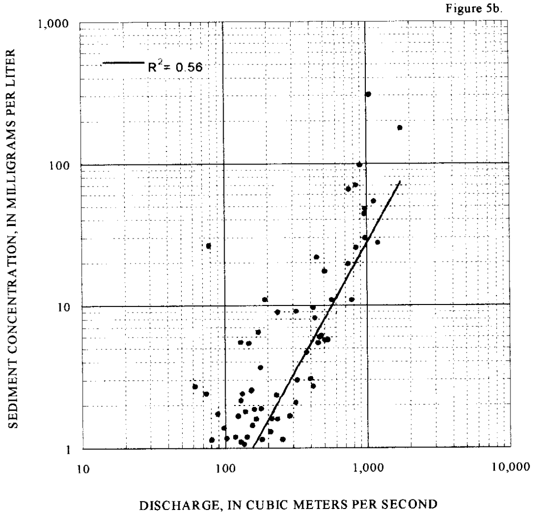


Figure 5b.



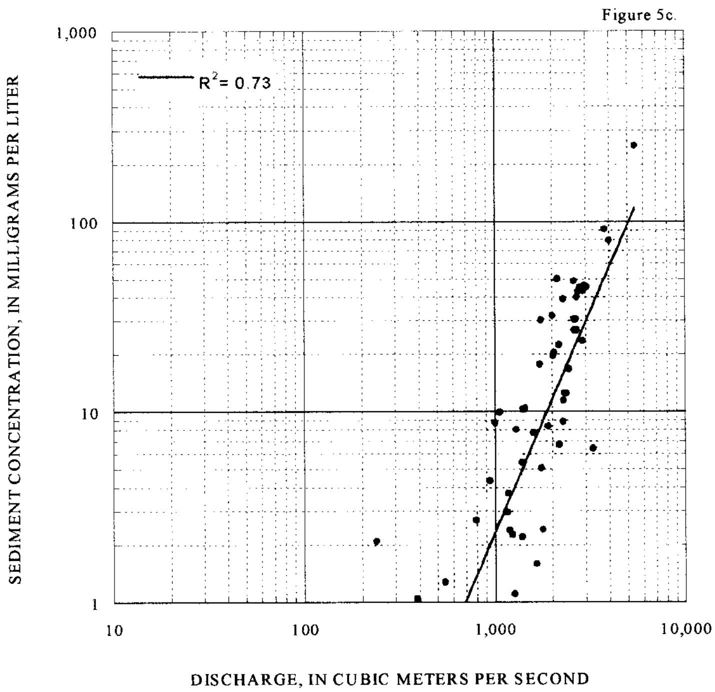
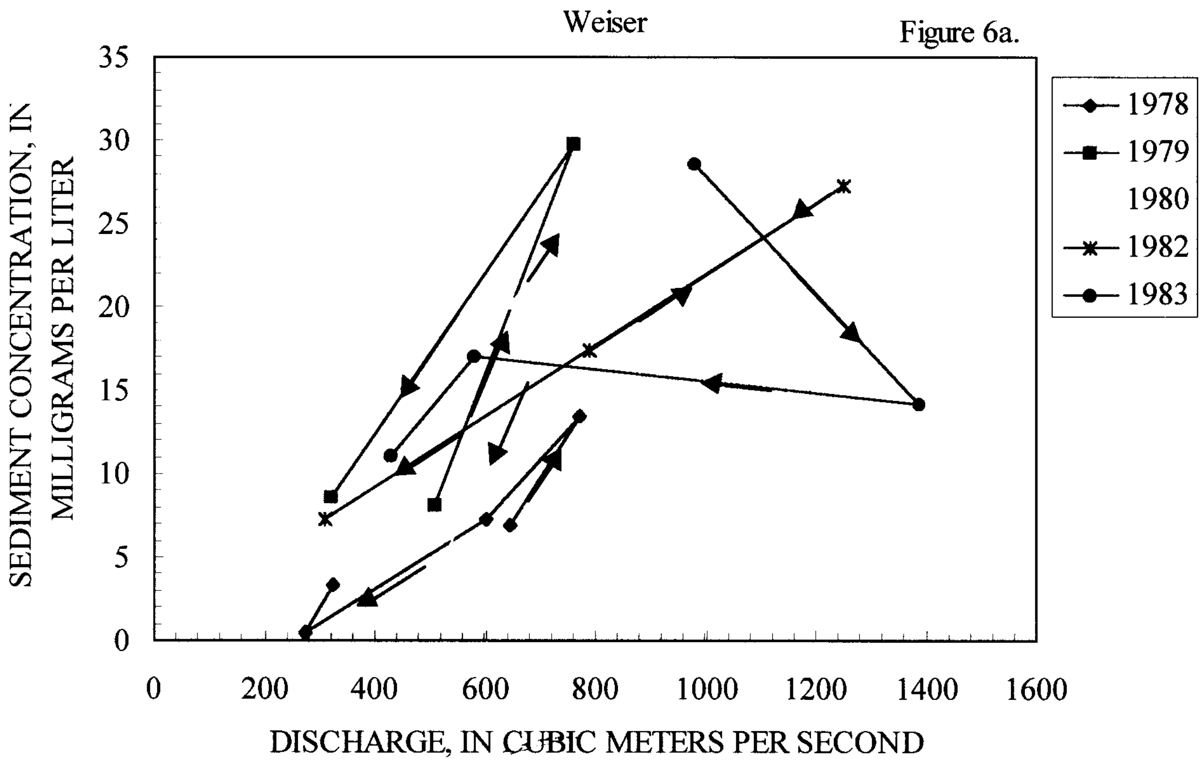
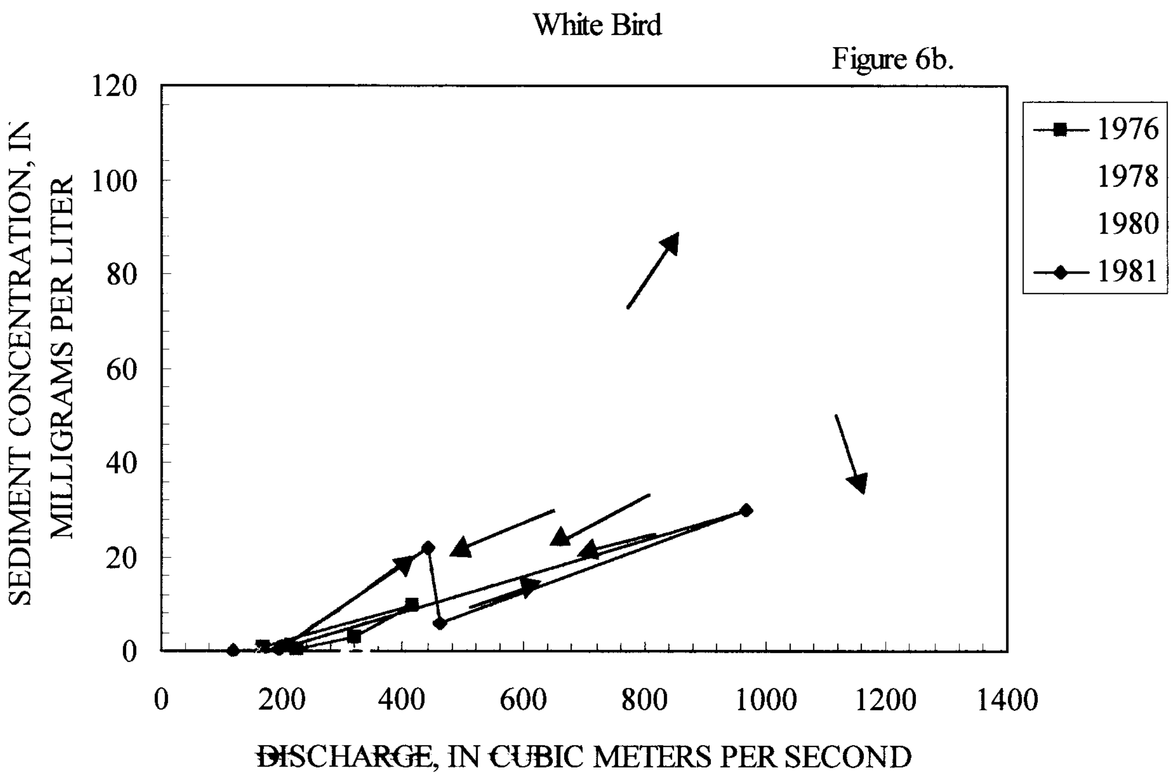


Figure 5. Sediment transport rating relations for the Snake River at Weiser, Idaho (a), Salmon River at White Bird, Idaho (b), and Snake River near Anatone, Washington (c). The lines shown are power functions fit to the measured data. The R^2 values are shown on each graph.


Weiser
Figure 6a.
SEDIMENT CONCENTRATION, IN MILLIGRAMS PER LITER
DISCHARGE, IN CUBIC METERS PER SECOND
0
5
10
15
20
25
30
35
0
200
400
600
800
1000
1200
1400
1600
1978
1979
1980
1982
1983


White Bird
Figure 6b.
SEDIMENT CONCENTRATION, IN MILLIGRAMS PER LITER
DISCHARGE, IN CUBIC METERS PER SECOND
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
1400
1976
1978
1980
1981

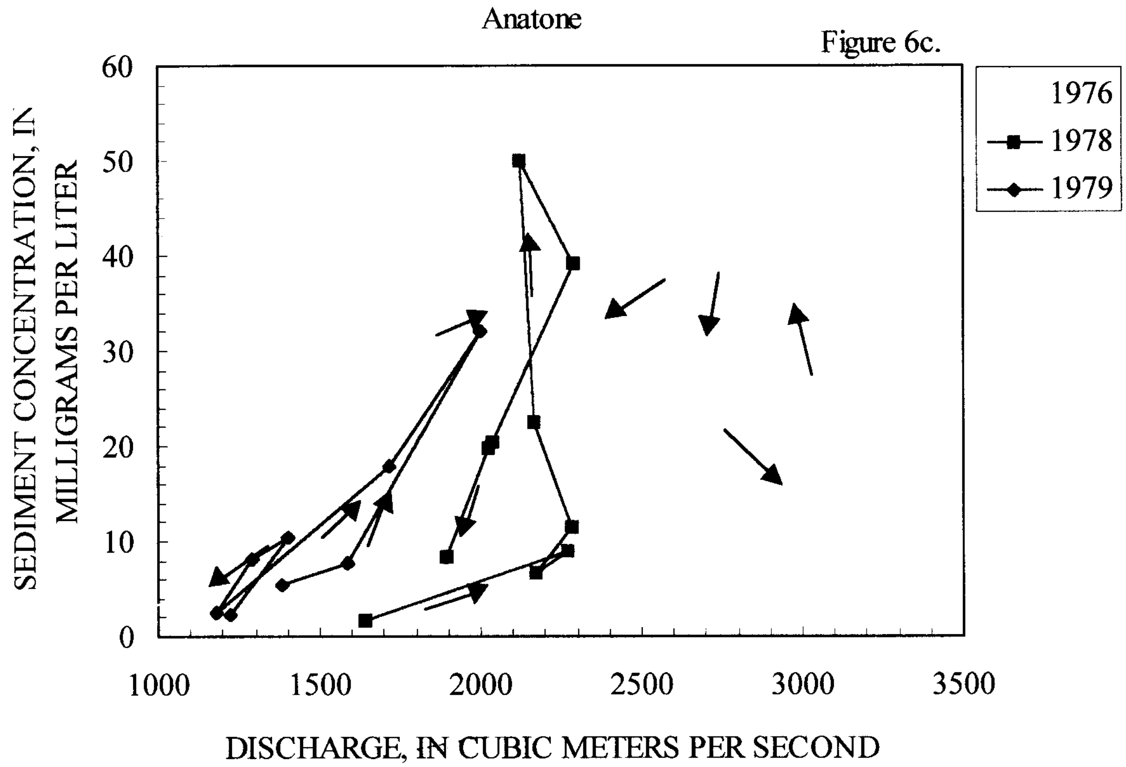


Figure 6. Hysteresis in sediment transport rating relations for the Snake River at Weiser, Idaho (a), the Salmon River at White Bird, Idaho (b), and the Snake River near Anatone, Washington (c). The plots show the concentrations of suspended sand for all measurements made during each indicated annual flood. The arrows indicate progression of time, beginning on the rising limb of the hydrograph.

Figure 7a.

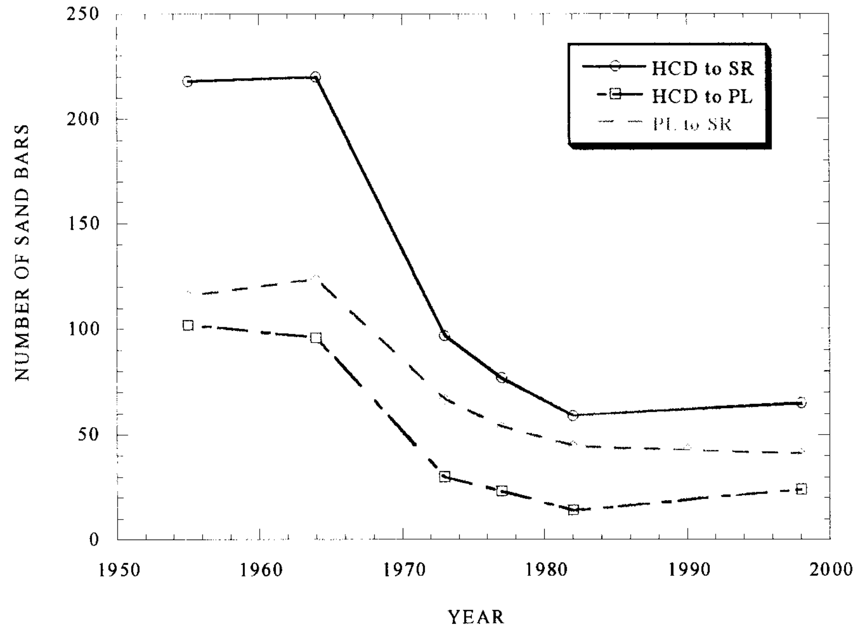


Figure 7b.

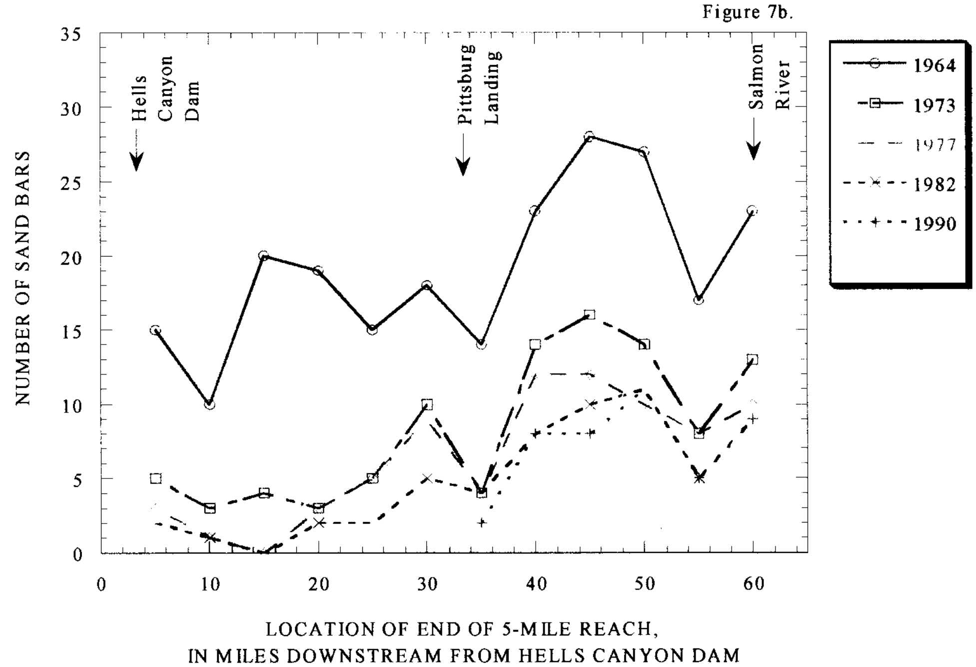


Figure 7. Results of sand bar inventory. Values for 1955 to 1982 are from photographic inventories and values for 1990 and 1998 are from field inventories. The 1990 field inventory did not include sand bars upstream from Pittsburg Landing. (a) the number of sand bars in the entire study reach and divided into the reaches upstream and downstream from Pittsburg Landing. (b) The inventory results shown by distance downstream from Hells Canyon Dam. The discharges at the times of each measurement are indicated in Table 1 and illustrated in Figure 4a.

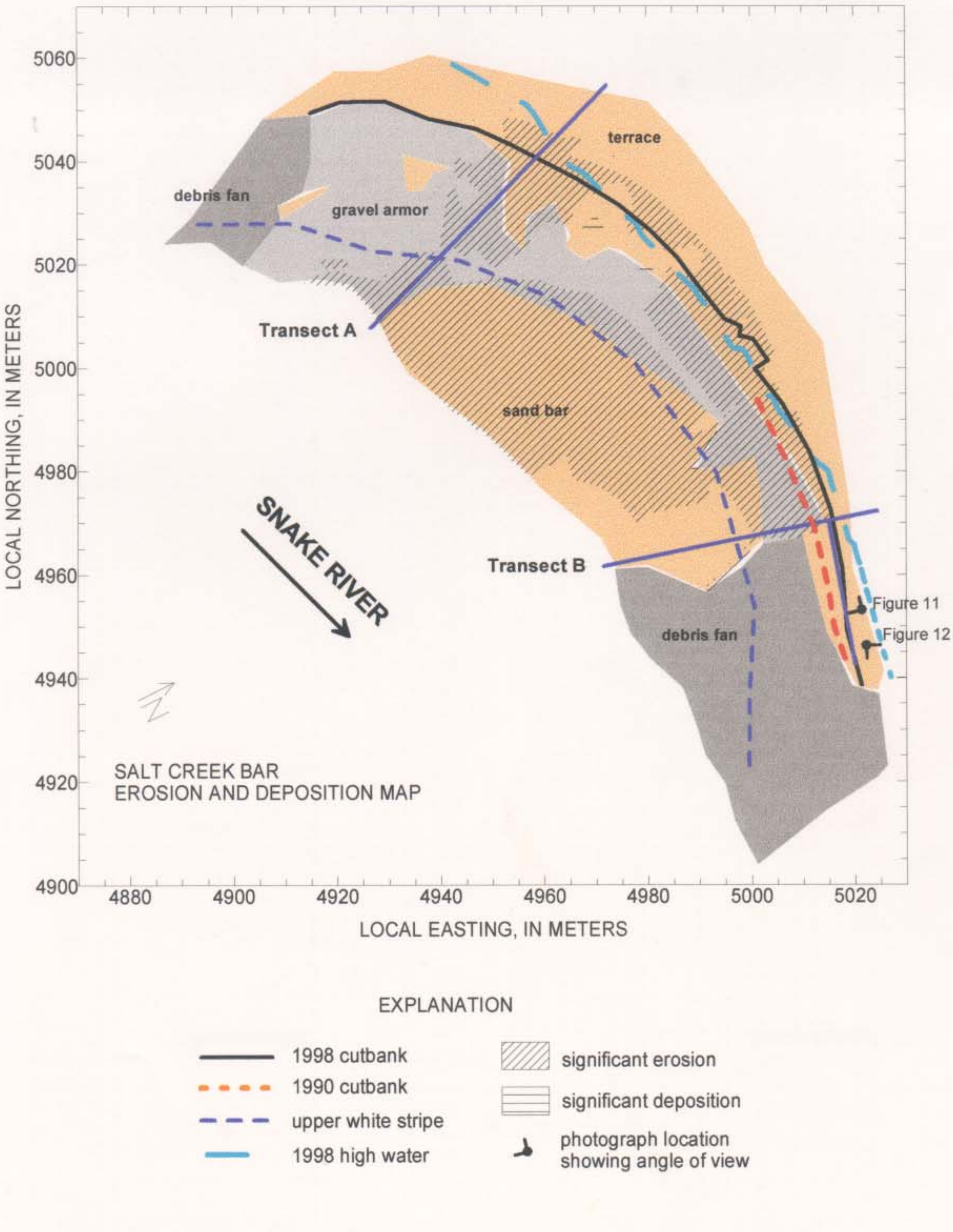


Figure 8. Map showing significant geomorphic features and erosion and deposition between 1990 and 1998 at Salt Creek Bar. Where the 1990 cutbank is not shown, it is in approximately the same location as in 1998. The upper white stripe is at the 850 m^3/s stage and the 198 high water was 2,675 m^3/s. A plot of topographic profiles along transects A and B is shown in Figure 10.

Figure 9.

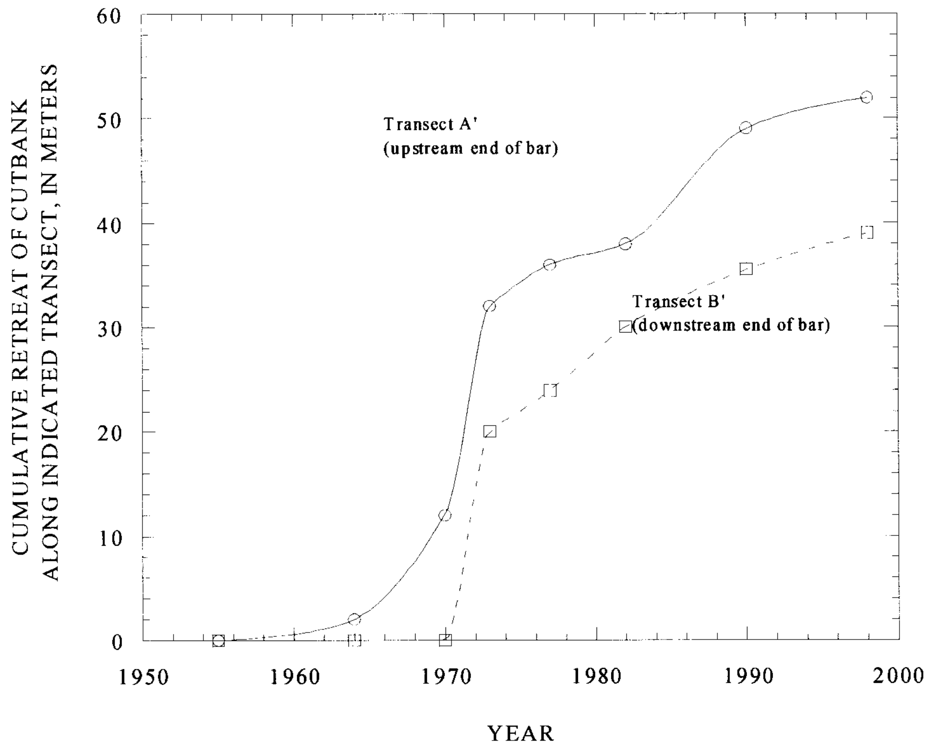
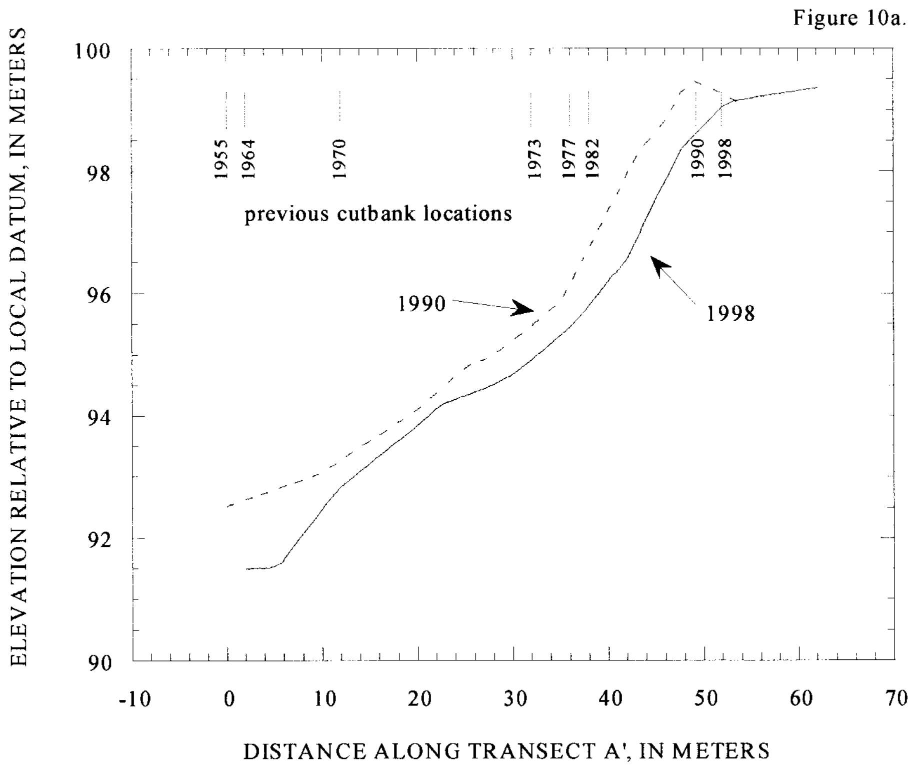


Figure 9. Time series showing rate of cutbank retreat at Salt Creek Bar between 1955 and 1998. Cutbank position determined from aerial photographs (1955 to 1982) and topographic surveys (1990 and 1998). Transect locations are shown in Figure 8.



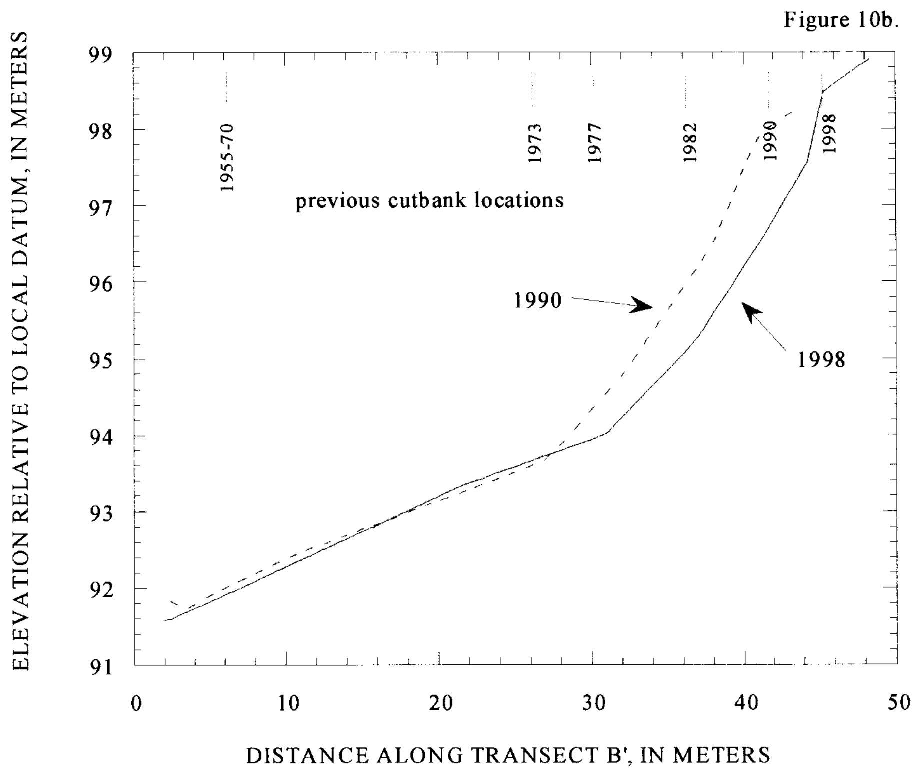


Figure 10. Topographic profiles along transects A and B, respectively at Salt Creek Bar. The locations of the profiles are shown in Figure 8. Previous cutbank locations were determined by analysis of aerial photographs (Grams, 1991). Distances are measured from an arbitrary point in the channel towards the terrace.

Figure 11a

Figure 11b

Figure 11. Matched photographs of Salt Creek Bar taken in 1990 (a) and 1998 (b). The view is upstream and shows erosion of the cutbank in the foreground and an increase in the area of the bar that is armored by gravel in the background. The location the photographs were taken from is shown in Figure 8.

Figure 12. Photograph showing features used to identify the elevation of the 1998 peak discharge at Salt Creek Bar. The location the photograph was taken from is shown in Figure 8.

Figure 13.

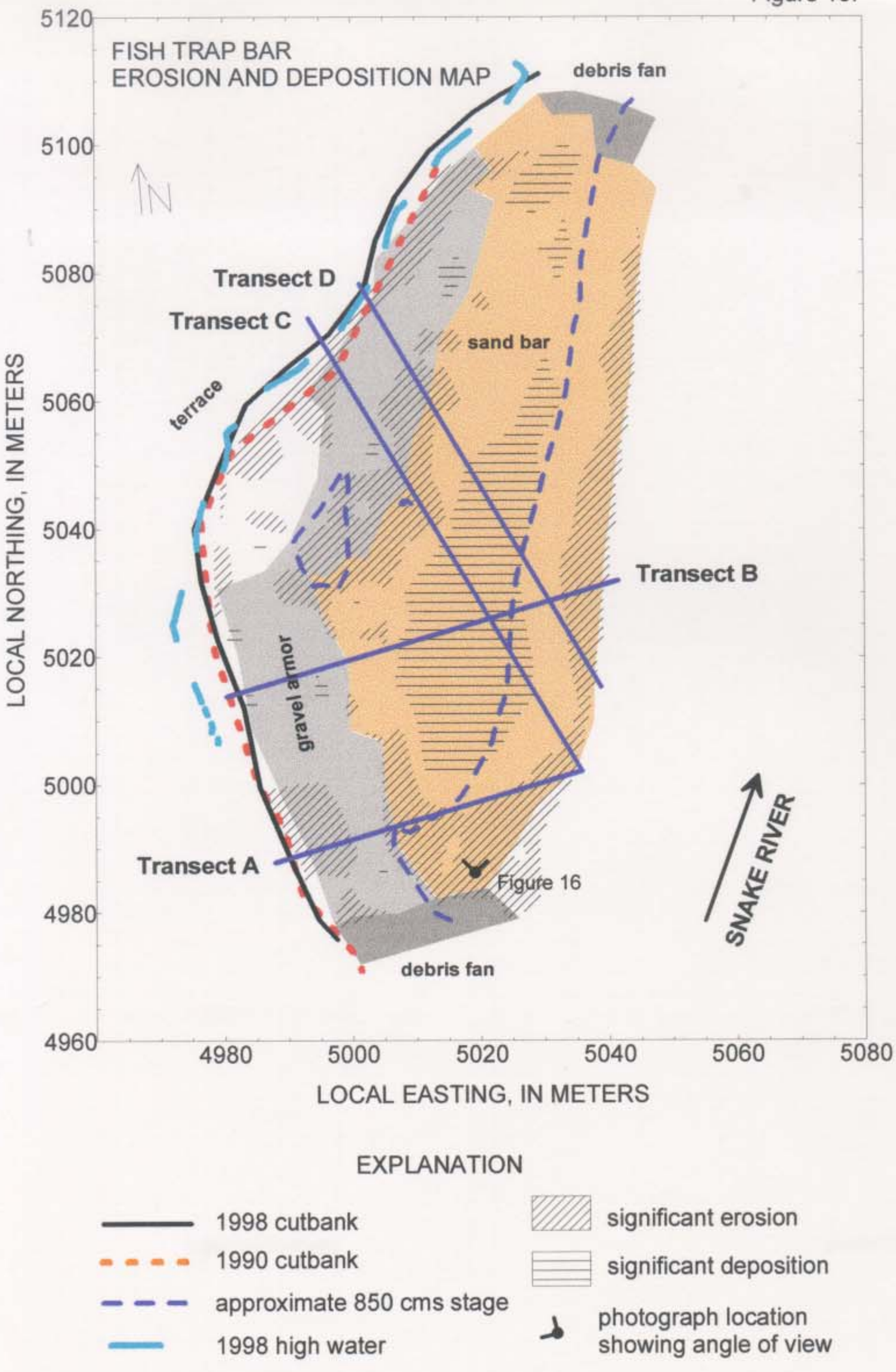


Figure 13. Map showing significant geomorphic features and erosion and deposition between 1990 and 1998 at Fish Trap Bar. A plot of topographic profiles along transects A and C is shown in Figure 15. Differences in cutbank location less than 1 m may be a result from different interpretations of the top of the bank between 1990 and 1998. These small changes are not considered significant.

Figure 14.

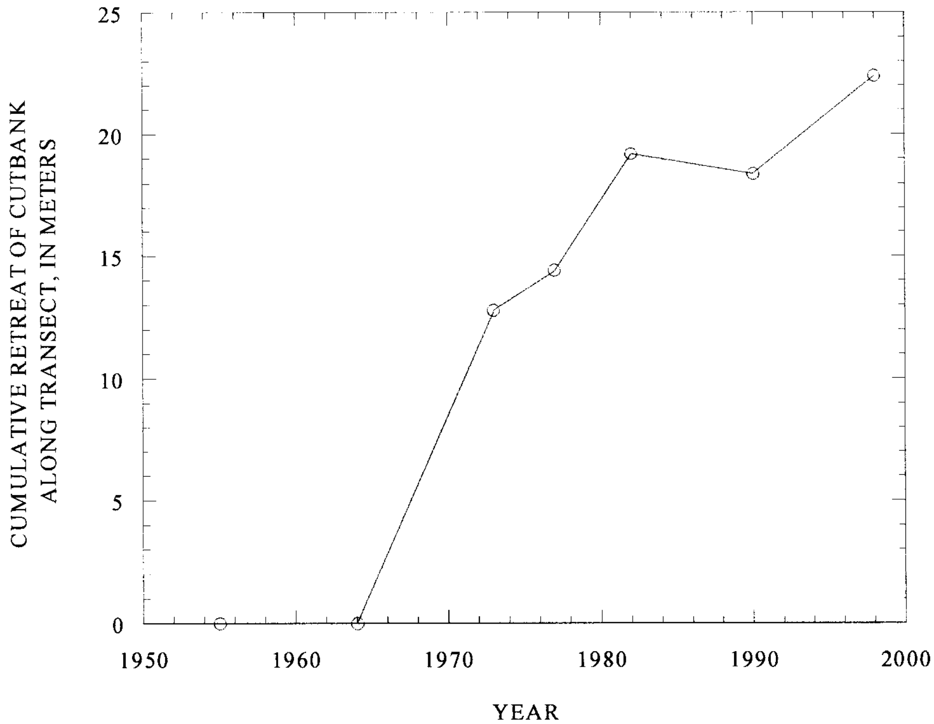


Figure 14. Time series showing rate of cutbank retreat at Fish Trap Bar along transect C between 1955 and 1998. Cutbank position determined from aerial photographs (1955 to 1982) and topographic surveys (1990 and 1998). Transect location is shown in Figure 13.

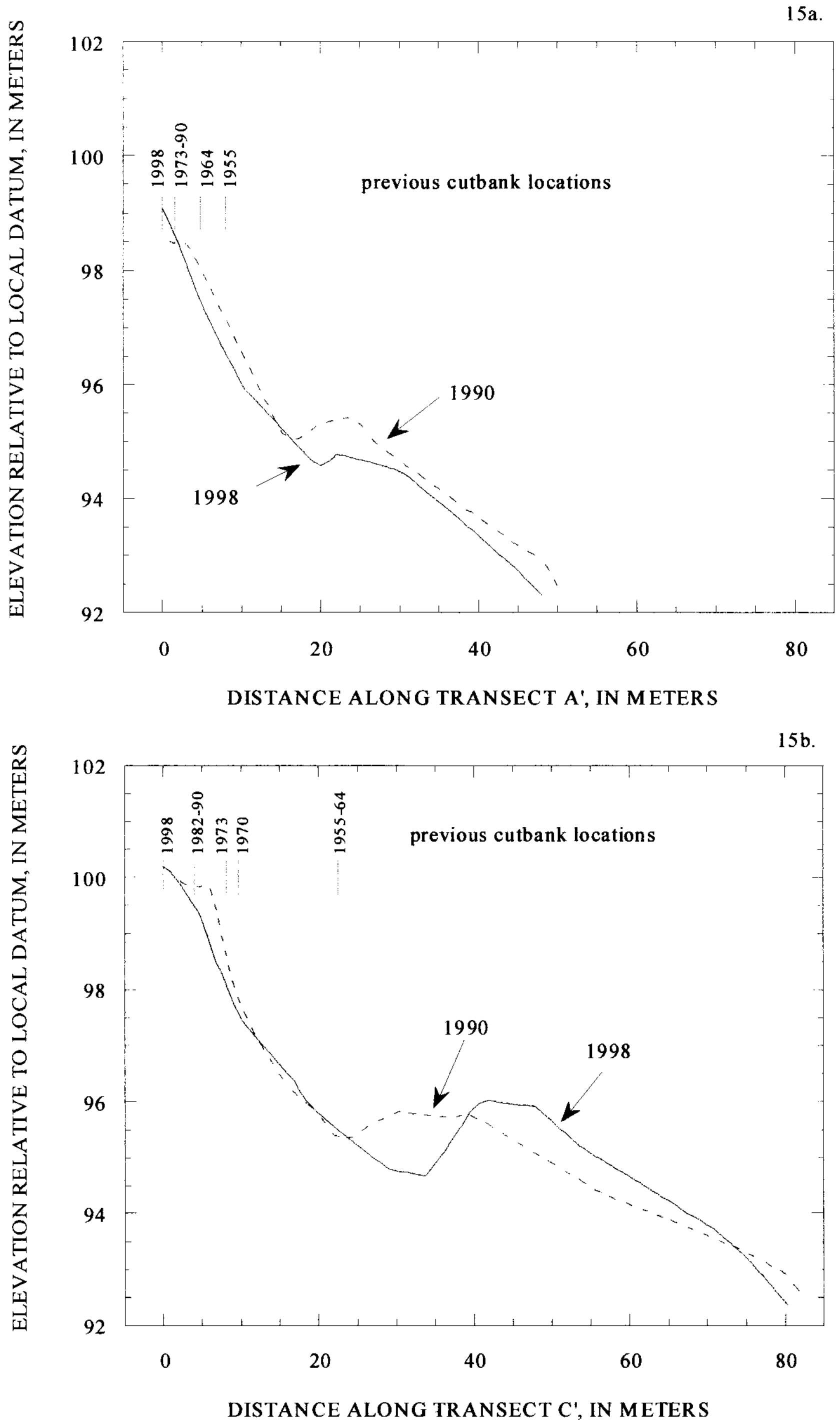


Figure 15. Topographic profiles along transects A and C, respectively at Fish Trap Bar. The locations of the profiles are shown in Figure 13. Previous cutbank locations were determined by analysis of aerial photographs (Grams, 1991).

Figure 16a

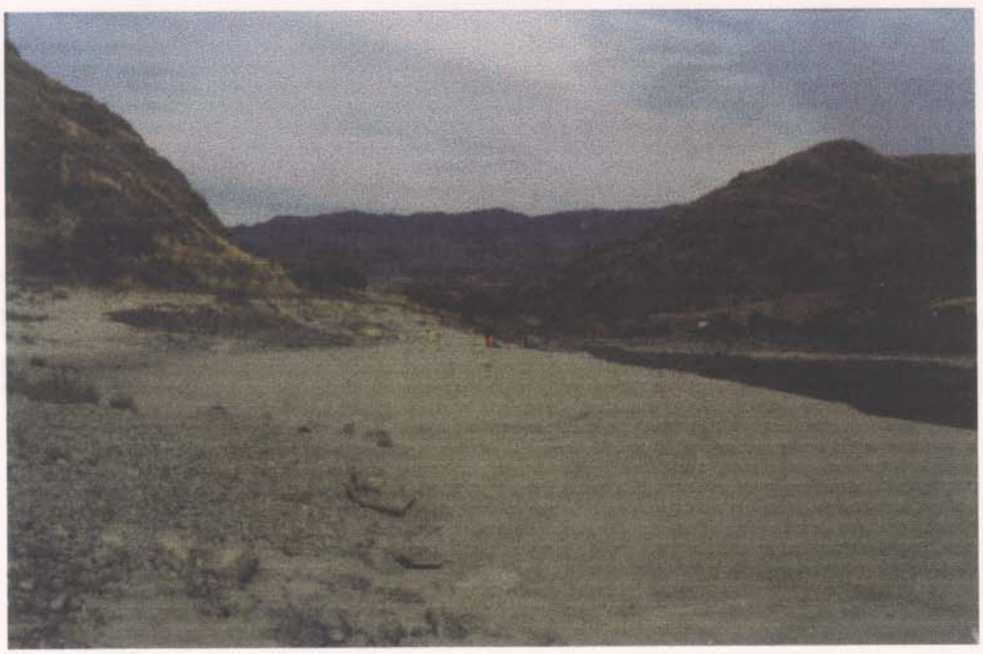


Figure 16b

Figure 16. Matched photographs of Fish Trap Bar taken in 1990 (a) and 1998 (b). The location the photographs were taken from is shown in Figure 13.

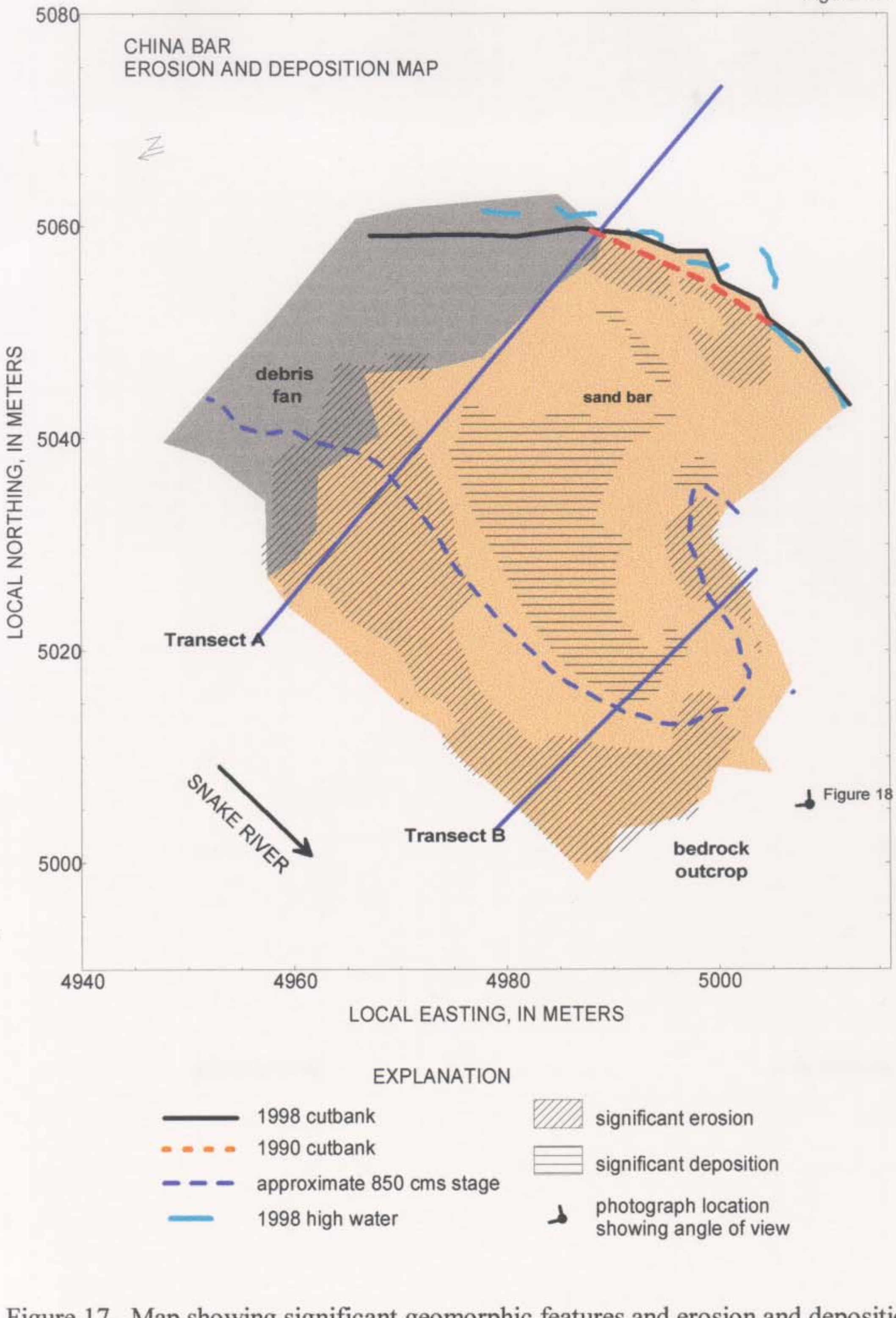


Figure 17. Map showing significant geomorphic features and erosion and deposition between 1990 and 1998 at China Bar. A plot of topographic profiles along transects A and B is shown in Figure 19

Figure 18a

Figure 18b

Figure 18. Matched photographs of China bar taken in 1990 (a) and 1998 (b). The location the photographs were taken from is shown in Figure 17.

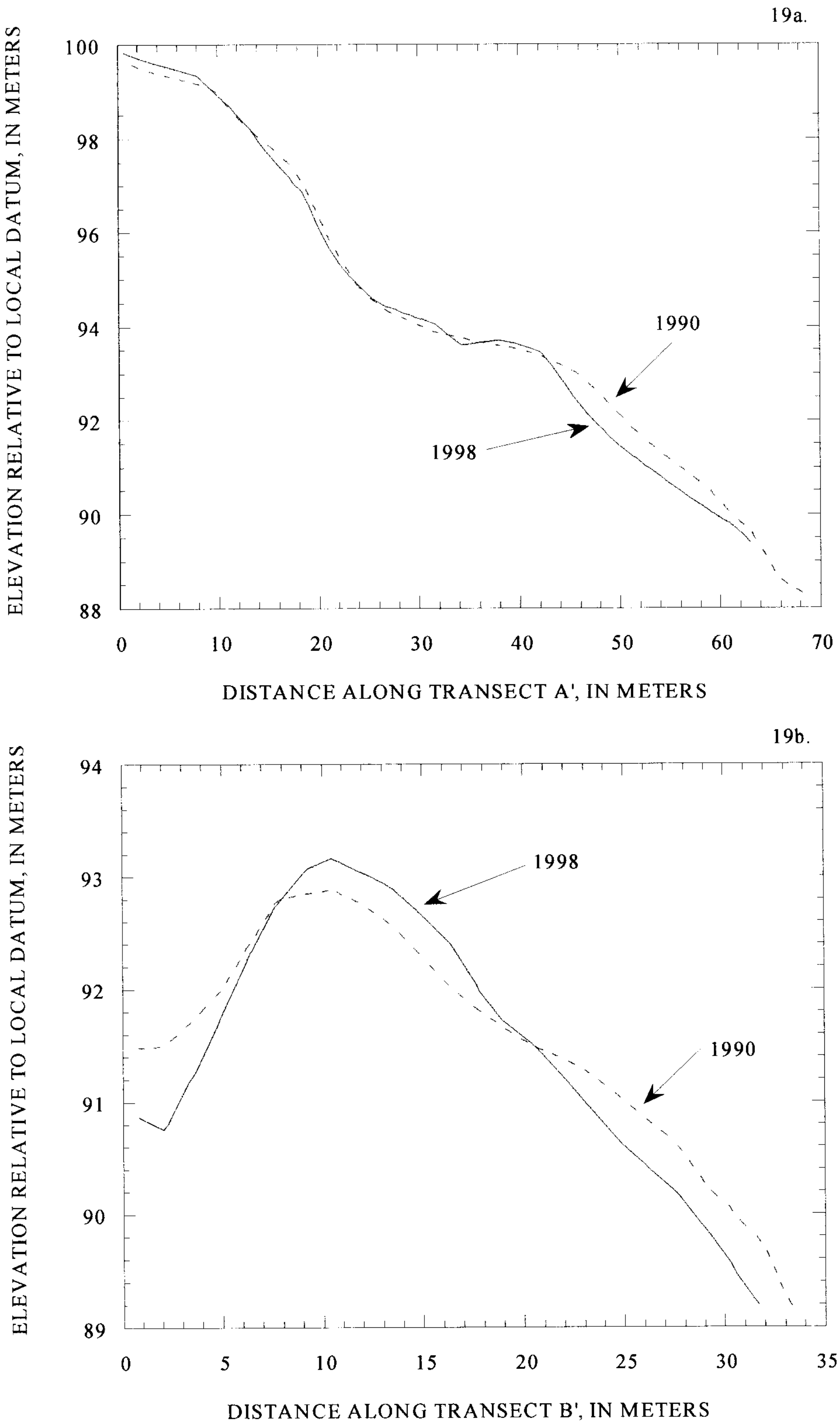


Figure 19. Topographic profiles along transects A and B, respectively at China Bar. The locations of the profiles are shown in Figure 17.

APPENDIX A: SAND BAR DATA INDEX

Appendix A. Sand Bar Data Index

Bar Index Number	Sand Bar Identification (1)	River Mile(2)	Site (3)	Sand Bar Size Category(4) 1964	1973	1977	1982	1990	Measured Area 1990 (5)	Inventory 1998 (6)
1	18-17 CM/L-1	246.9	HCD-Launch	5				nd	nd	
2	18-17 CM/L-2	246.9	HCD-Launch	5				nd	nd	
3	18-17 CF/L	246.8	HCD-Launch	5				nd	nd	
4	18-18 CM/L	245.8		15	5			nd	nd	
5	18-18 CM/R	245.7	Lamont Spr.	15				nd	nd	
6	18-245 CM/R	245.3	Square Beach	15	5	5	5	nd	nd	1
7	18-245 S/R	244.7	Brush Cr.	25	15	15	15	nd	nd	1
8	18-245 CM/R	244.6		5	5			nd	nd	
9	18-246 CM/R	244.2		5				nd	nd	
10	18-246 CM/R-2	244.0		5	5	5		nd	nd	
11	18-247 CM/R	243.4		5				nd	nd	
12	18-247 R/R	243.3		15				nd	nd	
13	18-248 CM/R-1	243.1	Warm Spr.	5				nd	nd	
14	18-248 CM/R-2	242.9		5				nd	nd	
15	18-248 R/L	242.9		5				nd	nd	
16	18-249 CM/R	242.5		5	5	5	5	nd	nd	1
17	18-249 R/L	242.2	Battle Cr.	15				nd	nd	
18	18-250 CM/L	241.9	Sand Dunes	5				nd	nd	
19	18-250 CM/R	241.6	Birch Spr.		5			nd	nd	
20	18-250 R/L	241.3		5				nd	nd	
21	18-251 CM/L-1	241.0		5				nd	nd	
22	18-251 CM/L-2	240.7		5	5			nd	nd	
23	18-240 S/R	240.0		5				nd	nd	
24	18-238 CM/R-1	238.7		5				nd	nd	
25	18-238 CM/R-2	238.5		5				nd	nd	
26	18-238 CM/R-3	238.3		5				nd	nd	1
27	18-262 CM/R	237.0	Dry Gulch	5				nd	nd	
28	18-262 R/R	236.6	Hastings	5				nd	nd	
29	18-263 CM/R	236.4		5				nd	nd	
30	18-263 CF/L	236.3		5	5			nd	nd	
31	18-264 CM/R	236.0		5				nd	nd	
32	18-264 R/L	235.8		5				nd	nd	
33	18-264 CM/R	235.5		5				nd	nd	
34	18-147 CM/R	235.1	Bernard Cr.	5	5			nd	nd	
35	18-149 CM/R-1	234.0		5				nd	nd	
36	18-149 CM/R-2	234.0		5				nd	nd	
37	18-149 CM/R-3	234.0		5				nd	nd	
38	19-224 CM/L	231.3	Rush Cr.	5				nd	nd	
39	19-225 CM/L	230.9		5				nd	nd	
40	19-225 CM/R	230.5		5				nd	nd	
41	19-294 R/R	229.8	Johnson Bar	35	25	25	15	nd	nd	1
42	19-294 CM/L	229.7		5				nd	nd	
43	19-293 CF/L	229.3		5				nd	nd	
44	19-293 S/R	229.2		5				nd	nd	1
45	19-293 R/R	229.1		5				nd	nd	
46	19-293 S/R	229.0		5	5	5		nd	nd	
47	19-293 R/R	228.8		15				nd	nd	
48	19-293 CF/L	228.7		15	5	5	5	nd	nd	1
49	19-293 CM/L	228.6	Yreka Bar	5				nd	nd	1
50	19-293 CM/R	228.5		5				nd	nd	
51	19-292 CM/R	228.4		5				nd	nd	
52	19-292 R/L	228.1		15				nd	nd	
53	19-292 CM/R	228.0		5				nd	nd	
54	19-292 CM/L	228.0		5				nd	nd	
55	19-292 CF/R	227.9		5				nd	nd	
56	19-292 R/L	227.8		5				nd	nd	
57	19-291 CM/R	227.6		5	5	5		nd	nd	
58	19-291 R/R	227.5	Pine Bar	35	35	35	25	nd	nd	1

59	19-291	CF/L	227.4		5				nd	nd	
60	19-291	CF/L	227.3		5				nd	nd	
61	19-291	R/R-1	226.8		5				nd	nd	
62	19-290	R/R-2	226.0		15	5	5	5	nd	nd	1
63	19-290	CM/R	225.9		5				nd	nd	
64	20-5	R/L	224.6		5				nd	nd	
65	20-5	R/L	224.4		15	5			nd	nd	1
66	20-5	CM/R	224.3	Big Bar	5	5	5		nd	nd	
67	20-6	CM/L	223.6		5				nd	nd	
68	20-7	CM/L-1	223.1		5				nd	nd	
69	20-7	CF/R	223.0		5		5		nd	nd	
70	20-7	CM/L-2	222.9		25				nd	nd	1
71	20-7	CF/L	222.8		15				nd	nd	1
72	24-169	R/L	222.4	Salt Creek	35	35	35	35	nd	nd	1
73	24-169	CM/L-1	222.2	Two Corral	25				nd	nd	1
74	24-169	R/R	222.1		15	5	5		nd	nd	1
75	24-169	CM/L-2	222.0		5	5	5		nd	nd	
76	24-170	CM/R	221.7		5	5	5	5	nd	nd	1
77	24-170	S/R	221.6		5				nd	nd	
78	24-170	R/R	221.5	Half Moon Bar	25	5	5		nd	nd	1
79	24-170	R/L	220.8		35	25	25	25	nd	nd	1
80	24-170	CM/R	220.6		5				nd	nd	1
81	24-163	CM/L	220.0	Yankee Bar	5	5	5	5	nd	nd	1
82	24-163	R/L	219.9		25				nd	nd	
83	24-162	CM/R	218.8	Kirby Cr.	35	35	35	35	nd	nd	1
84	24-162	CM/L-1	218.6		15				nd	nd	
85	24-162	CM/L-2	218.5		5				nd	nd	
86	24-190	CM/R-1	218.3		5				nd	nd	
87	24-190	CM/R-2	218.2		5	5	5		nd	nd	
88	24-190	CM/L	218.1		5				nd	nd	
89	24-190	CM/R-3	217.9		5	5			nd	nd	
90	24-189	CM/R	217.4		15				nd	nd	
91	24-189	R/R	216.9		25				nd	nd	
92	24-188	R/L	216.4	Fish Trap	35	35	35	35	nd	nd	1
93	24-188	R/R	216.3	Up.Pittsburg	15				nd	nd	
94	24-188	R/L	215.7		5				nd	nd	1
95	24-188	CM/L	215.6		15				nd	nd	1
96	24-187	CM/L	215.3		15				nd	nd	
97	24-158	S/L	214.7	Pittsburg Adm	25	35	25	25	nd	nd	1
98	24-158	R/L	214.7	Pittsburg Adm	35	15	15	15	25	28800	1
99	24-157	MC/M	213.9		5						
100	24-157	CM/L	213.9		15	15	5	5	5	2700	1
101	24-156	CM/L-1	213.2		5						
102	24-156	CM/R	213.1		5						
103	24-156	CM/L-2	213.1		5						
104	24-156	CM/L-3	212.6		5	5	5	5	5	2100	1
105	24-156	S/R	212.5		5						
106	24-156	R/R	212.4		15	5	5				
107	24-156	CM/R-2	212.3		5						
108	24-181	CF/R	211.9		5	5	5	5	5	T	
109	24-181	CM/L	211.9	McCarty Cr.	25	15	15	5	5	2700	1
110	24-181	CF/L	211.8		5						
111	20-20	CM/R-1	211.7		5						
112	20-20	CM/L-1	211.6		5						
113	20-20	CF/L-1	211.4		5	5	5	5	5	1200	1
114	20-20	CM/L-2	211.2		5	5	5				
115	20-20	CM/L-3	210.7		5						
116	20-20	CM/L-4	210.6		5						
117	20-20	CF/L-2	210.5		5	5					
118	20-20	CM/L-5	210.5		5	5	5				
119	20-20	CM/L-6	210.4	Somers Range	5	5	5	5	5	T	

120	20-20	CM/R-2	210.3	15	5	5	5	5	1400	1
121	20-21	CM/L-1	209.9 Camp Cr.	15	5	5				1
122	20-21	CM/L-2	209.7	5						1
123	20-22	CF/R	209.2	5	5	5	5	5	T	
124	20-23	R/R	208.3 Jones Cr. **	15	5	5	5	5	T	1
125	20-23	R/L	208.2 Lookout Cr	25						
126	20-24	CM/R	207.8	5	5					
127	20-24	S/R-1	207.5 Marlboro B.**	5	5	5	5	5	T	1
128	20-24	CF/R	207.4	5						
129	20-24	S/R	207.3	5	5	5	5	5	T	
130	20-25	CM/L-1	206.9	5						
131	20-25	CM/L-2	206.8	5						
132	20-25	S/R	206.7	5	5	5	5	5	T	
133	20-26	R/R	206.3 High Range**	25						
134	20-26	CF/R	206.0	5	5					
135	20-26	CM/L	205.9	5						
136	20-27	CF/R	205.8	5	5	5	5			1
137	20-27	R/R	205.7	5	5					
138	20-27	CF/L	205.5	5	5					1
139	20-27	CM/L	205.5	5	5	5				
140	19-267	R/L	205.3	15						
141	19-267	CF/R-1	205.1	25	15	15	15	15	S	1
142	19-267	CM/R	204.8	35	35	35	25			1
143	19-267	CF/L	204.8	5	5	5				
144	19-267	CM/L-1	204.6	5						
145	19-267	CM/L-2	204.5 Bob Cr.	5	5	5	5	5	T	1
146	19-267	CF/R-2	204.4	5						
147	19-267	S/R	204.2	15	15					
148	19-257	S/R	203.9	15	5	5	5	5	4500	1
149	19-257	CM/R	203.5	5	5	5	5	5	2800	
150	19-257	CF/L	203.4	15						
151	19-257	CM/L	203.1	5						
152	19-258	CM/R-1	202.9 Wolf Cr. Camp	5						
153	19-258	R/L	202.8	5						
154	19-258	S/R	202.8	5	5	5	5	5	120	
155	19-258	CM/R-2	202.5	5	5	5	5	5	1800	1
156	19-258	CM/L	202.4	5	5					1
157	19-258	CM/R-3	202.4	5	5					
158	18-187	S/L	201.9 Bar Cr.	15	5	5	5	5	9000	1
159	19-14	CM/R-1	201.6	5						
160	19-14	CM/R-1E	201.6	5						
161	19-14	R/R-1	201.5	15	5	5	5	5	5400	1
162	19-14	CM/R-2	201.2	35	25	25	25	25	28000	1
163	19-14	CM/R-3	201.1	15	15	15	5	5	5000	1
164	19-14	R/R-2	201.0	15	5	5	5	5	2500	1
165	19-14	R/R-3	200.9 Dry Cr. Camp	15			5	5	200	1
166	19-14	CM/L	200.7	5						
167	19-14	CM/R-4	200.3	5	5	5	5	5	2400	1
168	18-192	CM/L-1	200.1	5	5	5	5	5	800	1
169	18-192	CF/L-1	199.5	5						
170	18-192	CF/R-1	199.4	5						
171	18-192	CF/R-2	199.3	5						
172	18-192	CF/R-3	199.2	5						
173	18-192	CM/L-2	199.2	5						
174	18-192	CF/R-4	199.1	5						
175	18-192	CF/R-5	199.1	5						
176	18-192	CF/L-2	199.1	5						
177	18-83	S/L	199.0 Deep Cr. Camp	5	5	5	5	5	5600	1
178	18-83	CM/R	198.7	15	5					1
179	18-83	CM/L	198.5 Robinson Gulch	5	5	5	5	5	4800	1
180	18-83	CF/L-1	198.3 Dug Cr.	15	5					

181	18-83	CF/L-2	197.7		5						
182	31-248	R/L	197.4		15		5				
183	31-248	CM/R	197.3		5						
184	31-247	CM/R	195.3	Warm Spring	15	15	25	15	15	12600	1
185	19-20	CM/R-1	195.0		5	5	5	5	5	T	
186	19-20	CM/L-1	194.9		5						
187	19-20	CM/R-2	194.7		5						
188	19-20	CM/R-2/	194.3		5						
189	19-20	CM/R-2E	194.3		5						
190	19-20	CM/R-2(	194.2		5						
191	19-20	CM/R-3	194.1	Zig Zag	5	5	5	5	5	T	
192	19-20	CM/L-2	194.1		5						
193	19-20	CM/R-4	194.0		5	5	5	5	5	T	1
194	19-20	CM/L-3	194.0		5	5	5	5	5	T	
195	19-20	R/L	193.8		25	15	5				1
196	19-20	CM/R-5	193.5		5	5	5				
197	19-20	CM/R-6	193.3		5	5					
198	19-178	CM/L-1	192.7		5						
199	19-178	R/L	192.4	China Bar	15	15	15	15	15	13400	1
200	19-178	CM/R	192.2		5	5					
201	19-178	CM/L-2	192.2		5	5	5	5	5	600	1
202	19-178	CM/L-3	192.1		5	5	5	5	5	300	1
203	21-233	CM/L	190.9		35	25	15	5	15	14000	1
204	21-233	CM/R-1	190.8		5	5					
205	21-233	CF/L-1	190.3		5						1
206	21-233	CF/L-2	190.2		5						1
207	21-233	CM/R-2	190.0		5	5	5	5	5	1200	
208	21-235	CM/R-1	189.8		5						
209	21-235	CM/R-2	189.7		5						
210	21-235	CM/L-1	189.6		5	5	5	5	5	T	
211	21-235	CM/R-3	189.3		5	5	5				
212	21-235	CF/L-1	189.2		5						1
213	21-235	CM/L-2	188.7		5						
214	21-235	CM/L-3	188.6		5						
215	21-235	CR/R-1	188.6		5						
216	21-235	CF/L-2	188.5		5	5	5	5	5	2000	1
217	21-235	CF/R-2	188.4		5						
218	21-235	CM/L-4	188.3		5						
219	21-235	PB/R	188.3		5	5					
220	21-235	CM/R-4	188.2		5	15	5	5	5	T	1
221	21-235	CM/R-5	188.0		35	35	25	35	15	17500	1

(1) Numbers refer to identification numbers on the 1964 aerial photographs.
Letters signify deposit type. CM =channel margin, R=reattachment, S=separation.
The last number distinguishes deposits of the same type on the same photograph.
(2) Location of deposit in reference to COE river mile (distance upstream from the Columbia River).
(3) Name of site as identified in U.S. Forest Service river guide.
(4) Size category of sand bar in thousands of square feet.
Data from air photography is corrected according to 1990 field data.
(5) Area, in thousands of square feet, of deposits measured in 1990. "nd" indicates sites not included in 1990 inventory.
"T" signifies sites which contained a small area of sand (less than 5,000 square feet) not measured precisely.
(6) Sand bars were present at the sites indicated.