DEGRADATION OF ALLUVIAL SAND BARS ALONG THE SNAKE RIVER BELOW HELLS CANYON DAM, HELLS CANYON NATIONAL RECREATION AREA, IDAHO

Paul E. Grams and John C. Schmidt

Department of Geology
MIddlebury College
Middlebury, Vermont 05753

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ABSTRACT

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Grams, Paul E., Department of Geology, Middlebury College, Middlebury, Vermont 05753.

The number and area of sand bars along the Snake River in Hells Canyon has decreased by over 75 percent following closure of 3 large upstream dams constructed between 1957-67. Five aerial photograph series taken between 1955-82, supplemented by field work conducted in summer 1990, document these changes.

The greatest amount of sand-bar erosion occurred between 1964-73, during a period when 3 clear-water spillway floods occurred, each exceeding the pre-regulation mean annual flood by more than 20 percent. The rate of sand-bar erosion decreased after 1973 and decreased further after 1982. Erosion of alluvial terraces backing sand bars was also documented. Erosion of these terraces still continues at some sites.

The erosion of sand-bars in Hells Canyon greatly exceeds the erosion of similar eddy-system bars in Grand Canyon downstream from Glen Canyon Dam. The primary difference in regulation of these two rivers is that the ratio of total reservoir storage to mean annual flow is much lower on the Snake River. Therefore, the flood-control potential is much less. In fact, post-dam floods in Hells Canyon are similar in magnitude and frequency to those prior to regulation. In Grand Canyon, flood control is much greater and few large clear-water floods have occurred. The contrasting styles of downstream response in sand-bar change suggest that high magnitude flows in a sediment-starved system have been the primary erosive force in Hells Canyon.

1. INTRODUCTION AND PURPOSE

Bedrock-confined rivers typically contain zones of recirculating flow caused by downstream changes in cross-sectional area that occur over short distances. Fine-grained alluvial banks and bars along such rivers are typically restricted to: (1) these zones of recirculating flow, and (2) isolated channel margins.

The flows of many large rivers in the United States and internationally are regulated artificially by dams. Large dams are frequently located in bedrock gorges because these gorges are favorable sites for dam construction. Regardless of the reservoirs' primary purpose as water storage, flood control, or hydroelectric-power generation, dams alter the natural streamflow pattern and sediment transport regime of the adjacent downstream reach. These changes may significantly affect downstream river channel morphology, including the characteristics of alluvial sand bars. Because dams typically affect the character of downstream river channels , the study of these effects is an important aspect of geomorphology. The effects on wildlife habitats, particularly fish habitat, make river morphology changes important to biologists as well. Sand-bar changes are of concern to recreationists who frequently use these bars as campsites and boat moorings, and to others who are interested in preserving the natural features of remote and scenic areas such as Hells Canyon.

This paper describes the characteristics of alluvial sand bars along the Snake River in Hells Canyon, which forms part of the Idaho-Oregon border. Between 1958 and 1967 three dams were put into operation within and immediately upstream from Hells Canyon. Although changes in the downstream channel morphology have been observed by river runners, these changes have not been the subject of formal study. In this study changes in the frequency, areal extent, and volume of sand bars in the Snake River between 1955 and 1990 are evaluated. Sand bars are analyzed by type and distribution within the study reach, which covers 60 mi downstream from Hells Canyon Dam. The analysis utilizes aerial photography taken in 1955, 1964, 1970, 1973, 1977, and 1982. Field observations made in summer 1990 provide supplementary data. The pattern of change in sand bars is discussed in relation to the processes controlling sand-bar aggradation and degradation. Sand bars and the effects of dams on sand bars have been studied in detail on the Colorado River below Glen Canyon Dam. It is therefore useful to compare and contrast sand bars and the effects of dams on sand bars in these two systems.

Acknowledgments

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2. LITERATURE REVIEW

Effects of Dams on Alluvial Rivers

The effects of dams on stream flow is dependant upon the characteristics of the dam and the drainage basin. Generally, where diversions for irrigation are not significant, total annual runoff is conserved. Evaporation from reservoirs may contribute to a decrease in total runoff, dependant on the local climate. The distribution of flows, however, is often changed considerably. Streamflow regulated by large dams is typically characterized by lower magnitude peak flows of shorter duration than occur in unregulated rivers. For example, the post-dam mean annual peak flow of the Colorado River at Lee's Ferry, 17 mi below Glen Canyon Dam, between 1963 and 1982 was less than one-third the unregulated annual peak flow between 1921 and 1962 (Schmidt and Graf, 1990). Andrews (1986) found that the duration of large discharges on the Green River was significantly shorter following construction of Flaming Gorge Dam. In dams used for the generation of hydro-electric power, daily fluctuations in flow typically occur as power plant output varies to meet hourly demand for electricity. On the Colorado River at Lee's Ferry, for example, daily fluctuations between 1965 and 1982 were as high as 50 percent of the daily maximum flow (Schmidt and Graf, 1990).

Williams and Wolman (1984) determined that large dams may be up to 99-percent effective in trapping sediment. Sediment availability below large dams is, therefore, dependant on downstream tributary input, and river bank and bed erosion. Suspended sediment transport of the Colorado River at Lee's Ferry decreased from over 10,000 ppm to under 200 ppm subsequent to dam closure (Schmidt and Graf, 1990).

Andrews (1986) studied changes in the rates of sediment transport of the Green River as a function of distance below Flaming Gorge Dam. Andrews also determined that the sediment-transport rate at a given discharge and distance below the reservoir may be unaffected by flow regulation and sediment storage. Mean annual sediment discharge of the Green River decreased by 54 percent at a cross-section 105 mi downstream and by 48 percent at a cross-section 290 mi downstream. However, at distances greater than 160 mi downstream from the dam, these changes are not related to changes in sediment supply but rather to changes in the river's sediment-transport capacity. The characteristics of the Green River drainage basin have determined the relative effects of the dam on streamflow and sediment transport. Below Flaming Gorge Dam, most of the Green River's runoff is regulated by the reservoir, however, a majority of the sediment load enters from tributary basins entering the Green River below the reservoir. Thus, as one travels further downstream from the reservoir the portion of sediment supply withheld in the reservoir becomes increasingly small in relation to the total amount of sediment in transport. Changes in sediment transport downstream from a dam are, therefore, not determined solely by sediment trapping in the reservoir. Regulation of streamflow has been the most important effect of Flaming Gorge Dam. The decreased sediment transport, and resultant aggradation, at increased distances below Flaming Gorge Reservoir is a result of a decreased duration of large discharges able to transport the sediment load available for transport.

Petts (1979) examined the range of possible effects of dams on river channel morphology and distinguished three types of effects: degradation, aggradation and channel metamorphosis. Williams and Wolman (1984) observed channel-bed degradation immediately downstream from 27 of 29 reservoirs during periods ranging from a few years to a few decades following dam closure. Degradation has been greatest at locations nearest the dams. Maximum channel degradation at individual cross-sections varied from less than 3.3 ft to as much as 24.8 ft. Degradation of bed material immediately below reservoirs is considered to be a direct effect of sediment being trapped behind the dam (Andrews, 1986; Williams and Wolman, 1984). Stream-bed armoring typically restricts and eventually halts channel degradation. Armoring occurs as fine material is winnowed-out leaving as substrate only coarser, and less erodible, material. Williams and Wolman

(1984) observed an increase in average sediment size at channel cross-sections near dams over approximately the first 10 yrs following dam closure.

Degradation of bed material continues downstream until: (1) local controls of the bed emerge; (2) there is a decrease in flow competence; (3) there is enough sediment input to restore balance; (4) there is an increase in vegetation cover (Williams and Wolman, 1984). Local bed controls might consist of bedrock outcrop or other material resistant to erosion. Flow competence, or the ability of a stream to do work, is related to discharge. Sediment input from tributaries may be sufficient to maintain a stable channel. Vegetation may effectively hold together fine material, making erosion less likely.

Gregory and Park (1974) suggested that sediment trapping may only cause degradation in reaches within a short distance downstream from a dam but changes in streamflow patterns may affect much longer reaches of a river. Andrews (1986) confirmed this theory in his study of the Green River, in which reaches of degradation, no significant change, and aggradation were identified. The aggrading reach began 166 mi below the dam and occurred where, as described above, there was decrease in sediment transport caused by a decrease in sediment-transport capacity -- not a deficit in sediment influx. Sediment input by tributaries is significant in determining the downstream extent of degradation and the occurrence of aggradation in certain reaches.

Channel metamorphosis (Petts, 1979) is the complex response, over time, of the channel to hydrologic and sediment changes. This may include periods of degradation followed by periods of aggradation. A complete analysis of readjustment would include all of the many variables which are involved in determining river-channel morphology. Komura and Simmons (1967) developed an empirical relation describing degradation downstream from reservoirs. In a model they attempted to account for stream bed armoring but were unable to incorporate many of the other complexities such as: sediment input due to bank erosion and tributaries, subsequent breakdown of the armored layer, stream meander effects, vegetation, and variable discharge.

Sedimentation in Bedrock Gorges

Schmidt and Graf (1990) classified alluvial sand bars along the Colorado River in Grand Canyon based on bar location in relation to local flow conditions. Zones of recirculating current typically occur at channel expansions where downstream flow separates from the bank (Rubin and others, 1990). The recirculation zone persists on the shore-ward side of the eddy fence downstream to where downstream flow reattaches to the river bank at the reattachment point. Figure 1A shows a typical recirculation zone which consists of a primary eddy and, sometimes, a secondary eddy. Reattachment bars project upstream from the reattachment point and generally resemble the form of a spit (Figure 1B). Separation bars mantle the downstream end of channel constrictions and develop near the separation point. Channel margin deposits occur along the banks of a river and have the same general form as river terraces.

Rubin and others (1990) described the sedimentology of a typical reattachment bar. The main topographic features are the primary-eddy return channel, a linear ridge, a main platform, and an accretionary bank (Figure 2). The eddy-return channel is the route by which water flowing into the channel over the bar surface is circulated upstream and back to the main current. Ripple- and dune-form cross-bedding are common features, and inferred bedform migration directions correspond well with the pattern of recirculating flow (Rubin and others, 1990). Sediment transport directions are upstream and onshore over most of the bar but are downstream-directed in areas downstream from the reattachment point.

Average particle size of sediments forming reattachment bars in Grand Canyon is similar to the size distribution of the suspended sediment load of the Colorado River (Schmidt, 1990). Since the majority of a river's sediment load is transported during floods, most sand-bar aggradation occurs during flood events. Separation bars tend to consist of finer material and lie at higher elevations than reattachment bars. This is because sand which forms a separation bar is material that has remained in suspension as it

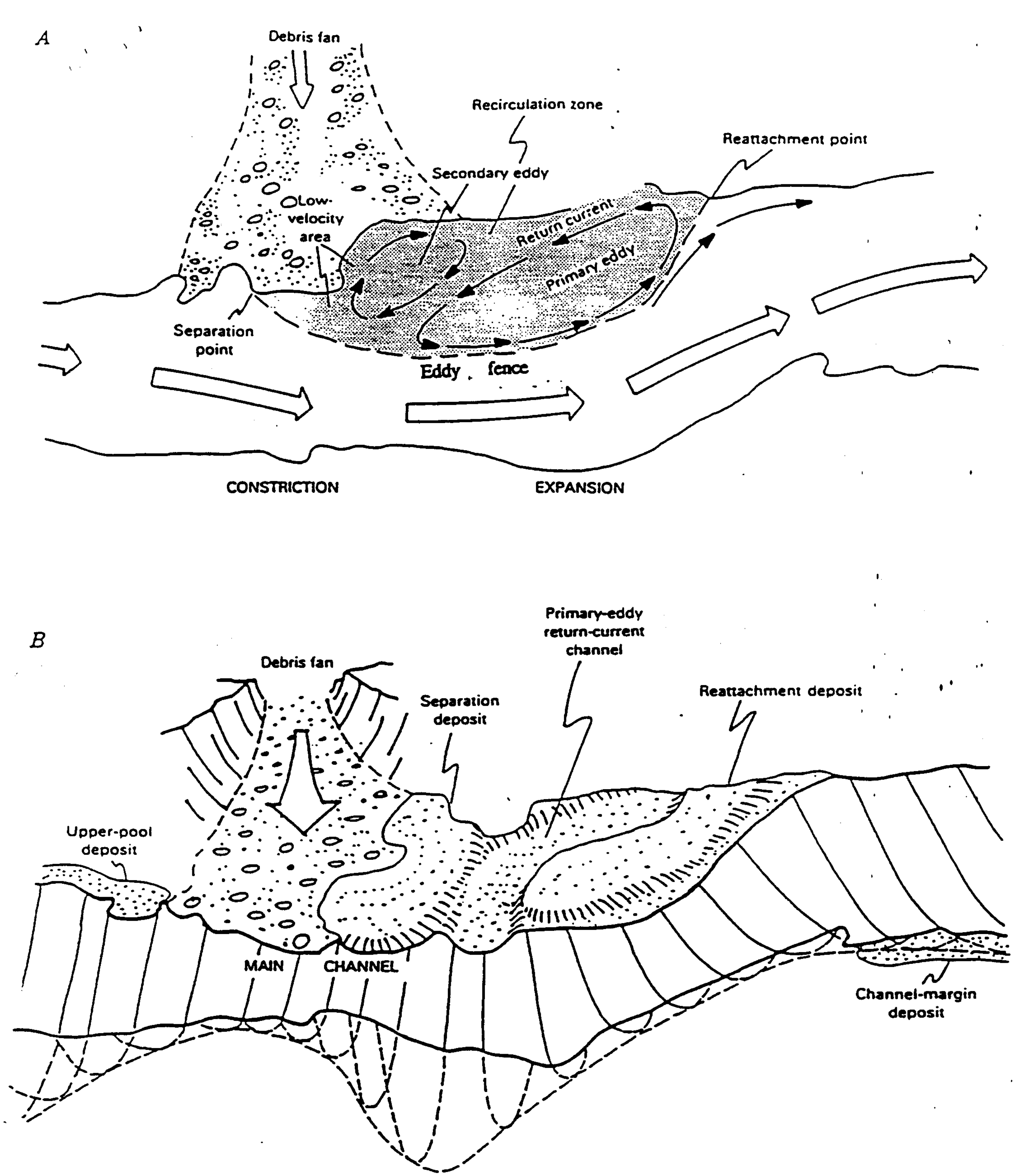


Figure 1. – Flow pattrns and configuration of bed deposits in a typical recirculation zone, Colorado River, Grand Canyon, Arizona. A, Flow patterns. B, Configuration of bed deposits. (Schmidt and Graf, 1990, Figure 3)

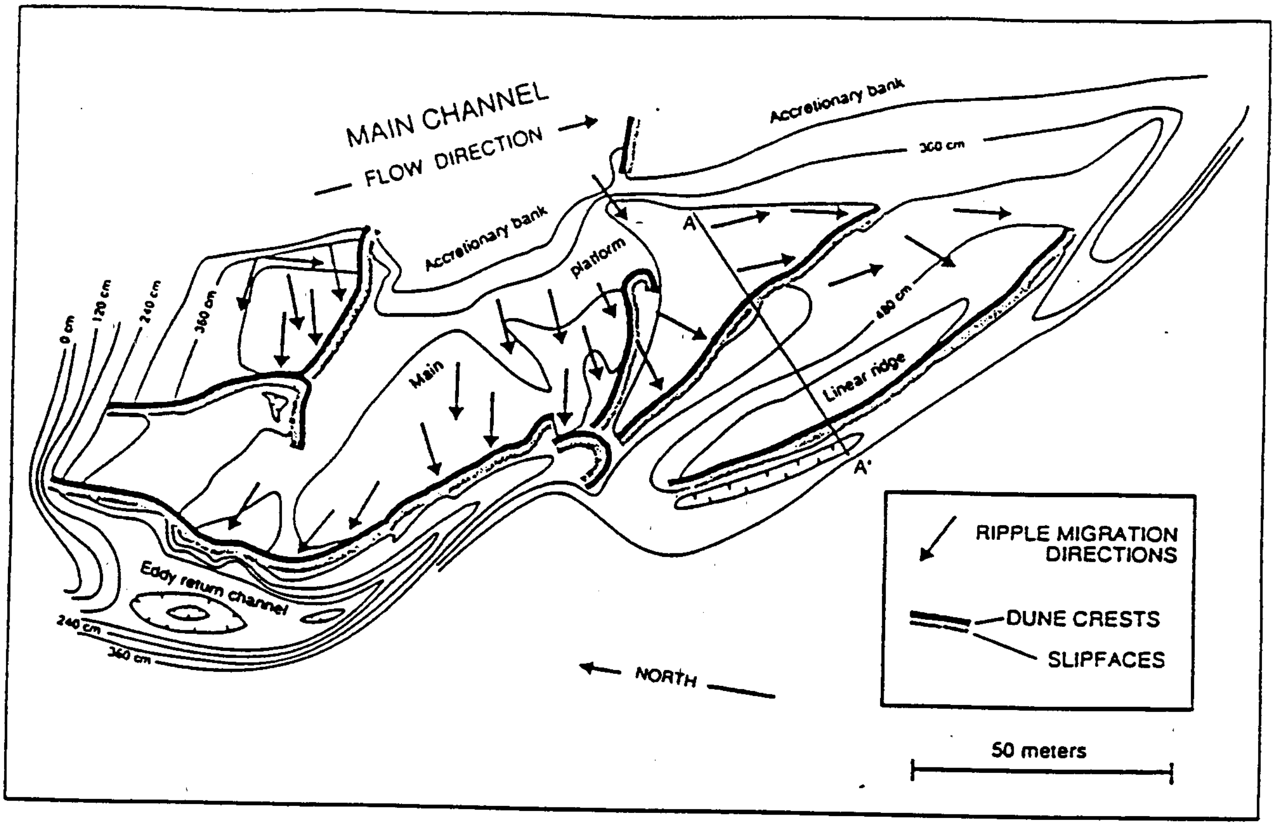


Figure 2. – Topographic map of a reattachment bar. Ripple migration directions were inferred from the orientation of symmetrical rib and furrow structures that were examined in horizontal section. Elevations were measured relative to an arbitrary datum. (Rubin and others, 1990, Figure 4)

is carried through the primary eddy and is deposited in the secondary eddy in low velocity areas as shown in Figure 1A (Schmidt and Graf, 1990). Dune and ripple bed-forms in separation bars typically migrate on-shore and upstream.

Schmidt (1990) described flow patterns and sedimentation in a typical recirculation zone during the passage of a flood. In the initial stages of a flood the reattachment point migrates downstream and the separation point migrates upstream resulting in a longer recirculation zone. Pre-existing sand bars are scoured and sediment is transported across the eddy-fence by turbulent boils. As the high discharge continues, sedimentation occurs near the separation and reattachment points. During recession of the peak flow, bars become exposed and the recirculation zone contracts. Degradation may also occur during flood recession. Schmidt and Graf (1990) evaluated sand bar change below Glen Canyon Dam along 125 miles of the Colorado River in the Grand Canyon. High flows in the Colorado River in 1983 and 1984 removed sand from recirculation zones in narrow reaches and resulted in aggradation in wide reaches. Reattachment bars were found to be slightly more susceptible to erosion than separation bars. In 1985 and 1986 fluctuating flows caused erosion of many bars of all types throughout the Grand Canyon (Schmidt and Graf, 1990). Thus, both extreme flows released by a dam and fluctuating flows which occur during standard operating conditions are capable of affecting sand bar extent.

Geomorphic Effectiveness and Channel Morphology

Wolman and Gerson (1978) defined geomorphic effectiveness as the "ability of an event or combination of events to affect the shape or form of a landscape." For destructive events, such as erosion of alluvial sand bars, the effectiveness also depends upon the "constructive or restorative" processes which operate during the intervening intervals (Wolman and Gerson, 1978). In addition to the magnitude of the flood, the timing of the event is equally important. As stated by Wolman and Gerson (1978):

> The geomorphic importance of a given event is governed not only by the absolute magnitude of the force or energy which it brings to bear

> on the landscape, but also by the frequency with which it recurs, the processes during intervening intervals between such recurrences, and the work performed during such intervening intervals.

Kochel (1988) considered the effects on river channel morphology of extreme floods which follow floods of a similar magnitude. The effects of the second flood are minor in comparison to the effects of the initial flood. Similarly, the role of a single discharge event in modifying channel form is dependant on existing channel form. Channel form, therefore, is the result of all antecedent flows making it impossible to associate form precisely with a particular 'channel-forming' discharge (Yu and Wolman, 1987).

Floods have been significant in determining sand bar aggradation and degradation in Grand Canyon (Schmidt and Graf, 1990). Therefore, the condition of sand bars in a bedrock gorge like Hells Canyon should be a result of: 1) the flow event responsible for initially building the sand bar; 2) the flow events subsequent to the initial event which remove sand from the bar; and, 3) the flow events subsequent to the initial event which rebuild the sand bar. When there is no sediment transport, rebuilding does not occur because there are no restorative processes and the existent bar-form is a result of the cumulative erosional events on the original form. Additionally, because no constructive processes are operating, the effects of erosional events of equal magnitude on bar-form would be expected to diminish each time that event recurs.

3. STUDY AREA

Description

The Snake River is one of the principal tributaries in the Columbia River basin. The drainage basin of the Snake River is approximately 108,800 mi^2, of which about 73,300 mi^2 is above Hells Canyon Dam. The Snake River flows into southern Idaho from its headwaters on the Yellowstone Plateau of northwestern Wyoming. The river flows west across southern Idaho and the Snake River Plain then at the Idaho-Oregon border

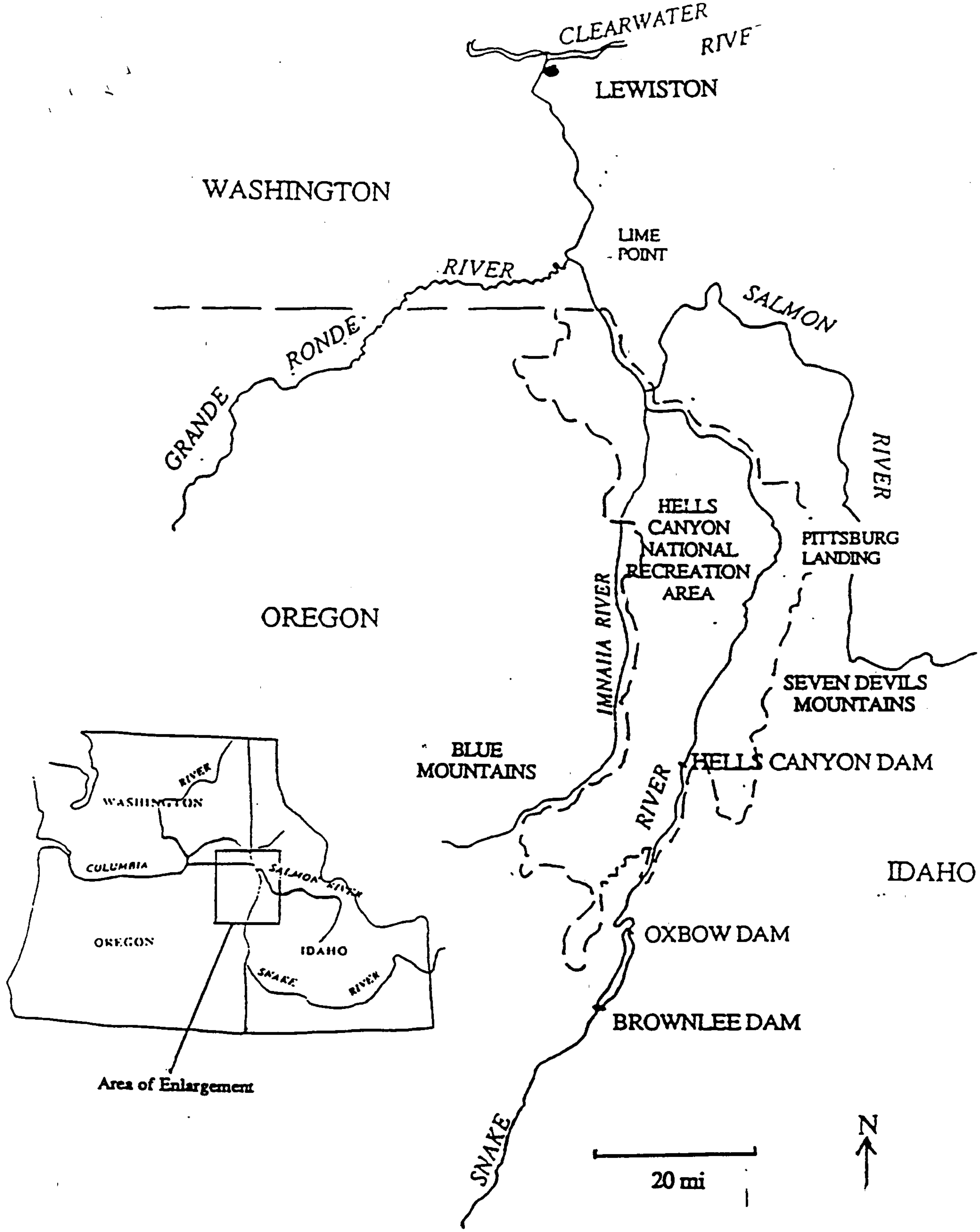


Figure 3. -- The Snake River in Hells Canyon National Recreation Area showing the locations of major tributaries and detailed study sites. Inset shows the Columbia River and Snake River basins in Washington, Oregon, and Idaho.

turns sharply northward and flows through a series of deep canyons (Figure 3). A few miles below Oxbow Dam at Oxbow, Oregon, the Snake River enters Hells Canyon. The river is about 4,000 - 6,000 ft below the western canyon rim for the next 60 mi. The highest peaks of the Seven Devils Mountains in Idaho are as much as 8,000 ft above river level. The river has carved Hells Canyon between these mountains and the Blue Mountains of Oregon on the west. The Snake River forms the boundary between Idaho and Oregon until the river emerges from the deep canyons and mountains near the confluence with the Grande Ronde River where it flows in a much shallower canyon within a flat, lava-filled basin. A few miles further north at Lewiston, Idaho, where the Snake River is joined by the Clearwater River, the Snake River turns west and flows into Washington, through the Columbia Plateau, to its confluence with the Columbia River.

The exact boundaries of what is properly called "Hells Canyon" are unclear. The upstream reaches of the canyon are submerged by the reservoirs, and on the downstream end the river emerges from the canyon gradually near the mouth of the Grande Ronde River. In the context of this paper, Hells Canyon refers to the free-flowing reach of the Snake River between Hells Canyon Dam and the northern, or downstream, border of the Hells Canyon National Recreation Area (HCNRA). The HCNRA is administered by the Wallowa-Whitman National Forest of the U. S. Forest Service.

Study locations are referenced by distance upstream from the Snake/Columbia River confluence in accordance with the norm used by the U. S. Army Corps of Engineers (COE). The study reach begins at river-mi 247.6, Hells Canyon Dam, and ends at river-mi 188.4, the confluence of the Snake and Salmon Rivers. The study reach therefore extends approximately 60 mi downstream from Hells Canyon Dam (Figure 4).

Most of the rocks in Hells Canyon are of Permian or Triassic age, with minor amounts of Jurassic rocks. These rocks are slightly metamorphosed volcanic flows and volcaniclastic basalts of the Blue Mountain Island Arc group of accreted terranes (Vallier, 1987). There also exist several gabbroic and granitic plutons. The Miocene Columbia

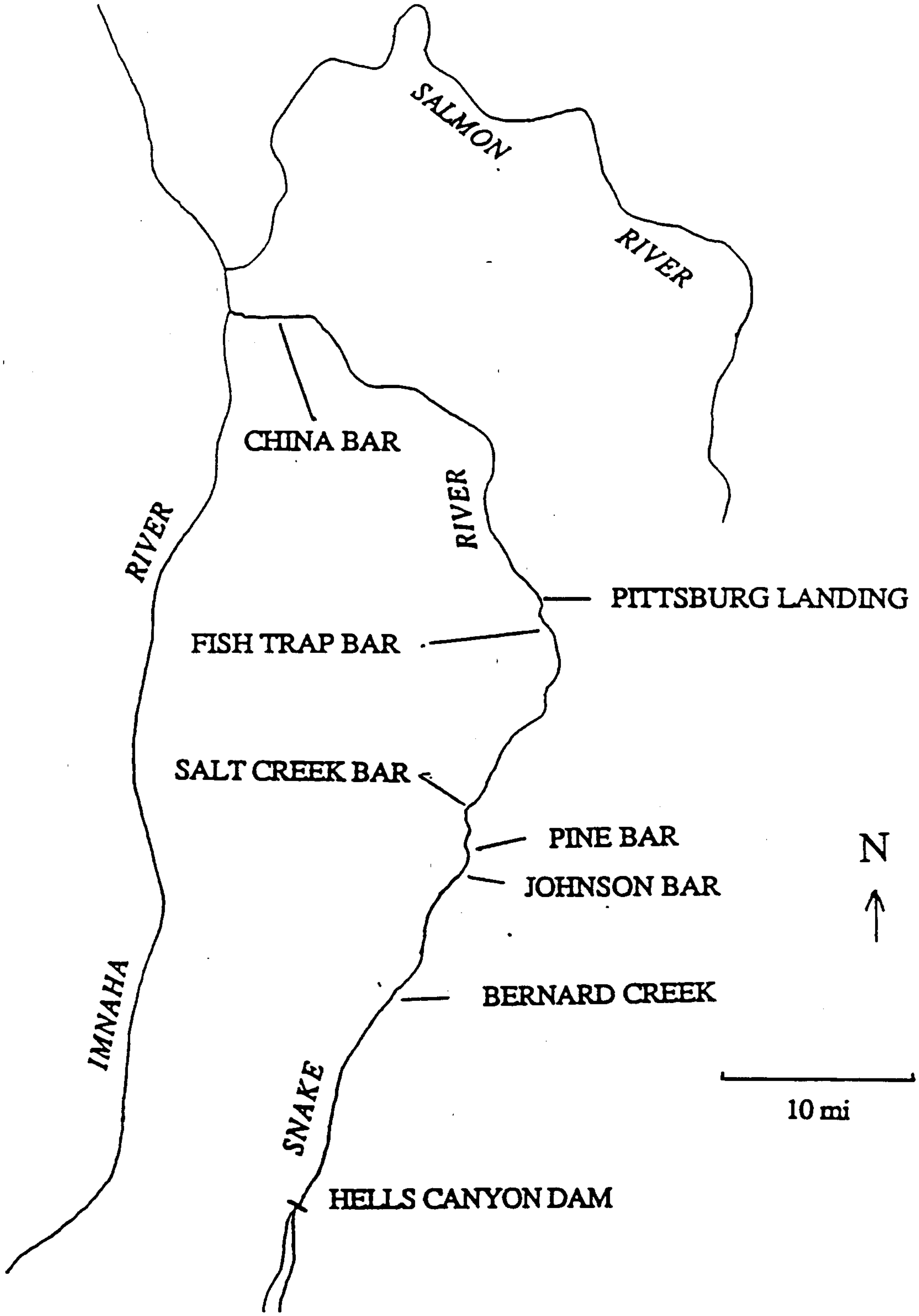


Figure 4. – The 60 mi reach of the Snake River between Hells Canyon Dam and the Salmon River Confluence showing the locations of detailed study sites.

River Basalt covers the older rocks in Hells Canyon. The most common rocks at river level are the Permian and Triassic formations. These rocks are generally erodible and form steep, talus-covered hillslopes. They are locally resistant, forming for very short reaches, steep-walled gorges. The Columbia basalt outcrops at river level occasionally in the northern part of the canyon. Large landslide deposits are common and have been found at several locations in Hells Canyon (Vallier, 1987).

Water from Glacial Lake Bonneville (ancestral Salt Lake) spilled over into the Snake River drainage at American Falls during the late Pleistocene. The resulting flood formed extensive terraces in Hells Canyon. Some of these terraces are as much as 400 ft above the present flood plain (Vallier, 1987). The terraces formed above large canyon constrictions where water pooled as it flooded the canyon. In addition to the Bonneville Flood terraces are frequent high flood terraces lower in elevation. These terraces often occur near sand bars, and are referred to in this report as high terraces.

Hydroelectric Dams

The three dams immediately above Hells Canyon are collectively referred to as the Hells Canyon Complex. All the dams of the Hells Canyon Complex were built and are currently operated by Idaho Power Company (IPCo) under license from the Federal Energy Regulatory Commission (FERC). The first completed and furthest upstream in the complex is Brownlee Dam, finished in 1958. It is also the largest with a storage capacity of 980,250 ac-ft. Oxbow Dam was completed shortly afterward in 1962 followed by Hells Canyon Dam in 1968. A summary of the filling dates and capacities of the Hells Canyon reservoirs is contained in table 1.

Additional dams were proposed in the vicinity of Pittsburg Landing and just upstream from the mouth of the Imnaha River. The site near the Imnaha, called the Wild Mountain Sheep site was approved by the FERC before public opposition resulted in the inclusion of the Hells Canyon reach of the Snake River in the National Wild and Scenic

Table 1. -- Project completion dates and storage capacities of the Hells Canyon Complex.

Dam	Began Filling Res.	Res. Filled By	Active Storage
Brownlee	May 1958	June 1959	980,250 ac-ft
Oxbow	February 1961	March 1961	5,420 ac-ft
Hells Canyon	October 1967	November 1967	98,820 ac-ft

(U.S. Department of Energy, BPA, 1985)

Rivers System in 1975. This designation requires that this portion of the Snake remain 'free-flowing' and establishes the area as a 'National Recreation Area.'

The river is used by recreational boaters and anglers. The many challenging rapids make the river attractive to white-water rafters who typically float the river from the launch at Hells Canyon Dam to either Pittsburg Landing, where there is road access, or to a landing just below the mouth of the Grande Ronde River. The float of the entire canyon typically takes about 6 days. Power boaters, both commercial and private, make daily sight-seeing and fishing cruises through Hells Canyon.

Rules Governing Operations of the Hells Canyon Complex

The total storage capacity of the Hells Canyon Complex of dams and reservoirs is 1,084,490 ac-ft. Ninety percent of this capacity is held by Brownlee Reservoir (DOE/BP, 1985). Brownlee, therefore, is the true regulating instrument of the flow through Hells Canyon and discharges from it are generally passed unchanged through Oxbow Dam and Hells Canyon Dam. Between 1966 and 1987 the average discharge at Snake River at Hells Canyon Dam was 16,193,000 ac-ft/yr, or 22,350 ft^3/s. The storage capacity of the Hells Canyon Complex is 7 percent of mean annual runoff. The low ratio of reservoir storage capacity to basin runoff for the Hells Canyon Complex, less than 0.26, indicates that these dams have relatively little ability to regulate floods because the reservoirs will either be full or will fill very rapidly. In contrast, the ratio of storage to mean annual runoff in the Colorado River at Glen Canyon Dam, which has a high degree of ability to regulate floods, is 2.32. Once the reservoirs of the Hells Canyon Complex are full, floods flowing into

Brownlee Reservoir will be passed directly through the system. An additional effect of regulation is that the flood hydrograph will taper off more rapidly after the peak then a typical flood-hydrograph. In other words, the peak flow will be released through, but once it has occurred, the flow will be restricted as soon as there is available reservoir storage.

IPCo operates the Hells Canyon Complex in accordance with four basic constraints: flood control, power generation, downstream minimum flows, and ramp rates. IPCo is required to drawdown the reservoirs each spring to a level determined by the COE as the necessary buffer to avoid extreme floods that would threaten river developments downstream. Reservoirs begin storing when the COE determines it necessary for flood control. The elevation that the COE requires in Brownlee Reservoir for flood control is determined by the flood control rule curve (DOE/BP, 1985). Typically, the reservoirs are full by July 1. Total volume of releases and mean annual discharge, however, are not affected because there are no diversions from any of the reservoirs.

The Hells Canyon Complex is a part of a regional power grid which connects IPCo's electrical system with other utilities in the Northwest. There are several factors related to this complex power network which IPCo must consider in determining the operations of the Hells Canyon hydro-electric facilities. Some of these factors are: projected demand for power from IPCo customers, water availability (projected flows and storage), the relative availability of IPCo's other power resources (coal-fired plants), and the market for power on the regional grid (either selling to or purchasing from other utilities). IPCo develops an annual operating plan which takes into account the above factors. Heavy power load periods are in the summer, during irrigation season, and in the winter. The Hells Canyon reservoirs are therefore operated to be at storage capacity by July 1 and are then drawn down considerably in the late summer. Refilling typically begins in October in preparation for the heavy winter loads.

The FERC license held by IPCo to operate the dams in the Hells Canyon region stipulates several downstream flow operating constraints. A minimum of 5,000 ft^3/s must be released below Hells Canyon Dam at all times and no less than 13,500 ft^3/s must reach Snake River at Lime Point, below the confluence with the Salmon River. A minimum of 8,400 ft^3/s must be maintained for at least 30 hrs each week for navigation purposes. During the summer boating months of July, August and September the power company must supply an additional 92 hrs/wk of 8,400 ft^3/s flows. The weekly average minimum must be no less than 5,850 ft^3/s. Downstream fluctuations must be minimized by not exceeding a ramping rate of 1 ft/hr as measured at the stage recorder at Johnson Bar. This is required to reduce adverse effects on navigation, and fish spawning and rearing. An incident during the spring of 1982 in which there was a rapid drawdown and refill of Brownlee Reservoir as a result of flood control requirements imposed on IPCo by the COE. This event precipitated IPCo to establish guidelines for rates of draft and refill of the reservoir. (DOE/BPA, 1985). These guidelines are summarized in table 2.

Table 2. -- Guidelines governing maximum ramping rates in Brownlee Reservoir.

Period	Refill (ft/day)	Drawdown (ft/day)
1-day	9.0	3.0
7-day	8.0	2.4
Continuous	6.0	1.8

4. METHODS

Hydrologic Analysis

The U. S. Geological Survey (USGS) continuous recording gage, "Snake River at Hells Canyon Dam", was installed in 1966. The record for the gage, "Snake River at Oxbow, Oregon" contains daily discharge data for the period 1926 - 1971. The 6-yr period of overlap allows use of standard streamflow extension techniques (Searcy, 1960).

Streamflow extension allows reconstruction of the record for the Hells Canyon Dam gage for the period 1926 - 1965. The correlation was used to determine daily flows, peak annual flows, and flow duration curves at Hells Canyon Dam. For the period 1958 - 1966 Snake River at Oxbow, Oregon, was relocated to Snake River below Pine Creek at Oxbow, Oregon. The two sites are very near one another and are treated as the same site.

Analysis of Sand Bars

Aerial Photographs and Sand Bar Frequency Analysis

Using aerial photography, sand bars were initially analyzed for frequency of occurrence. These methods require photographs of at least 1:24,000 scale. At larger scales the sand bars become less distinguishable. Table 3 summarizes the series of aerial photographs used.

Table 3. -- General information on aerial photographs.

Photography Date		Approximate Scale	Mean daily discharge at Hells Can Dam, in ft^3/s	Discharge variability for preceding 6 hrs, in ft^3/s [3]
1955[1]	8/20	1:20,000	10,900	500
	8/21		11,000	500
	9/3		10,800	250
	9/4		11,100	250
1964[1]	8/17	1:12,000	10,800	
	8/18		11,000	--
	8/24		10,300	--
	8/6/65		14,000	--
1970[1]	7/31	1:14,000	11,900	11,950 - 12,070
	8/10		10,300	10,106 - 10,736
	7/15/71		17,100	--
1973	3/22	1:12,000	18,000[2]	na
1973	3/23	1:12,000	12,000[2]	na
1973	3/24	1:12,000	7,700[2]	na
1973	3/25	1:12,000	5,000[2]	na
1977	9/9	1:12,000	5,310	4,870 - 5,000
1982	8/19	1:12,000	14,100	--

[1]Different reaches of the Snake River in Hells Canyon are covered on different dates.
[2]Photographs taken during steady flow conditions.
[3]Determined from continuous stage records provided by USGS-WRD, Idaho District.

Each photo series covers, at a minimum, the Snake River between Hells Canyon Dam and the Salmon River confluence. Hourly discharge information is reported for the photography dates for which it could be determined. The hourly discharge, or hourly flow variability, was determined from the continuous recording stage record for the 1970 and earlier photographs, and from hourly stage data for the 1977 photographs. Stage-wave travel time studies have been calculated for releases from Hells Canyon Dam (Bayha, 1974). A discharge of 7,700 ft^3/s was found to take 5.5 hrs to arrive at China Bar. At that velocity the stage-wave would take an additional 0.5 hr to reach the Salmon River confluence. Hourly variations were therefore determined for 6.0 hrs preceding the time of photography. Because only the 1977 photographs provide information concerning the time of day the photographs were taken, the instantaneous discharge estimates for the other years are based on the assumption that the photographs were taken at approximately 1200 hrs. The mean daily discharge in all instances where both daily and hourly data are available is a reasonable approximation for the flow at the time the photographs were taken. The March 1973 photography was repeated on four consecutive days during a controlled release study period. Discharge information is important because water level will affect the apparent area of exposed sand contained in a bar on the air photos.

All sand bars within the 60 mi study reach that were visible on the 1964 air photos were catalogued according to location and bar-type. The 1964 photograph series was chosen for the initial classification because it shows more detail than the 1955 series. The bar-type classification is dependant upon the sand bars' position in relation to local channel geometry, and the topographic form of the bar itself, consistent with the categories proposed by Schmidt and Graf (1990). Deposits classified as separation or reattachment bars are those that are located in a channel expansion and within assumed zones of recirculating flow. Their shape resembles a typical separation or reattachment bar, as described above. Channel margin bars are sand deposits that are not obviously associated with a recirculation zone below a constriction, and do not have a particularly distinctive form. A fourth category is cove-fill bars. These are areas of sand which fill a specific cavity or channel irregularity, often bedrock defined, along the river bank. They do not appear to be associated with large recirculation zones. However, the differences between cove-fill and channel margin bars is often ambiguous. These two types were therefore considered together in the bar type data analysis.

The sand bar frequency analysis was accomplished by counting the number of sand bars in each photo series including the 1955, 1964, 1973, 1977, and 1982 series. All locations which contained sand in the 1964 photos were relocated and examined closely for sand for each of the other years. In order to evaluate areal changes in sand bars it was necessary to calibrate the air photos with sand bars observed in the field.

Field Analysis of Sand Bars

Sand Bar Inventory

An inventory of sand bars was conducted in the field during summer 1990 using the above identification and classification system as a framework. Field work was accomplished on two river float trips, July 7 - 13, and July 20 - 25. The first trip began at Johnson Bar (river-mi 229.8) and ended at China Bar (river-mi 192.4). The second began at Pittsburg Landing (river-mi 214.9) and ended at the public landing below the mouth of the Grande Ronde River. Jet-boat transportation to Johnson Bar and from China Bar was provided by the U. S. Forest Service.

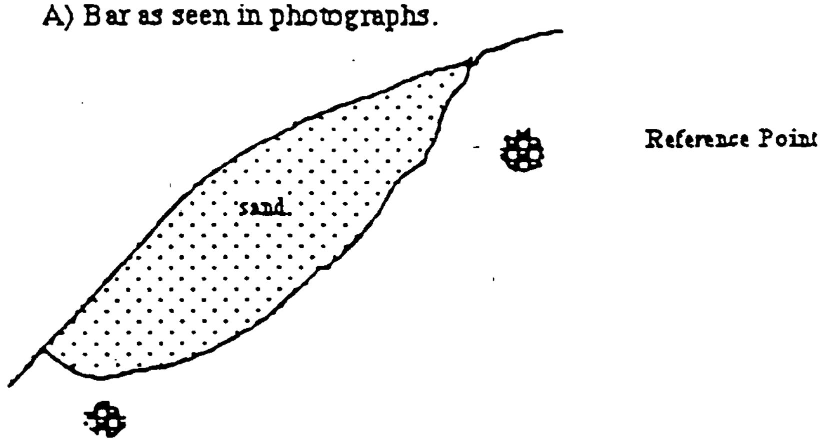
At 65 sites below Pittsburg Landing, the area covered by sand was measured in the field. Area of the bars as they appeared in the 1964 photographs was estimated by determining the extent of the beaches relative to landmarks easily recognizable both in the photographs and at the site (Figure 5). The estimated beach dimensions were then measured on the site.

Detailed Study Sites

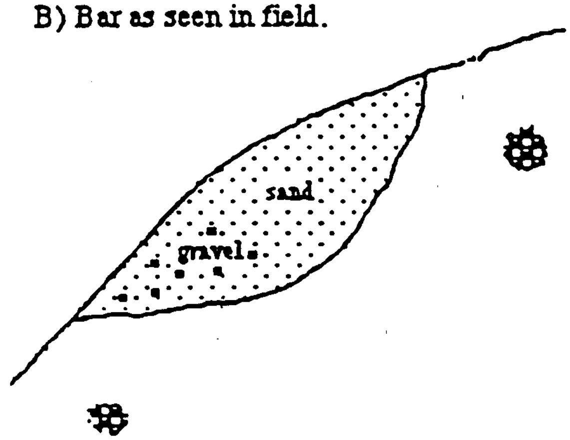
At three sites individual sand bar changes and characteristics were studied in greater detail. Topographic surveys were made using a laser theodolite. Permanent benchmarks

Figure 5. -- Determination of sand loss using stable reference points.

A) Bar as seen in photographs.



B) Bar as seen in field.



were established at each site which will allow future surveys to be conducted for the purpose of measuring changes in sand bar elevation. Significant bar-features mapped included: bar form, abutting debris fans and gravel bars, bedrock outcrops, the water line at time of survey, and other features, such as stable landmarks, identifiable on the aerial photos. At two of the detailed sites the bar sedimentology was assessed by digging shallow trenches which exposed the sand bars in cross-section. Maps of the surficial geology were made for the reaches including the detailed sites utilizing air-photography and field observations. Mapping units were river-deposited sand, river-deposited gravel, high flood terraces, Bonneville flood terraces, colluvium, debris fans, and bedrock.

Using stable reference points such as large rocks or trees, erosion of sand bars and high terraces over the past 35 yrs was measured at some of the detailed sites. Exact methods varied for each site and are discussed in more detail with the description of each site.

Areal Analysis Using Field Calibrated Aerial Photography

Following the field study, the aerial photos were reanalyzed in greater detail. Bars measured in the field were divided into five size classes: no sand cover, less than 10,000 ft^2, less than 20,000 ft^2, less than 30,000 ft^2., and less than 40,000 ft^2 Very few bars in Hells Canyon are larger than 40,000 ft^2.

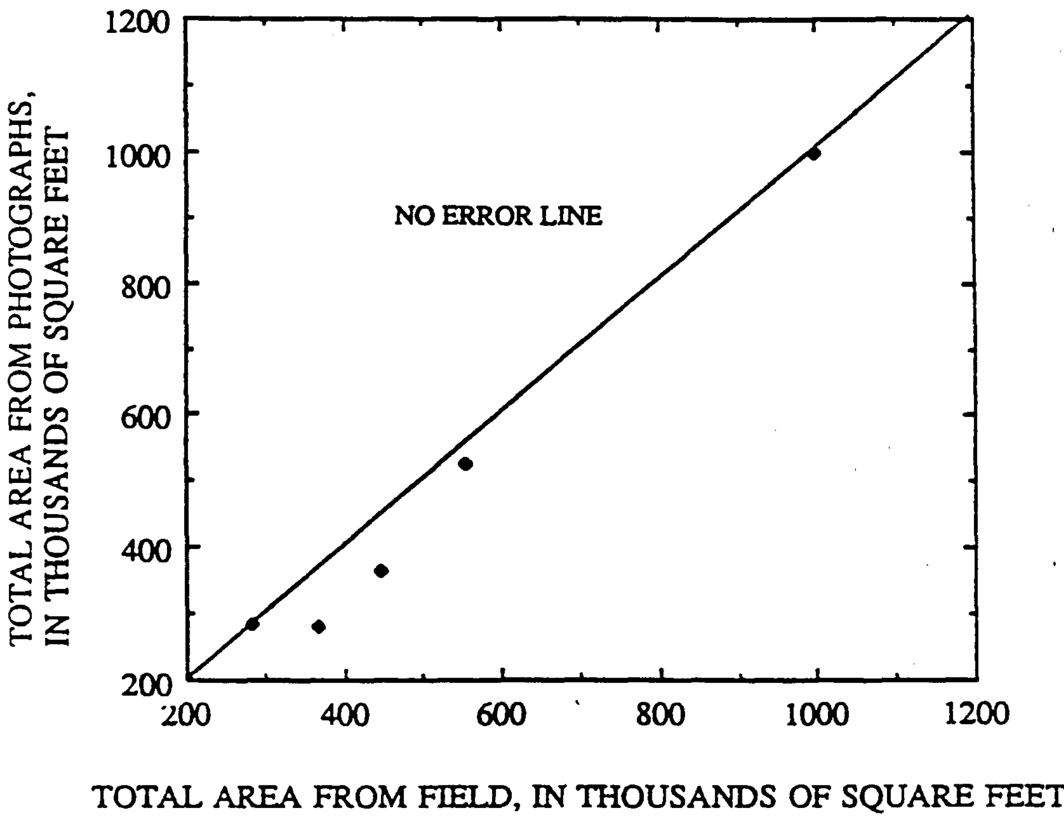
Representative bars of each size class were selected and traced from the 1964 photographs. The scale difference between the different photo series was determined on a stereo-zoom transfer scope. Scale was then adjusted by enlarging the bar traces by the correct amount for each photo series on the stereo-zoom transfer scope. With a separate legend of bar size classes for each photo series all sand bars identified in the 1964 photos were relocated and sized on each of the photos including the 1964, 1973, 1977, and 1982 series. For statistical purposes, the sand bars of each size class were given values for the midpoint of each size class (5,000 ft^2, 15,000 ft^2, 25,000 ft^2, and 35,000 ft^2). The large scale of the 1955 photographs does not permit this type of detailed analysis. Therefore, the

1955 photographs, which would best represent the initial condition of sand bars are used only in the analysis of detailed sites and the sand bar frequency analysis. The frequency analysis, however, revealed bar exposure to be very similar in 1955 and 1964. Therefore, the condition of the sand bars in the 1964 photographs is considered the initial condition in the areal analysis.

Difficulties with the air photography analysis included: (1) differentiating between sand and gravel in some photographs (18 of 125 bars classified as being devoid of sand in the 1982 photographs actually contained sand in the field, which results in an error of 14.4 percent in sand bar frequency); (2) error due to different river stage, and (3) error in accurately transferring scales on the zoom transfer scope.

The data from aerial photography analysis were therefore corrected in accordance with the 1990 field data. Based on comparing air-photos with field observations there was no evidence to suggest bars aggraded during the 1982 - 1990 interval, therefore bars which had been classified as empty of sand based on the 1982 photographs but were found to contain sand in the field were assigned to the same size category to which they belonged in 1990. In some cases values were interpolated between the 1990 size category and the bars size in earlier photographs. This correction was made only for the reach below Pittsburg Landing. Figure 6 shows the degree of difference between the total area of sand below Pittsburg Landing as determined solely from the aerial photographs and the total area as determined from the field data. Thus, air photo analysis tends to slightly underestimate bar size for small bars.

Figure 6. -- Disagreement between area of sand deposits as determined from field analysis and as determined from photo analysis.



5. RESULTS

Streamflow Data in Hells Canyon

The three dams and reservoirs of the Hells Canyon Complex have had only slight effect upon the general flow characteristics of the Snake River in Hells Canyon. This section describes historic streamflow in Hells Canyon and draws a comparison between streamflow conditions, pre- and post-regulation.

Extension of Streamflow Record of Snake River at Hells Canyon Dam

Streamflow at Oxbow, Oregon, was correlated with streamflow at Hells Canyon Dam to allow extension of the gauging record at Hells Canyon into the pre-dam era. Figure 7A is a scatter-plot of mean daily discharge at Hells Canyon Dam and corresponding mean daily discharge at Oxbow, Oregon, over the 6-yr period of overlapping record. Two outliers were removed and the best-fit linear relationship was determined by least squares regression.

The equation resulting from this correlation is:

$$Q_{HCD} = 1.073\, Q_O - 349$$

where: Q_{HCD} = daily discharge at Hells Canyon Dam, in ft^3/s.
Q_O = mean daily discharge at Oxbow, Oregon, in ft^3/s.

The correlation coefficient of this relation is 0.97. In a plot of residual *vs* predicted values points cluster around zero and scatter randomly outward (Figure 7B). This shows that there is no systematic error in this regression relation. Figure 7B also shows that at low flows up to 25,000 ft^3/s the predicted streamflows are typically accurate to ± 2,000 ft^3/s. At discharges greater than 25,000 ft^3/s predicted streamflows are accurate to ± 5,000 ft^3/s. Figure 8 is a plot of mean daily discharge at Hells Canyon Dam and at Oxbow, Oregon for a year typical in the 6-yr overlap period. It shows that the flow at Hells Canyon Dam is consistently greater than flow at Oxbow, Oregon, as would be expected for a downstream station. Daily discharge values for Snake River at Hells Canyon Dam for the years 1926 - 1965 were calculated using the regression equation. Peak annual

Figure 7A.--Correspon g mean daily discharges, Snake River Iells Canyon Dam and Snake River at Oxbow, Oregon from 1966 to 1971. The best-fit line is described by the equation: Q(HCD) = 1.07 Q(OX) - 349.

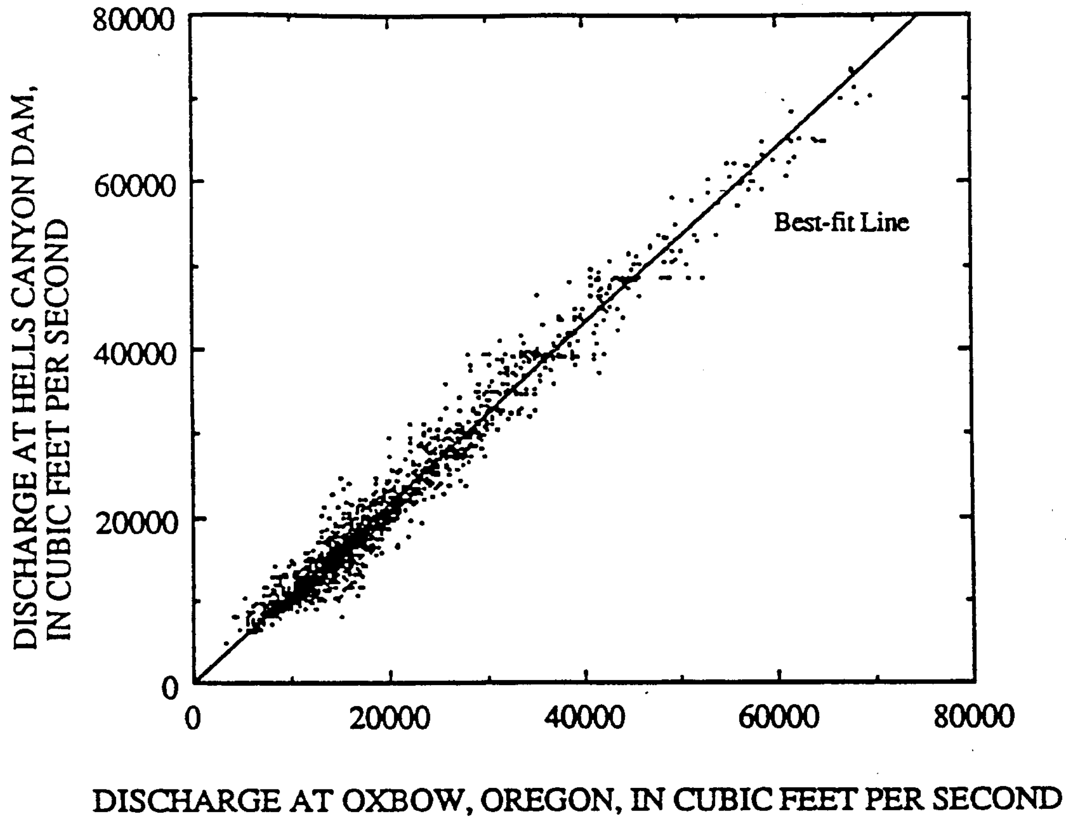


Figure 7B. -- Plot of residual vs. predicted dischages from regression equation.

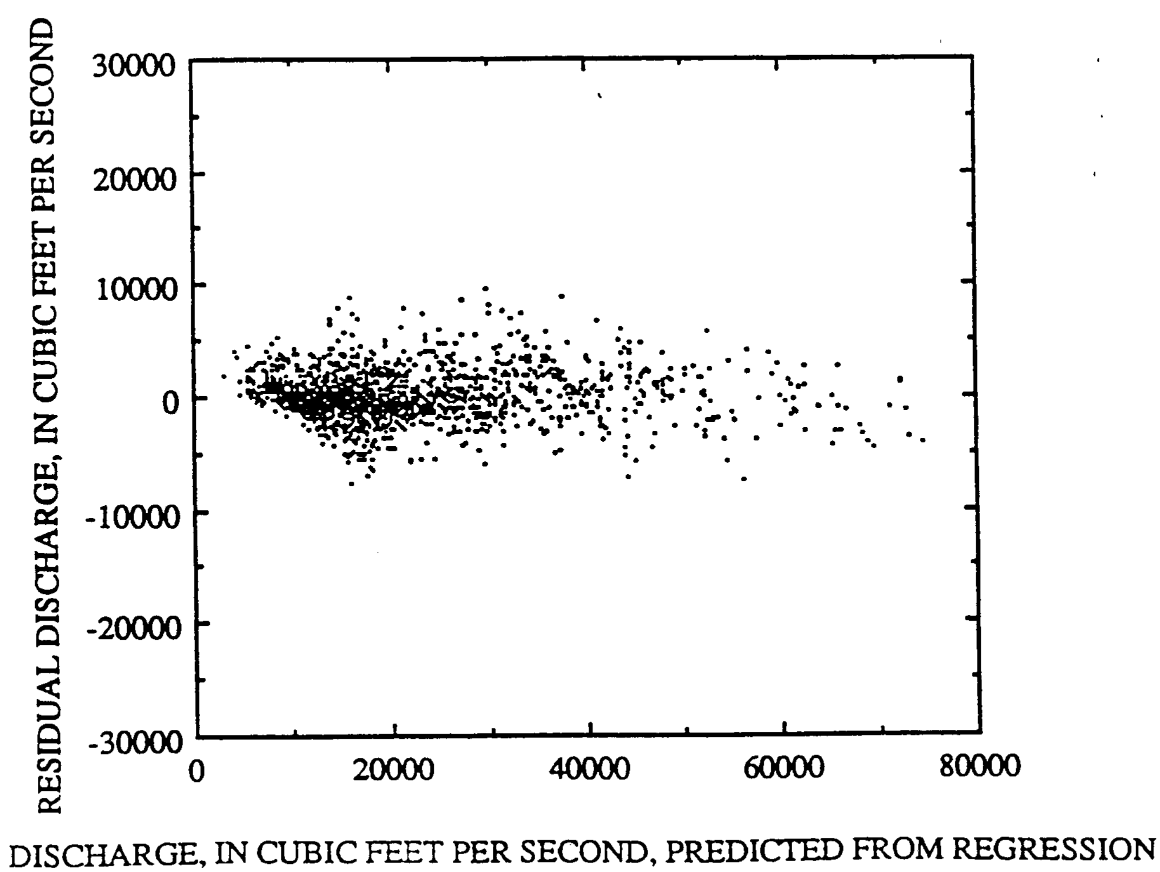


Figure 8. -- Mean d... discharge, Snake River at Hells Cany... Dam and Snake River at Oxbow, Oregon for water year 1968

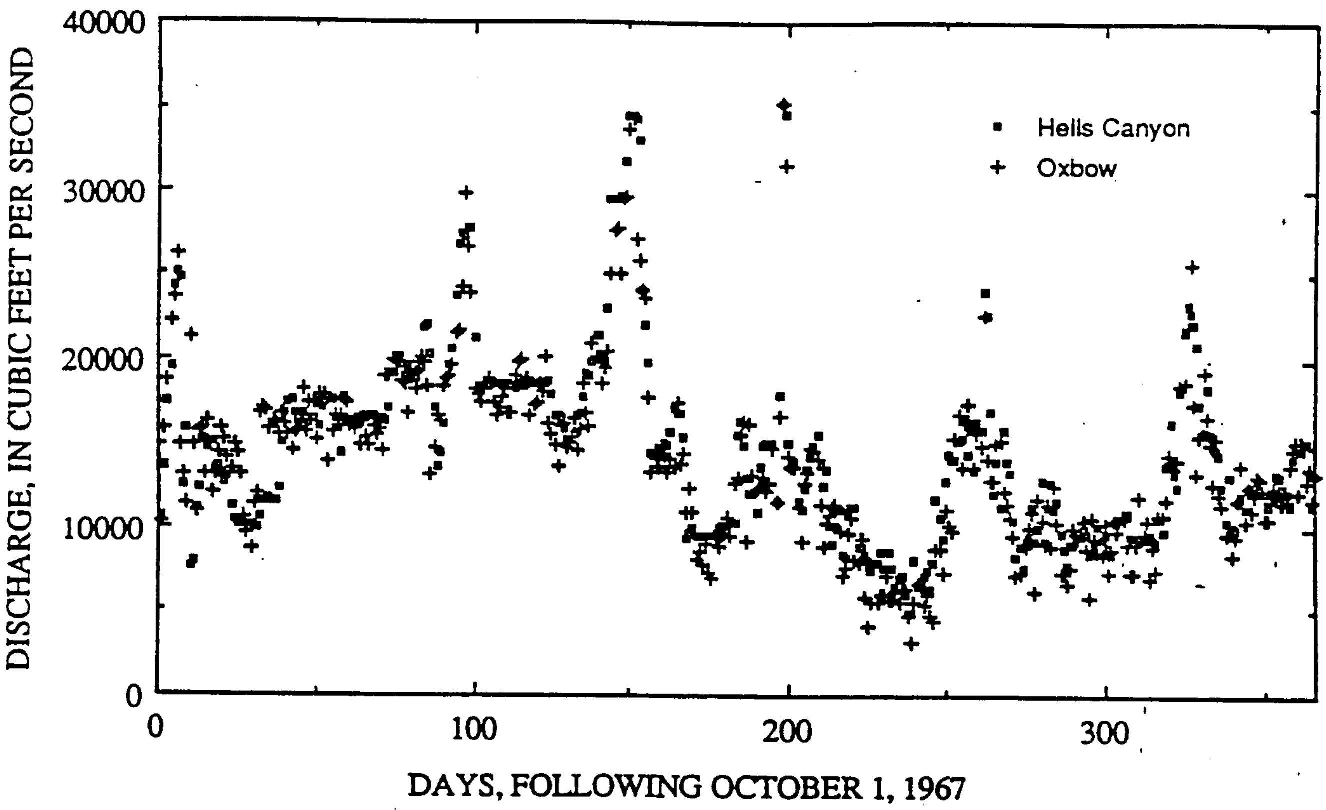
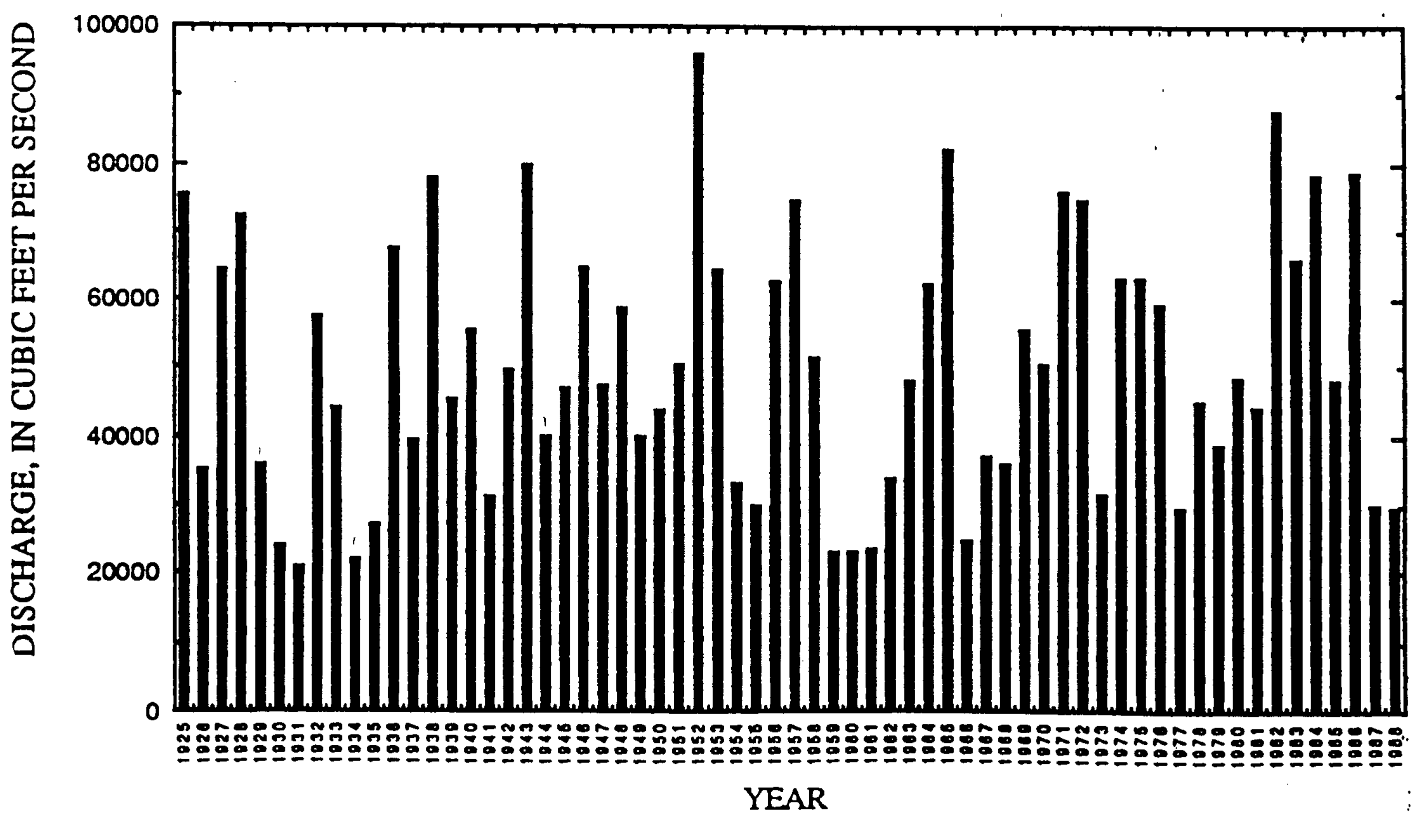


Figure 9. -- Annual maximum discharge, Snake River at Hells Canyon Dam, 1925 - 1988



Peak flood recurrence intervals pre- and post-Brownlee Reservoir are very similar, as shown in Figure 10, and are approximately the same as the flood recurrence interval for the entire record. For example, the pre-reservoir 10-yr flood is 75,000 ft^3/s and the post-reservoir 10-yr flood is about 78,000 ft^3/s. The 10-yr flood for the entire record is also 78,000 ft^3/s. The mean annual flood, that with a recurrence interval of 2.3 years, is about 50,000 ft^3/s in both time intervals.

Yearly Flow Distribution

Comparisons of annual hydrographs taken from representative years pre- and post-Brownlee Reservoir suggest that the dams of Hells Canyon have not had large impact on the yearly flow distribution. Figure 11 compares the annual hydrographs for two years in which the peak flow approximated the mean annual flood for the entire record (A and B), and for two years in which the peak flow was about 80,000 ft^3/s, the flow with a recurrence interval of 20 yrs (C and D). In both pre-reservoir hydrographs there are two distinct peaks, likely associated with snowmelt originating in different parts of the drainage basin. In the post-reservoir hydrographs the yearly spring flood covers approximately the same time-span as the pre-reservoir flood but is not as clearly split into two separate peaks. Another effect of regulation is the removal of the spikes of the peak flows, especially at about the 30,000 ft^3/s level, which is on the upper-end of the range of power plant capacity at Hells Canyon Dam. During a flood, flow is held at the upper level of power plant capacity as long as possible, to avoid spilling water in an effort to store it for future power generation. Although the distribution of daily flows over one year under dam operations are very similar to pre-reservoir conditions, variations on a weekly or daily basis are greater. These variations are probably caused by: (1) diurnal fluctuations in demand for electricity; (2) high power plant output on week-days and low power plant output on week-ends; (3) the minimum flows which are required to be met only a certain number of hrs/wk for navigation purposes (discussed in "Rules Governing Operations of Hells Canyon Complex"). The weekly fluctuations are evidenced by the several small

Figure 10. -- Maximum flow recurrence interval, Snake River at Hells Canyon Dam, 1923 - 1988.

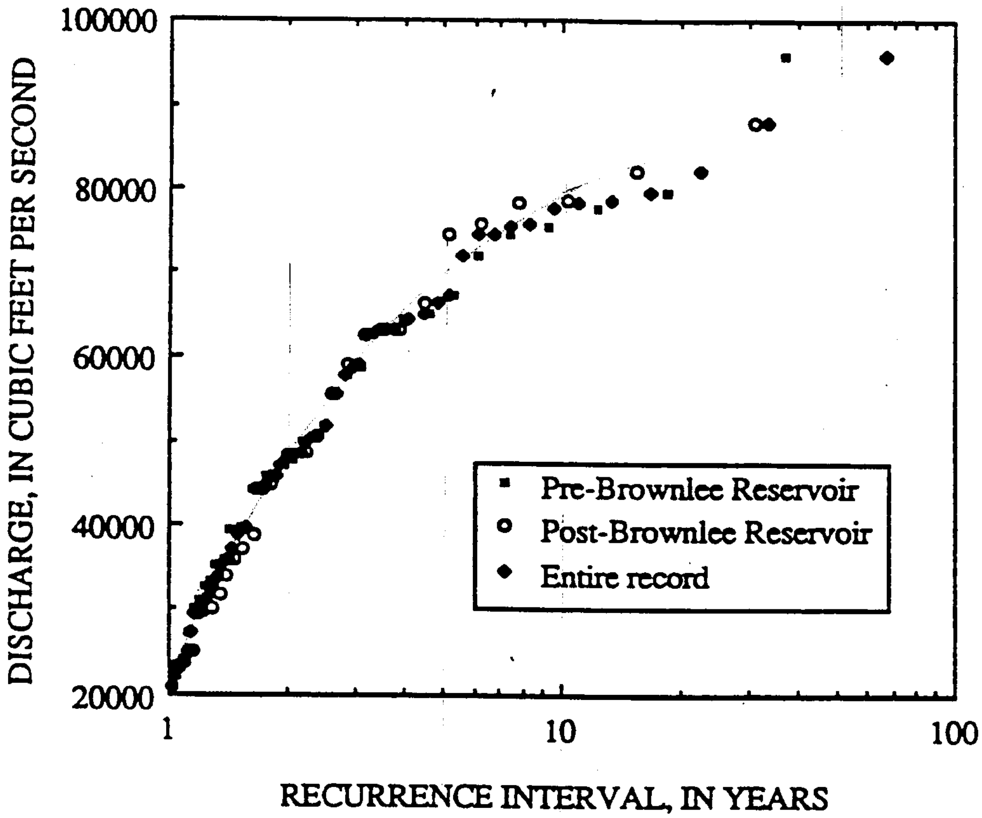


Figure 11 A. -- Mean daily discharge, Snake River at Hells Canyon Dam, water year 1942.

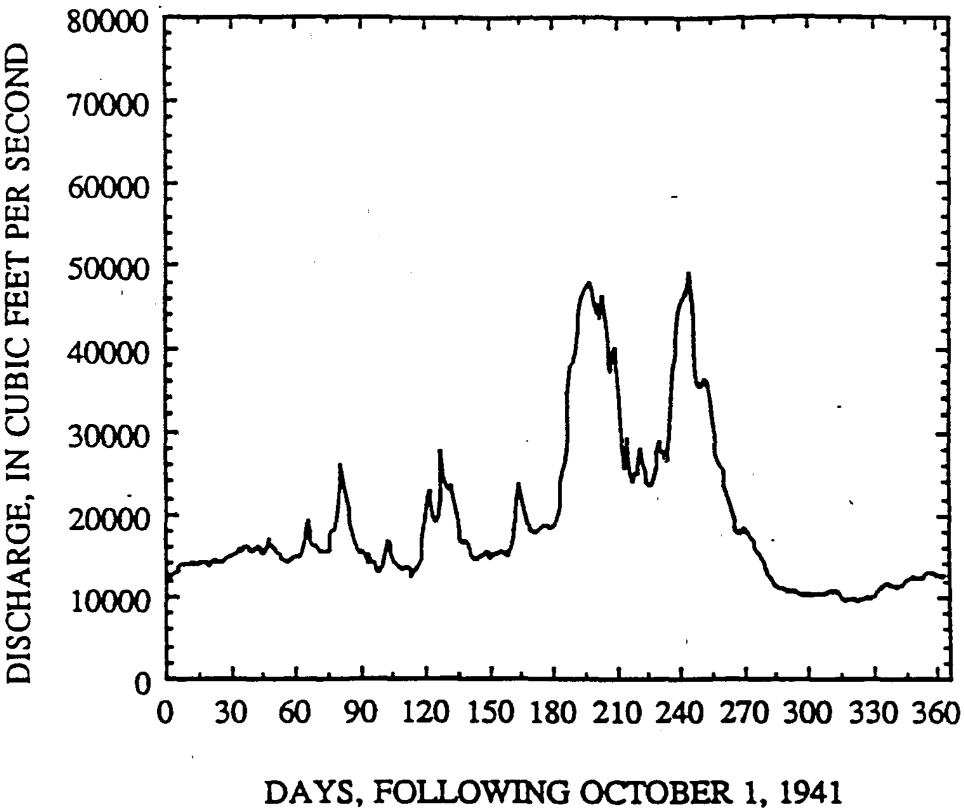


Figure 11 B. -- Mean daily discharge, Snake River at Hells Canyon Dam, water year 1980.

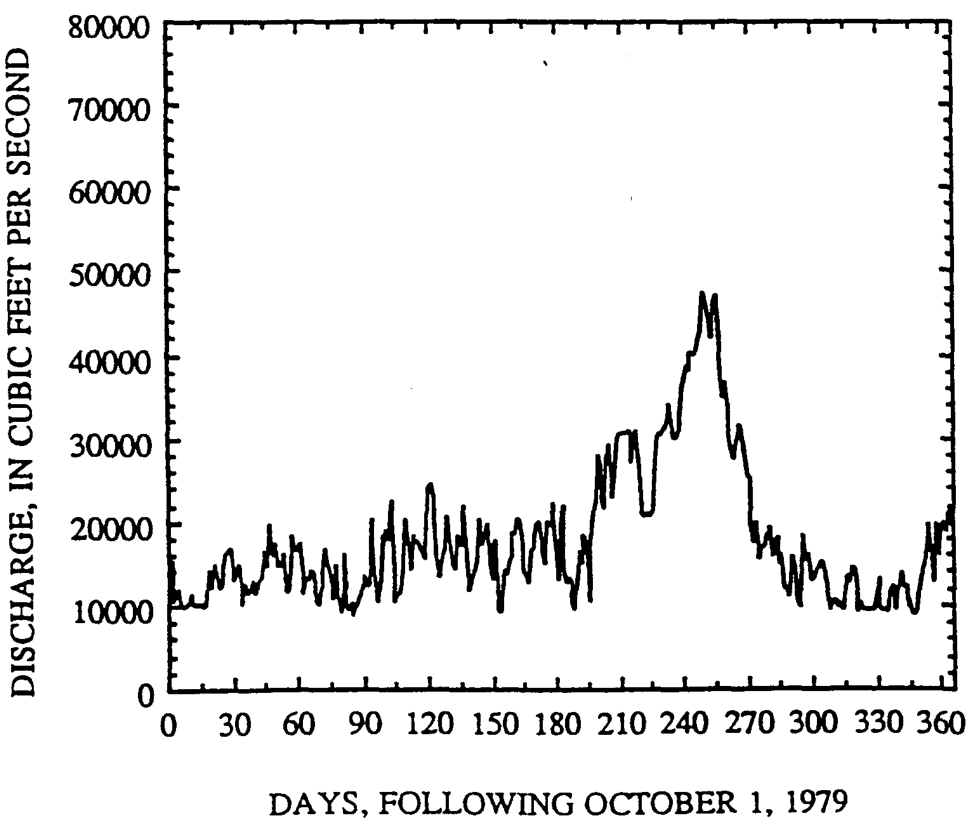


Figure 11 C. -- Mean daily discharge, Snake River at Hells Canyon Dam, water year 1943.

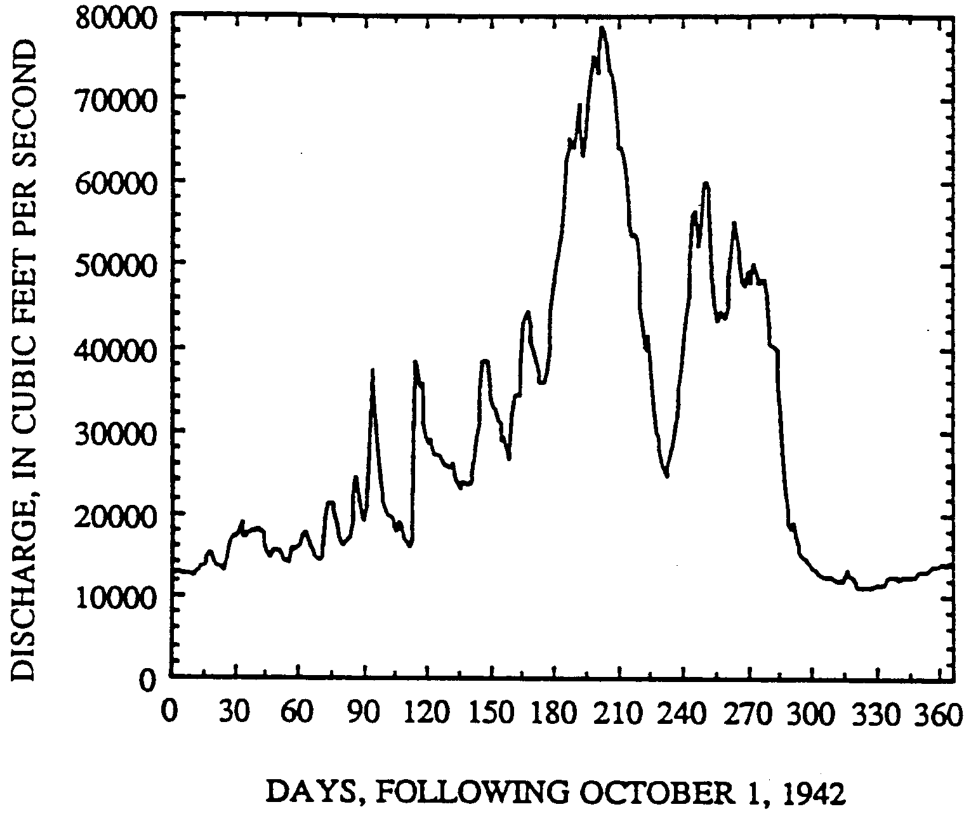
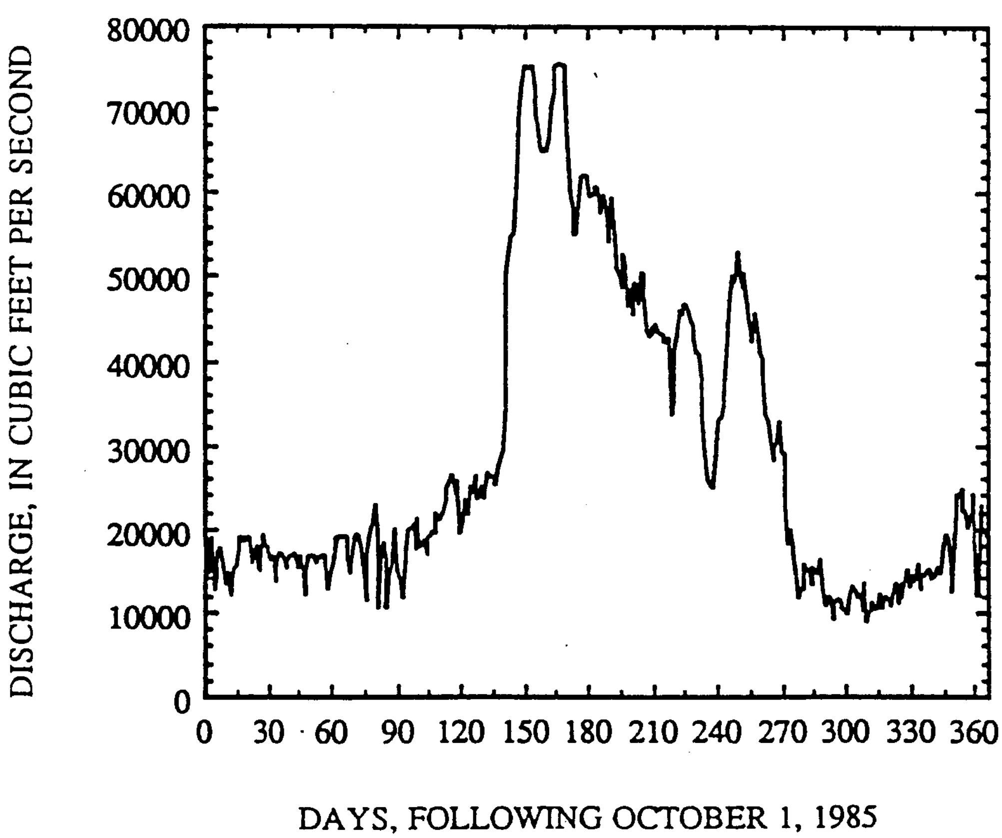


Figure 11 D. -- Mean daily discharge, Snake River at Hells Canyon Dam, water year 1986.



peaks. Another effect of regulation is the removal of the spikes of the peak flows, especially at about the 30,000 ft^3/s level, which is on the upper-end of the range of power plant capacity at Hells Canyon Dam. During a flood, flow is held at the upper level of power plant capacity as long as possible, to avoid spilling water in an effort to store it for future power generation. Although the distribution of daily flows over one year under dam operations are very similar to pre-reservoir conditions, variations on a weekly or daily basis are greater. These variations are probably caused by: (1) diurnal fluctuations in demand for electricity; (2) high power plant output on week-days and low power plant output on week-ends; (3) the minimum flows which are required to be met only a certain number of hrs/wk for navigation purposes (discussed in "Rules Governing Operations of Hells Canyon Complex"). The weekly fluctuations are evidenced by the several small spikes and troughs on the post-reservoir hydrographs where the pre-reservoir hydrographs follow a smoother line.

Flow duration curves show the distribution of mean daily flows over a given time interval. They show the percentage of time (on horizontal axis) discharges of given magnitudes (on vertical scale) are equalled or exceeded during the given time interval. Thus, the pre- and post-Brownlee Reservoir flow duration curves are compiled from mean daily discharge values for every day in each of the periods. Curves representing different periods may be better compared by normalizing for the amount of total runoff. This is done by dividing the discharge for each duration by the average discharge for the given time period. A more complete discussion of flow duration curves may be found in Searcy (1959).

Figure 12 contains flow duration curves comparing the periods, pre- and post-Brownlee Reservoir. The post-reservoir curve is uniformly higher indicating that for this period there is more water in the system. For example, the flow exceeded 20 percent of the time is about 24,000 ft^3/s pre-regulation and about 30,000 ft^3/s post-regulation (Figure 12 A). However, if these curves are normalized for varying mean annual flows, one sees that

Figure 12 A. -- Flow duration curves, pre- and post-Brownlee Reservoir.

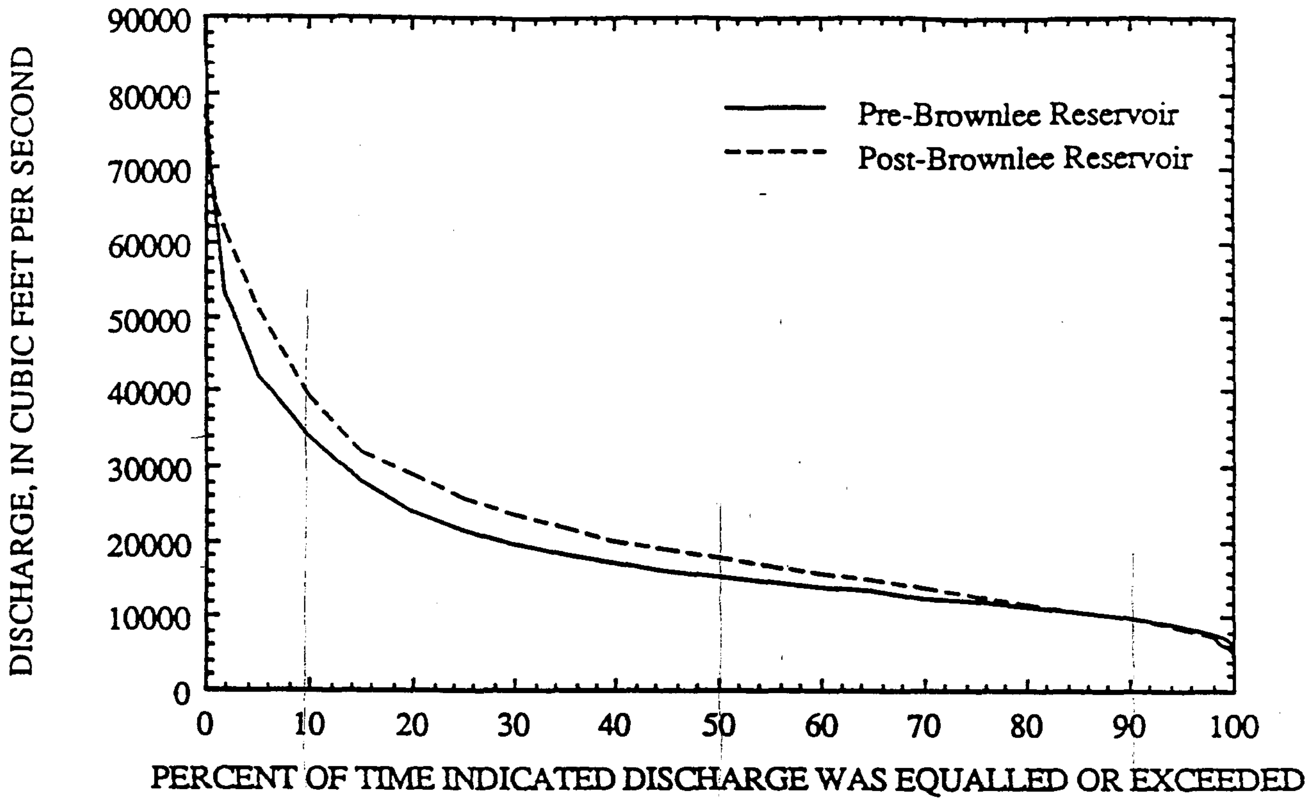
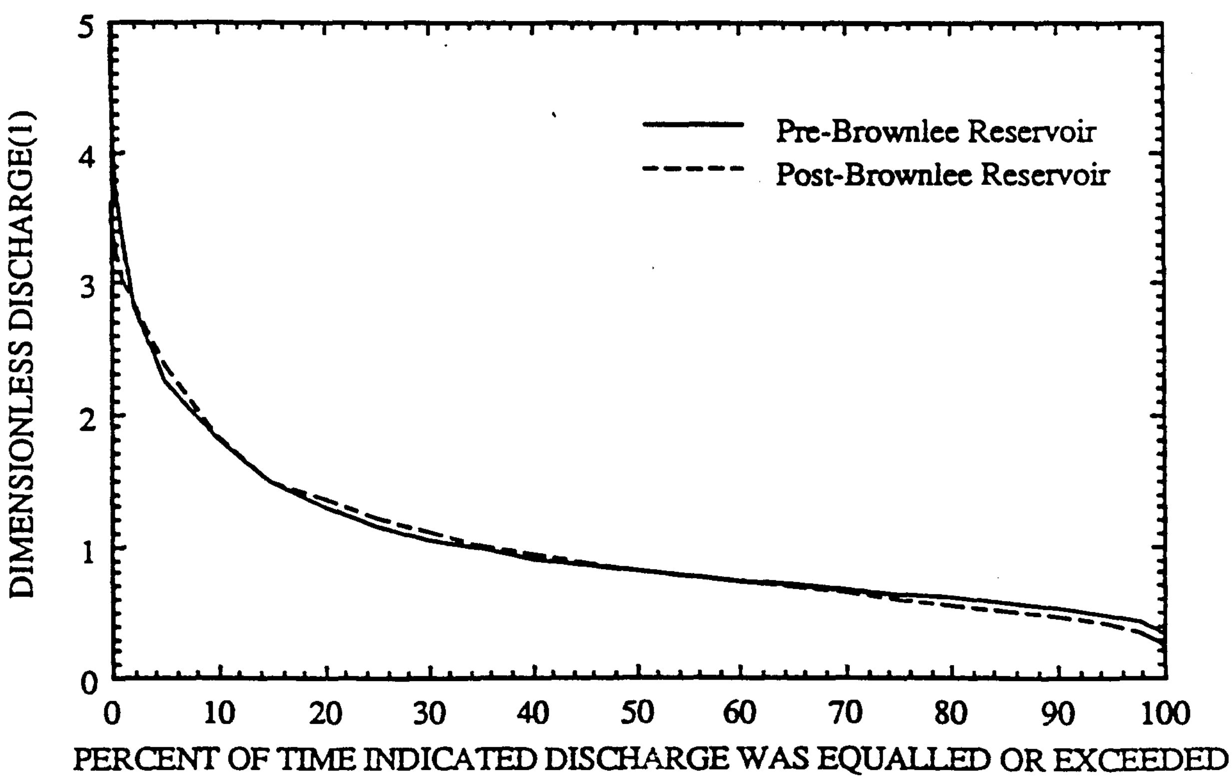


Figure 12 B. -- Unitless flow duration curves, pre- and post-Brownlee Reservoir.



(1) Calculated by dividing discharge for indicated duration by mean discharge for the given period.

there has been little change in the shape of the the duration curves (Figure 12 B). Small differences are, however, apparent at the extreme ends of the duration scale.

The highest peak flows were slightly higher in the pre-reservoir period. Discharges 3.0 times the mean annual discharge were exceeded 1.7 percent of the time pre-reservoir and 1.0 percent of the time post-reservoir. These changes demonstrate a slight role of the complex in controlling the duration of floods in the drainage basin. On the low-end of the scale the flow that was exceeded 90 percent of the time was 0.51 times mean annual discharge pre-reservoir and 0.45 times mean annual discharge post-reservoir. These changes in duration of low flows are likely related to operation of the dam for hydroelectric power generation. Discharges for other durations are listed in table 4. Thus, while regulation has not significantly changed the shape of the flow duration curves, it has effectively lowered both the highest and the lowest flows.

Table 4. -- Flow-duration characteristics pre- and post-Brownlee Reservoir.

	Dimensionless Discharge for Indicated Duration[1]			
	High Flows		Low Flows	
Interval	1.0 percent	5.0 percent	95.0 percent	99.0 percent
Pre-Brownlee Res.	3.35	2.24	0.45	0.38
Post-Brownlee Res.	3.05	2.37	0.39	0.28

[1]Dimensionless discharge calculated by dividing discharge for indicated duration by the average flow for the given period.

The discharge data were also analyzed to describe flow conditions for the intervals which bracket years of air-photo coverage (Figures 13 A and B). The shapes of the duration curves using dimensionless discharge units, pre- and post-regulation, are very similar. There are small differences at the upper- and lower-ends of the duration scale. The first two time intervals are marked by higher peaks and also higher low flows than the subsequent intervals. This corresponds to the simple pre- and post-Brownlee Reservoir values discussed above.

Figure 13 A. -- Flow duration curves during intervals between aerial photography.

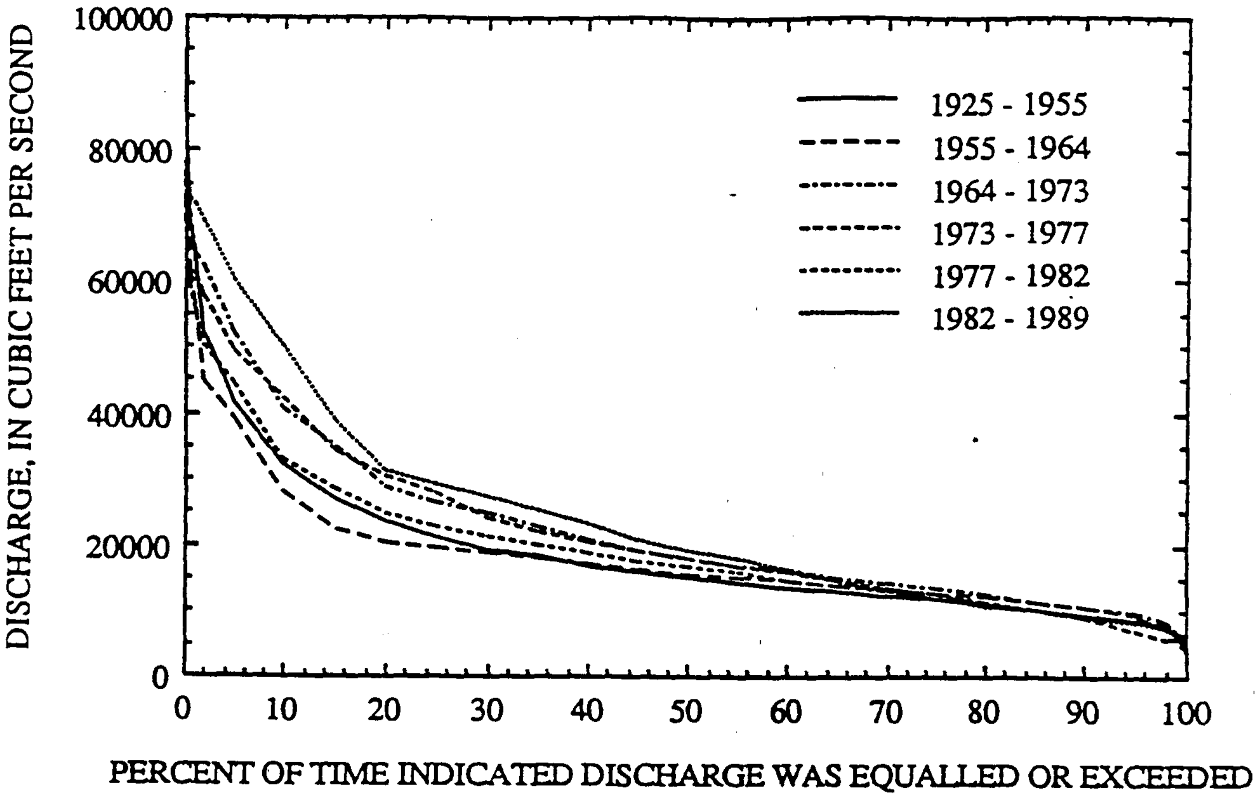
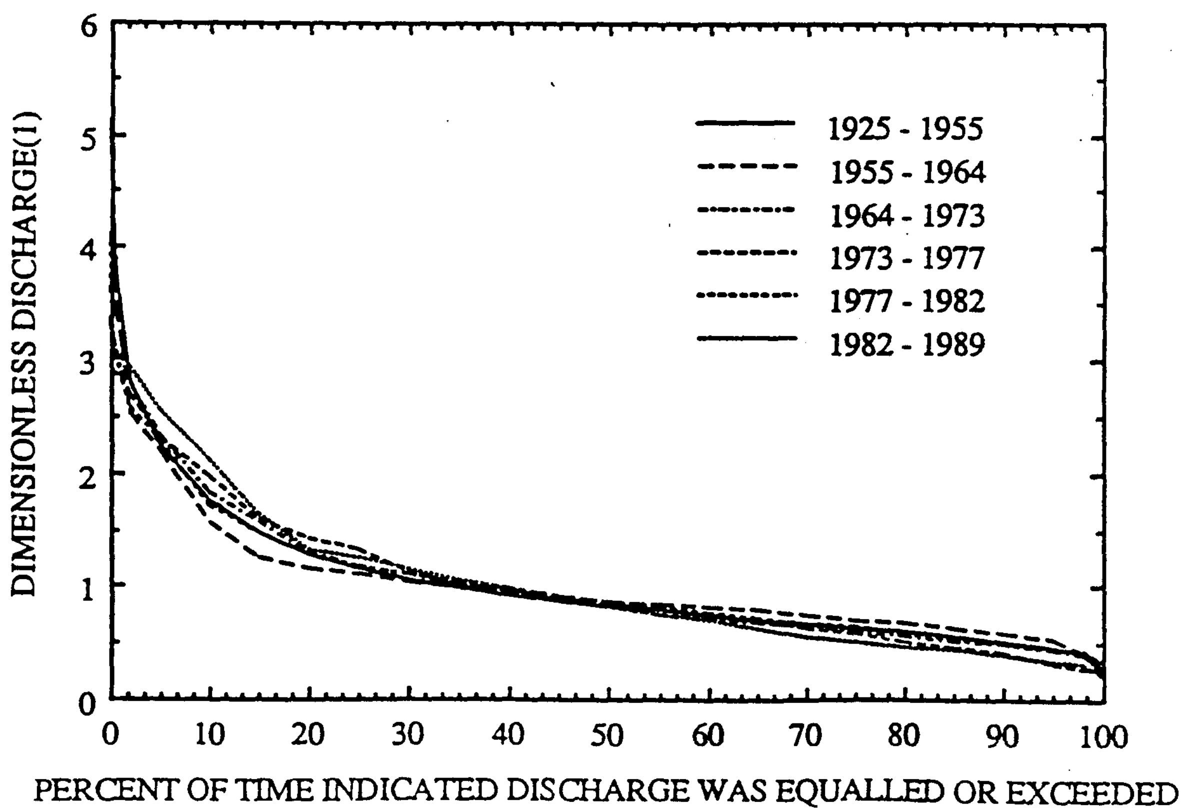


Figure 13 B. -- Unitless flow duration curves during intervals between aerial photography.



(1) Calculated by dividing discharge for indicated duration by mean discharge for the given period.

Figures 14 and 15 show the number of days per year discharges of 30,000; 40,000; 50,000; 60,000; and 70,000 ft^3/s were equalled or exceeded. Figure 14 covers the intervals between aerial photography dates and Figure 15 covers each year between 1966 and 1987. As the flow duration curves illustrated, between 1964 and 1977 water was relatively abundant and high flows were more frequent, though there were also years of low flow. For example, discharges in excess of 40,000 ft^3/s were attained for 70 dys/yr and 60 dys/yr in the periods 1964 - 1973 and 1973 - 1977, respectively. But in the periods 1926 - 1955 and 1955 - 1964 the same flow levels were attained for only 34 dys/yr and 24 dys/yr The 1977 - 1982 interval is similar to the first two intervals; less water was in the system and high flows were relatively infrequent. During the final interval, 1982 - 1989, there was significantly more water and high discharges were reached for a greater number of days. For example, the 40,000 ft^3/s or greater flow was reached 111 dys/yr in this period.

Summary of Hydrologic Changes

The three dams of the Hells Canyon Complex have had a minor impact on the yearly distribution of streamflow in the Snake River in Hells Canyon. The flow duration curves are essentially the same pre- and post-regulation, however the post-regulation period is characterized by relatively more water, due presumably to climatic differences. While very large floods still occur, regulation has reduced the duration of flood peaks. Weekly variations in flow, caused by regulation, are also visible on the annual hydrograph. These variations may result in lower low flows. There also occur daily fluctuations in flow which do not appear on the annual hydrograph. Critical flow events in the intervals between air-photography are summarized in table 6.

Figure 14. -- Daily flow exceedence during intervals between aerial photography, Snake River at Hells Canyon Dam, 1926-1989.

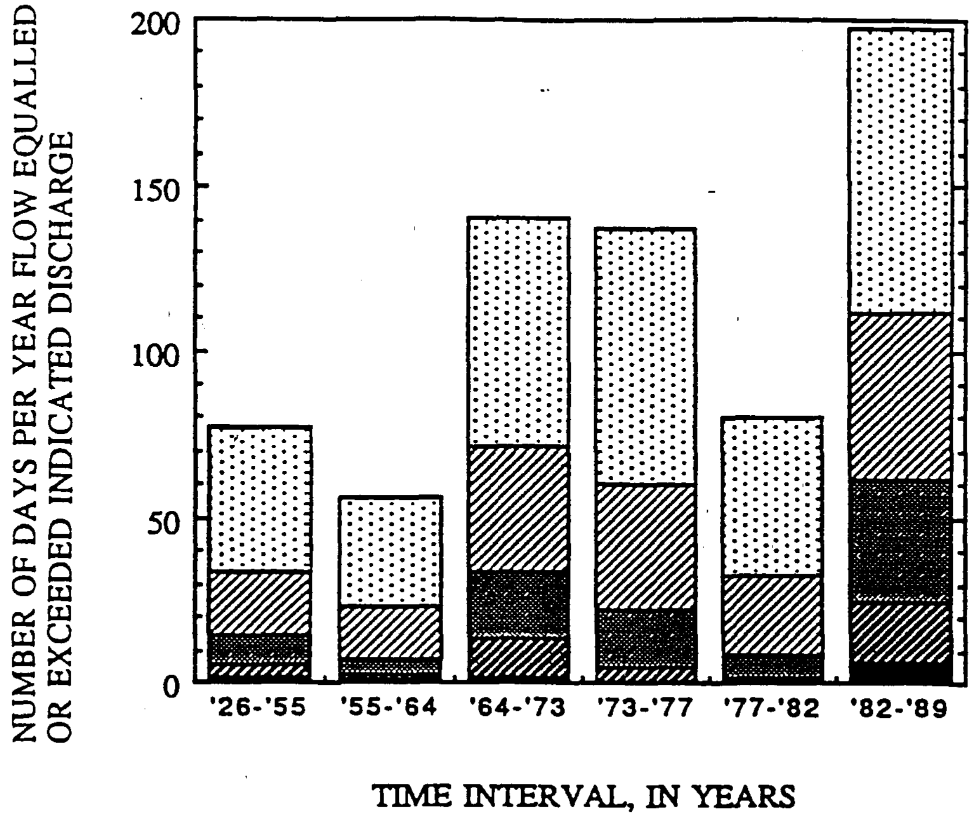


Figure 15. -- Daily flow exceedence for each year, 1966 - 1987.

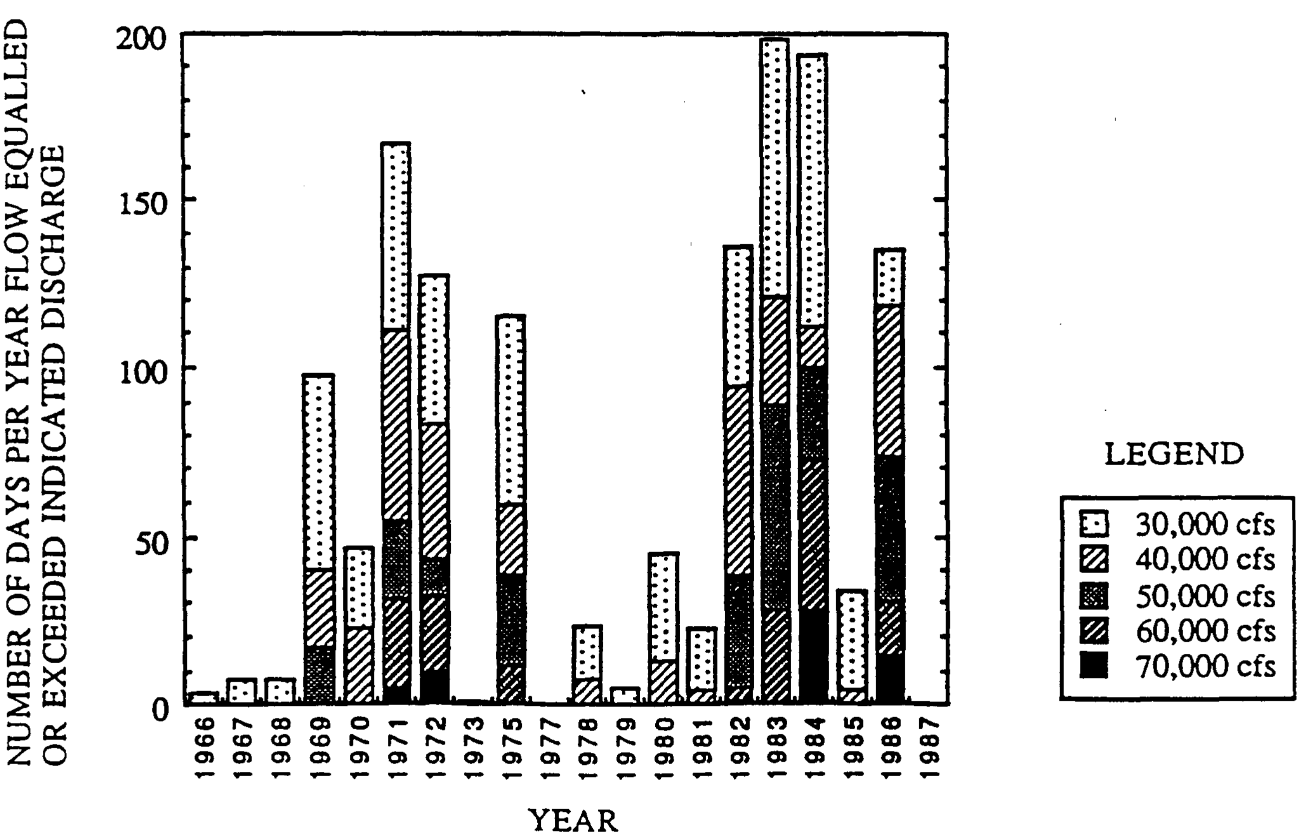


Table 5. – Critical flow events during intervals between aerial photography.

Interval[1]	Three highest peak annual flows and year in which they occurred			Tenth percentile flow
	First	Second	Third	
1925 - 1955	95,900 1952	79,700 1943	77,800 1938	32,000
1955 - 1964	74,600 1957	62,900 1956	62,500 1964	28,000
1964 - 1970	82,100 1965	55,600 1969	50,600 1970	41,000 (for 1964-1973)
1970 - 1973	75,800 1971	74,700 1970	---	
1973 - 1977	63,300 1974	63,200 1975	59,200 1976	43,000
1977 - 1982	87,800 1982	48,600 1980	44,900 1978	33,000
1982 - 1988	78,600 1986	78,400 1984	66,200 1983	50,000

[1]All air-photos were taken following the peak flow of that year, except those taken in 1973.
[2]That discharge equalled or exceeded 10 percent of the time.

Sand-Bar Characteristics and Change

Observations made during summer 1990 confirmed that there exist sand bars in Hells Canyon similar to sand bars previously identified along other bedrock rivers. Separation and reattachment bars similar in form to those common in the Grand Canyon were frequently recognized in Hells Canyon. In Hells Canyon separation and reattachment bars typically form in channel expansions below constrictions created by small tributary fans which extend into the main channel of the Snake River. Less commonly these constrictions are formed by bedrock outcrops extending into the channel. Sedimentologic analysis of reattachment bars revealed characteristics similar to typical reattachment bars.

Detailed Study Sites

Pine Bar

Pine Bar is a large sand bar located at river-mi 227.5, below the mouth of Willow Creek. A channel constriction is formed by a bedrock outcrop that projects into the channel upstream of the bar, and a debris fan, upstream of the bedrock outcrop. The channel expansion which contains the bar is located on the outside of a gentle bend in the river. Figure 16 is a surficial geologic map of the reach showing significant features. By form and location, Pine Bar was classified as a reattachment bar. It contains a distinctive eddy return channel, which is best visible in Figure 17 A and B at the upstream end of the bar where the return channel rejoins the main current, and in the photograph, Figure 18, between the bank and the isolated island of sand. The entire return channel is visible in Figure 17 E, F, and G where the channel separates the bar-crest from the bank. The two large boulders, or bedrock islands, (point A in Figure 16) in the center-right of the channel create turbulence which is likely responsible for the 'half-moon' shape of the bar. Figure 18 is a photograph of the bar taken in July, 1990. As visible in the oblique-photograph (Figure 19) the crest of the present bar as viewed at 6,900 ft^3/s is detached from the bank and consists predominantly of gravel, and mixed sand and gravel. The bottom of the

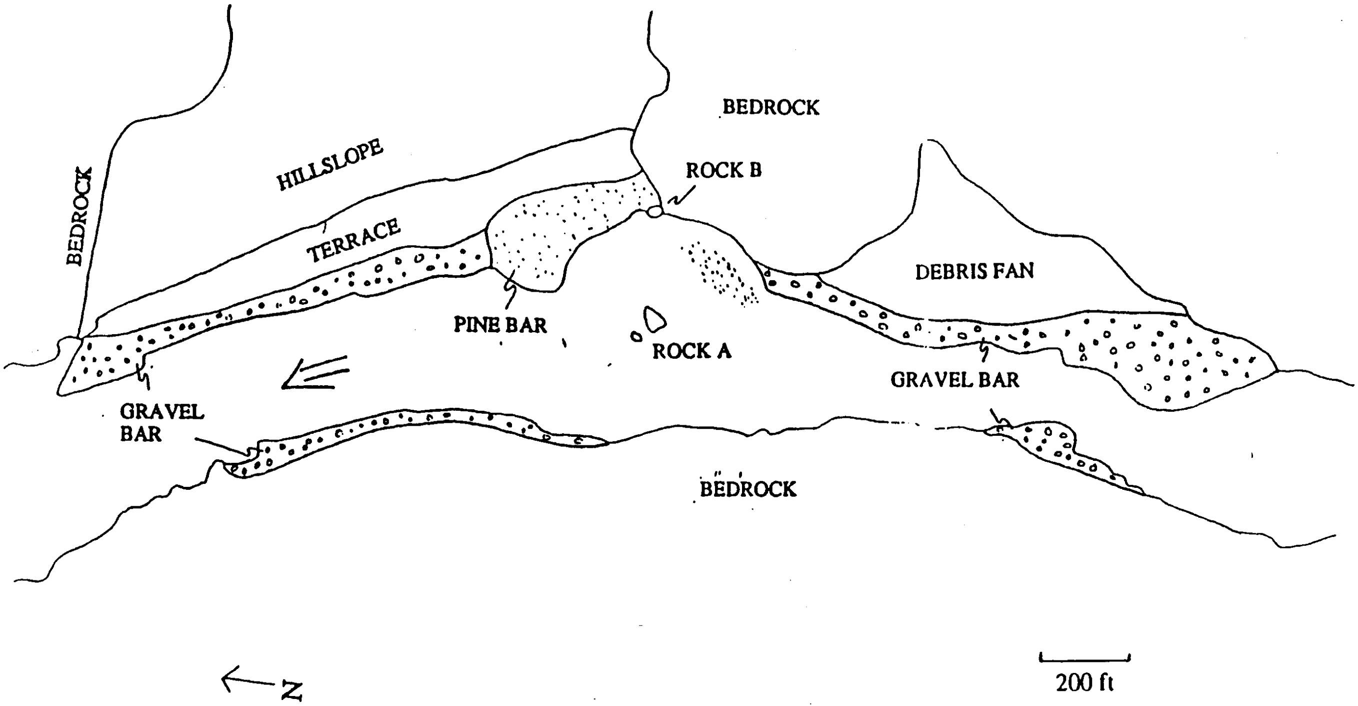
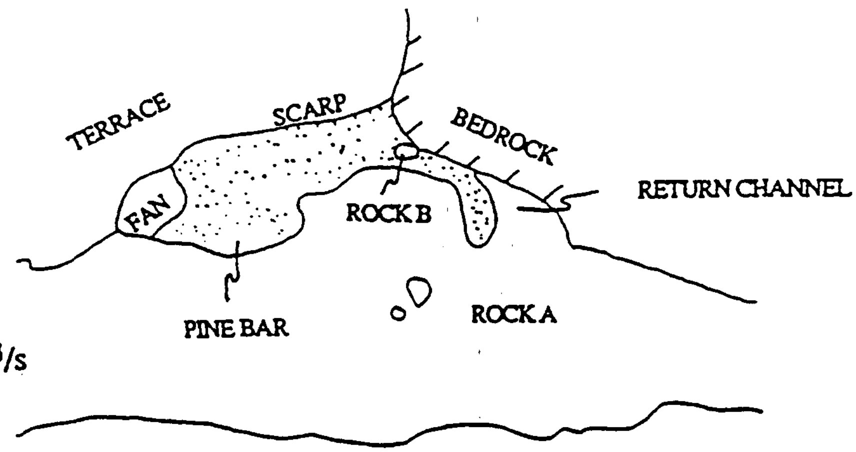
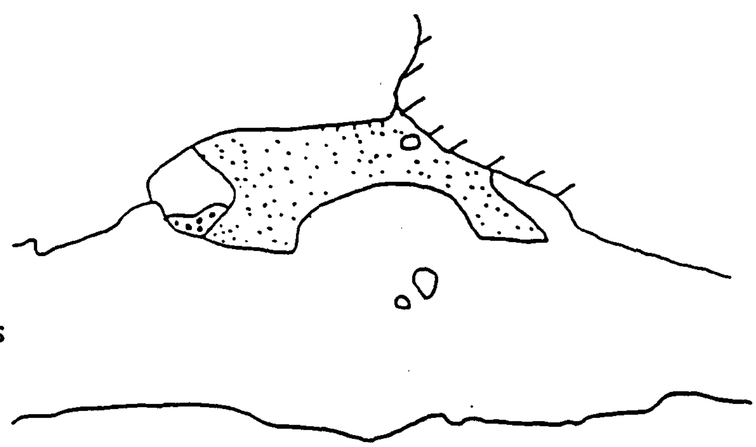


Figure 16. -- Surficial geology of the reach including Pine Bar.

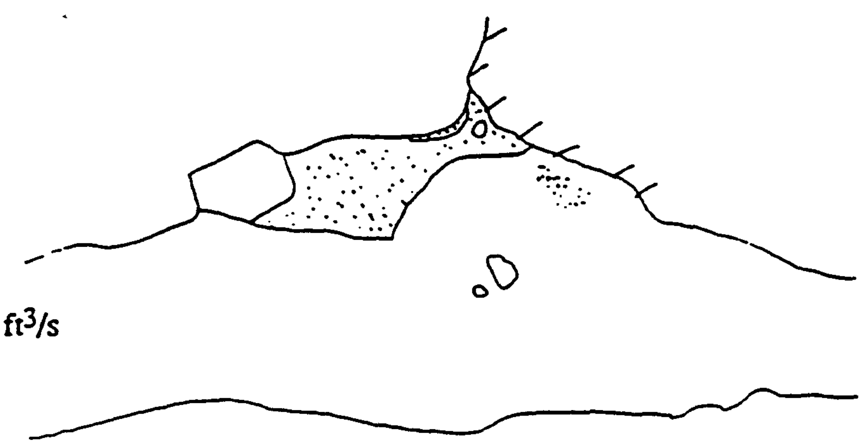
Figure 17. A-G --Pine Bar from each year of photographic coverage showing decrease in exposed sand relative to reference rocks A and B. Year and discharge at time of photograph are given for each diagram.



A) 1955
11,000 ft^3/s



B) 1964
11,800 ft^3/s



C) 1970
11,900 ft^3/s

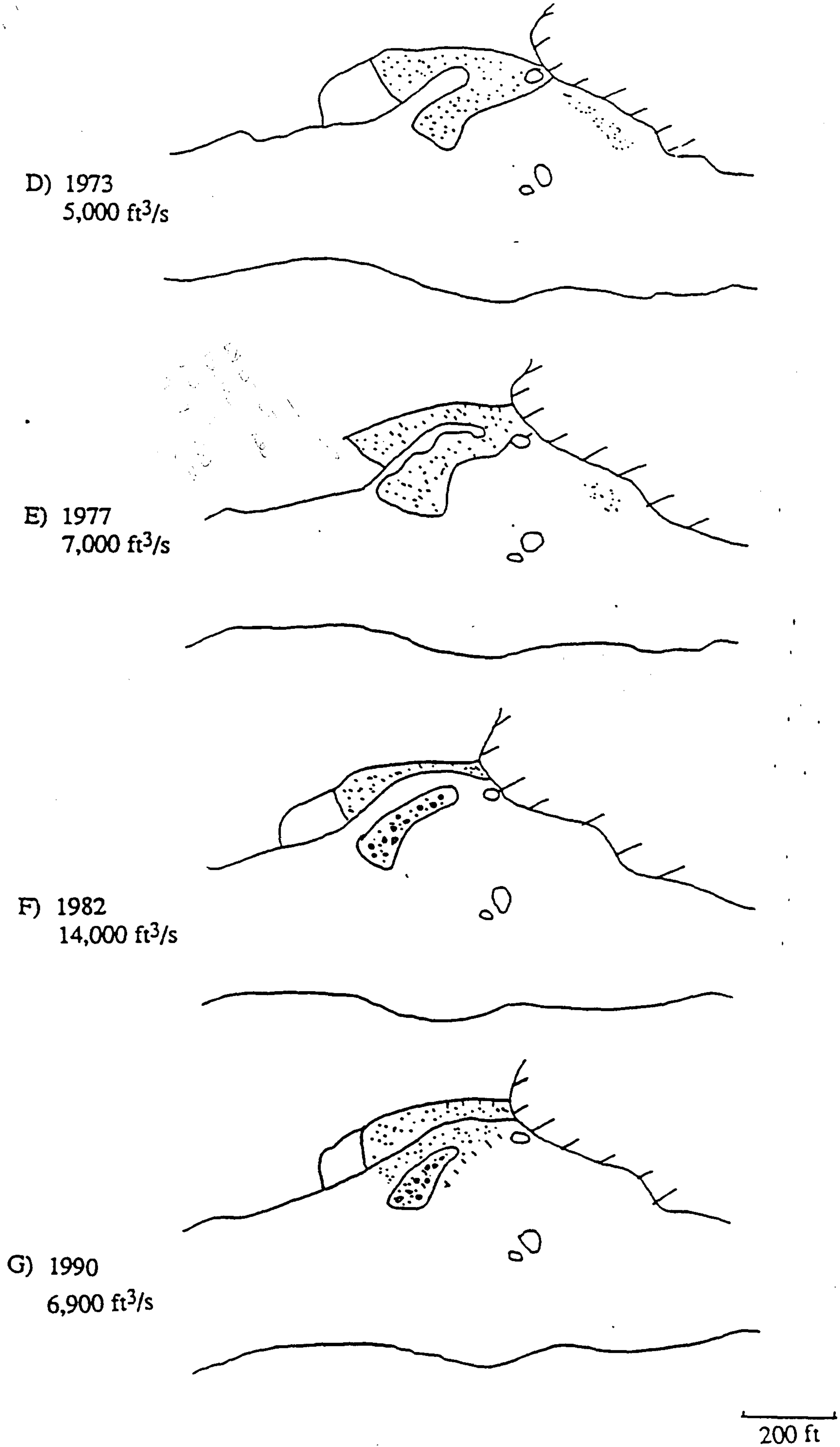

D) 1973
5,000 ft³/s
E) 1977
7,000 ft³/s
F) 1982
14,000 ft³/s
G) 1990
6,900 ft³/s
200 ft

Figure 18. – Photograph of Pine Bar looking upstream, summer 1990. Rock A is visible in mid-channel in background. The bar crest is in the middle of the photo on the right, the return channel is between the bar crest and the river bank in the foreground.

Figure 19. – Photograph of Pine Bar looking upstream at gravel-covered bar crest, summer 1990. Rock B is visible on the bank at river right, off the upstream tip of bar crest.

return channel is sand and the exposed bar surface is fine sand. On the downstream end of the beach is a small fan of fine sediment deposited by a tributary flowing through a mineralized zone on the hill slope.

Behind the beach is a high terrace which is separated from the lower bar surface by a large cutbank. The high-terrace is an alluvial deposit, generally consisting of finer material than the sand bar below. At this site it is about 10 ft above the bar surface; formed by a flow event considerably larger than would be required to submerge the sand bar. The terrace is covered with grass, shrubs, and moderately large trees. It must, therefore be an old deposit, formed by only very large floods. The high terraces at the other detailed study sites described below also fit this general description. At this site, as well as other sites containing high terraces, the scarp is evidence that the terraces are eroded back by flow events which submerge the sand bars.

Surficial geologic maps of the bar drawn from the air photos show that the amount of sand covering the crest of the bar and filling the return channel has changed significantly (Figure 17 A-G). The mean daily discharges on the aerial photography dates for 1955, 1964, and 1970 were all similar and much higher than the mean daily discharges on the photography dates for 1973 and 1977. Therefore, if the bar area had remained stable throughout the interval, 1955 - 1977, there should appear to be a larger area of exposed sand in the low-discharge photographs. That there is a decrease in the area of exposed sand on the low-discharge photographs indicates that there must be an actual decrease in bar size. Moreover, apparent decreases in area seen on the photographs must also be minimum amounts of change. If the discharge were equalized, the area of exposed sand would be even less in the low-discharge photographs.

In the 1964 photograph a prominent rock outcrop, point B in Figure 17, is completely enveloped by sand of the bar surface. The same rock marks the outward and the upstream edge of the beach in the 1973 and 1977 photographs. In the 1964 photograph the beach projected out along the bedrock wall to the main channel, whereas that sand in the subsequent photographs covers a smaller area and is submerged. Between 1964 and 1970 sand along the upstream wall was degraded, though not completely eroded. Between 1970 and 1973 the front of the beach was eroded back further and the return channel was scoured. From 1973 to 1977 there occurred continued sand loss along the upstream wall; and by 1982 no sand was visible here (although discharge is considerably higher in that photograph). In 1990, at low discharge, there was no sand visible along that portion of the eddy. The cutbank in the high terrace at the upstream end of the beach has migrated-back slightly between 1973 and 1977.

The composition of the bar crest shifted from sand to gravel between 1977 and 1982. By 1990 the surface is mostly fine gravel, on top, and mixed sand and gravel near the water line.

There is insufficient survey control at this site to apply a scale to the surficial maps and to quantify the changes. However, reasonably accurate estimates may be made by applying the scale developed by survey control at the Salt Creek Bar site which is 5 mi downstream. Because the same series of aerial photographs were enlarged to the same degree in creating the maps for each site the scales should be similar. Using this scale for measurement and rocks A and B as reference points, the sand bar eroded back an estimated 60 ft along the line connecting rocks A and B between 1964 and 1977.

Table 6. -- Erosion of Pine Bar along baseline A-B, 1964 - 1990.

	1964-1970	1970-1973	1973-1977	1977-1982	1982-1990
Erosion along line A-B, in feet	15	30	15	30	0

The amount of erosion along the baseline estimated to have occurred during each photo-interval is summarized in table 7. A significant proportion of the change in sand coverage took place between 1970 and 1973 (Figure 17 C and D). Even with the discharge in the 1973 picture less than half of what it was in 1970 the decrease in sand bar size is considerable.

Salt Creek Bar

Salt Creek Bar is a large reattachment bar located at river-mi 222.5 on the left bank. Figure 20 is a surficial map of the reach, extending upstream and downstream of Salt Creek Bar. The bar is in a channel expansion below a constriction formed by a large debris fan on the left bank above the bar. A second debris fan abuts the bar on the bar's downstream side. Near the river bank the debris fans contain mostly cobbles and boulders, further up the slope they are covered by vegetation. The present bar is about 330 ft long and 165 ft wide. The bar surface slopes up from the river gradually and flattens to form a platform 5.0 - 6.5 ft above river level at about 7,000 ft^3/s. This platform consists of clean, medium-grained sand. Behind the platform is a steep scarp which cuts into a high terrace. There is a strip of vegetation covering the back of the platform and part of the cutbank. The high terrace is covered by large dunes of wind-deposited sand. Figure 21 is a photograph, taken July, 1990, which shows in the foreground the upstream debris fan, behind it is the bar, and the cutbank. Figure 22 is a close-up photograph of the cutbank and the aeolean dune on the top of the high terrace, to the left of the cutbank.

Bar sedimentology was examined in trenches along the flat platform of the sand bar. The upper 1.8 ft of the bar is composed of medium-grained sand deposited in four sequences of three-dimensional, dune-form cross-bedding (Figure 23). The size of the structures, the grain-size, and the three-dimensional form indicate high transport rate and high velocity at the time of deposition. This suggest that deposition occurred during an event of relatively high flow. The dune migration directions are on-shore and upstream. As the bar built it migrated towards the bank and the return channel. Figure 24 shows these units and the pattern of bar migration. Underlying the sequence of dunes is a mud layer. This deposit is likely a remnant of a pre-regulation flood, as there is no apparent

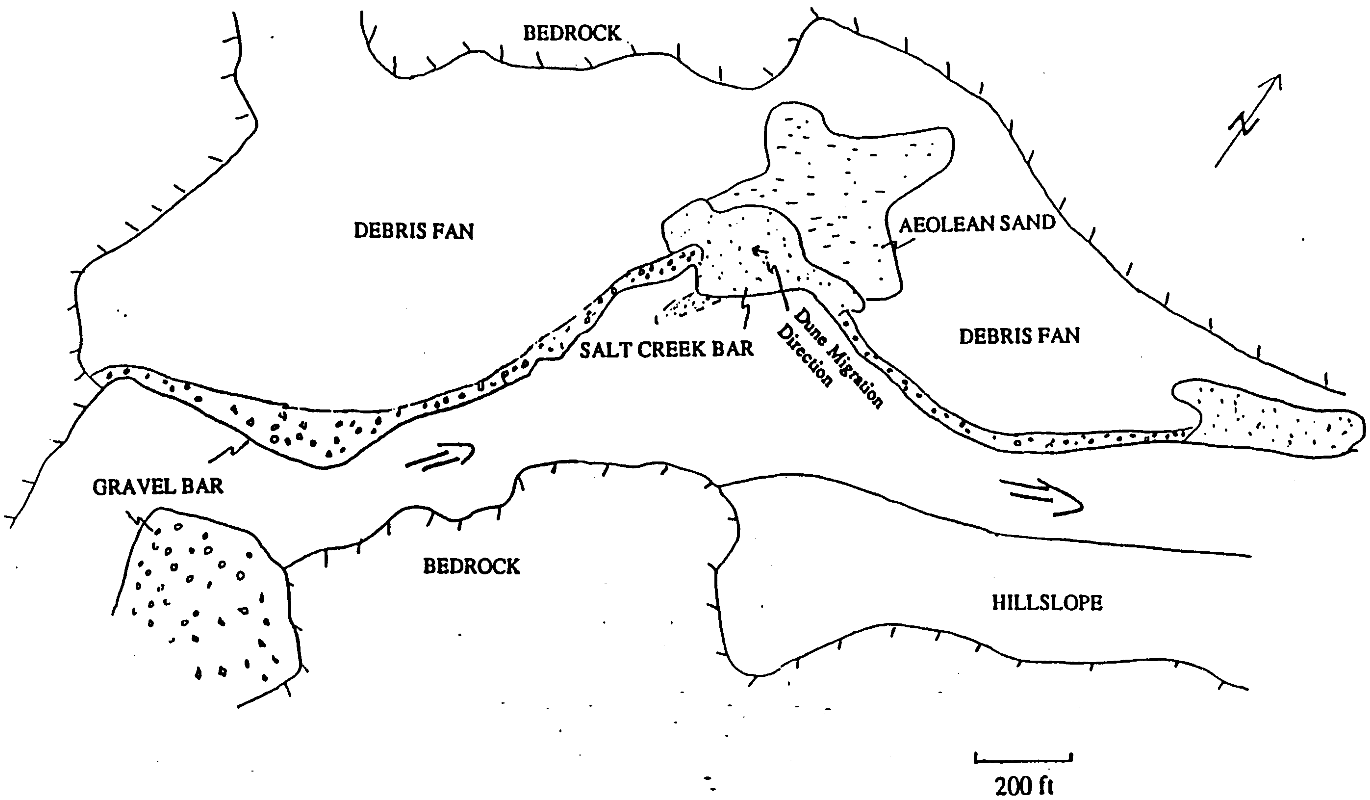


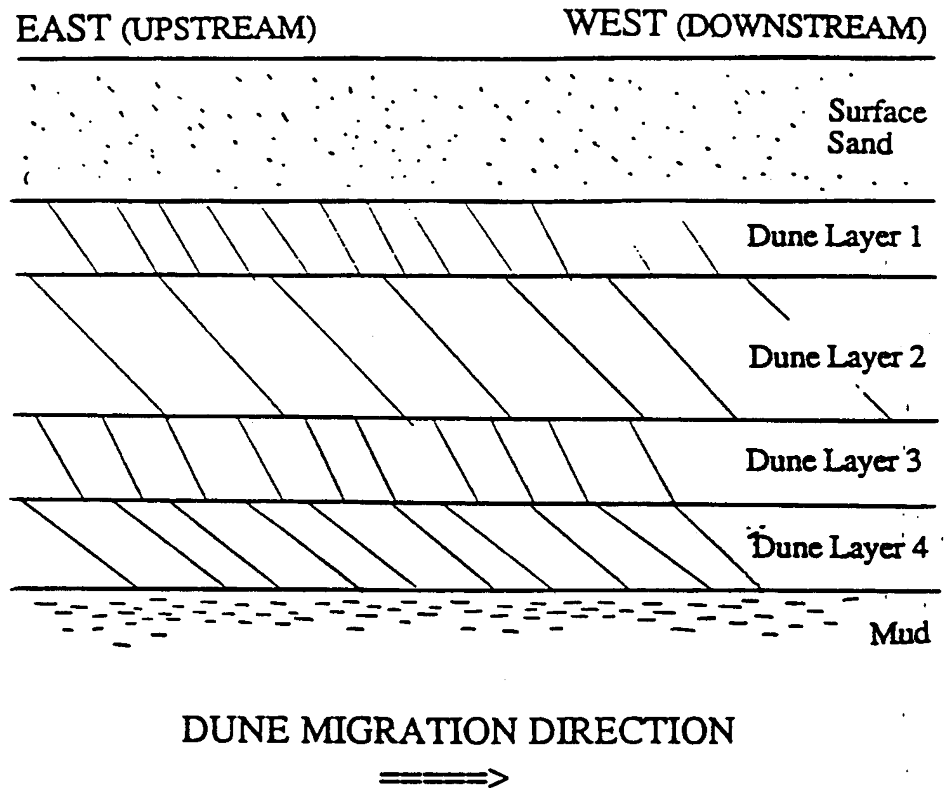
Figure 20. -- Surficial geology of the reach including Salt Creek Bar.

Figure 21. -- Photogra)f Salt Creek Bar looking downstream. .mmer 1990. Cutbank in left background.

Figure 22. -- Photograph of cutbank at Salt Creek Bar, summer 1990.

Figure 23. -- Photograph of exposed trench at Salt Creek Bar, summer 1990. Dune cross-bedding is visible, arrow indicates dune migration direction.

Figure 24. -- Sketch of sedimentary structures exposed in trench at Salt Creek Bar.



source of clay and silt in Hells Canyon. The sedimentology well matches that of a typical reattachment bar.

The cut bank in the high terrace at the rear of the bar consists of a finer-grained sand than is contained in the beach. Climbing ripples with bottom- and top-sets preserved are migrating in a downstream direction. (Figure 25) The steep angle of climb in these ripples indicates that they were deposited very rapidly, and therefore in conditions of low-velocity and large quantities of sediment. This high terrace was possibly formed in the pool above a constriction during some very high flood event.

Hackberry trees which skirt the beach on the surface of the high terrace are individually recognizable in all of the aerial photographs. Six reference points (A-F) based on tree locations were marked on the photos and surveyed. These reference points are end-points for baselines placed on scaled surficial maps made from each photo series (Figure 26 A-F). Measurements from the baselines to the edge of the beach indicate the progress of cutbank erosion. The mean daily discharge at this site for the day each picture was taken was: 11,000 ft^3/s for 1955, 12,500 for 1964, 11,900 for 1970, 7,700 for 1973, between 5300 and 6,900 for 1977 and 14,000 for 1982. The discharge at the time of the survey in 1990 was about 6,900 ft^3/s (from hourly reading at Hells Canyon Dam, corrected for stage-wave travel time).

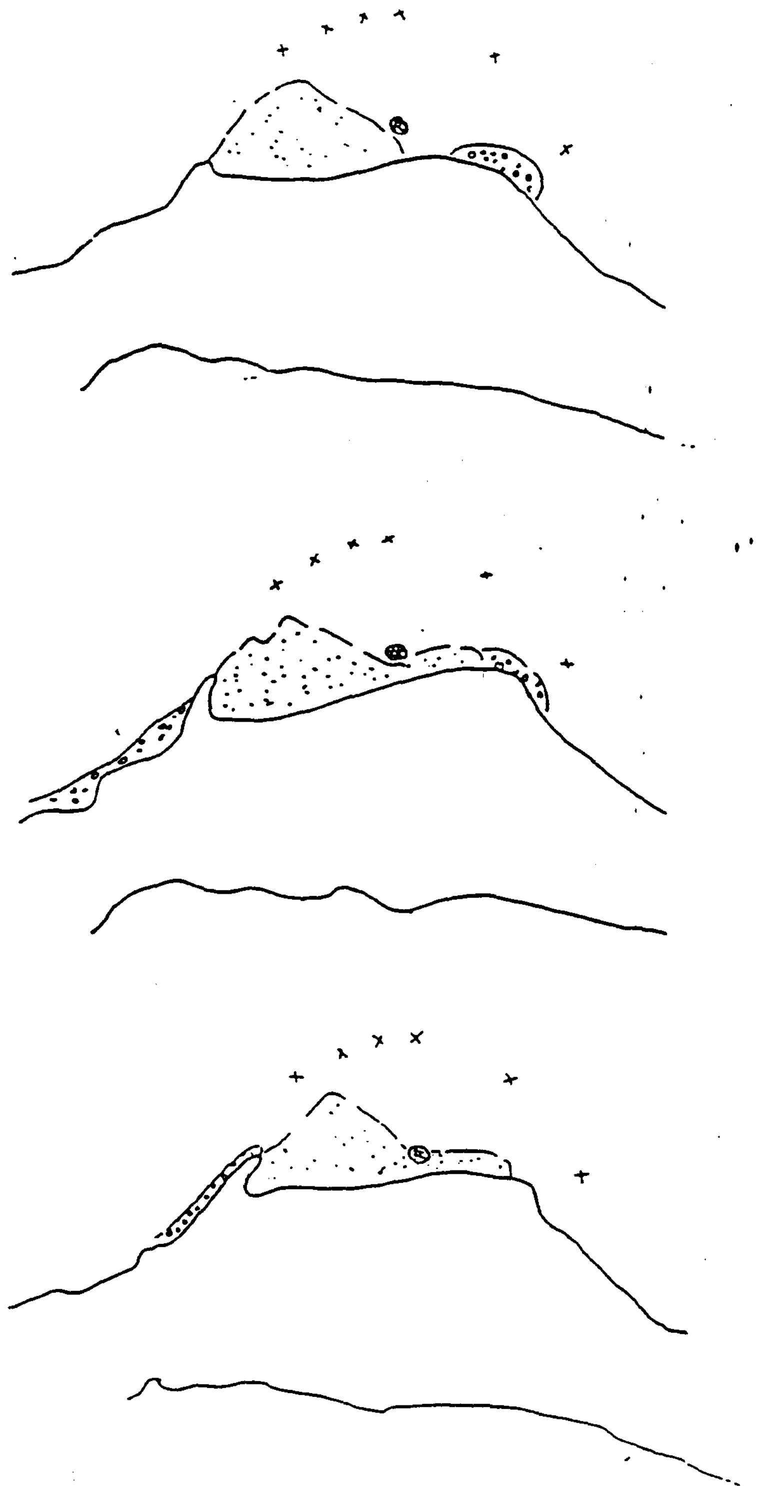
The scarp has eroded back as much as 180 ft as measured from baseline B-C, 150 ft, from A-F, and 70 ft, from A-B. Figure 27 shows the average rate of erosion for each interval between 1955 and 1990. The most rapid rate of erosion occurred between 1970 and 1973. In addition to the cutbank erosion the air photos show a back-migration of the front of the beach. The water line along the sand bar is closer to the left bank in the 1973 and 1977 photographs in which the discharge is much less. The 1973 waterline is at least 75 ft closer to a fixed reference point on the bank than it was in 1955.

Volume of material eroded from the high terrace was estimated by calculating the volume of the wedge, because the previous bank may have sloped down to the bar surface,

Figure 25. -- Photograph of climbing ripples in exposed cutbank at the back of Salt Creek Bar. Ripple migration direction is left-to-right, which is downstream.

Figure 25. -- Photograph of climbing ripples in exposed cutbank at the back of Salt Creek Bar. Ripple migration direction is left-to-right, which is downstream.

Figure 26. A-F --Salt Creek Bar from each year of photographic coverage showing decrease in exposed sand relative to indicated reference points. Year and discharge at time of photograph are given for each diagram.

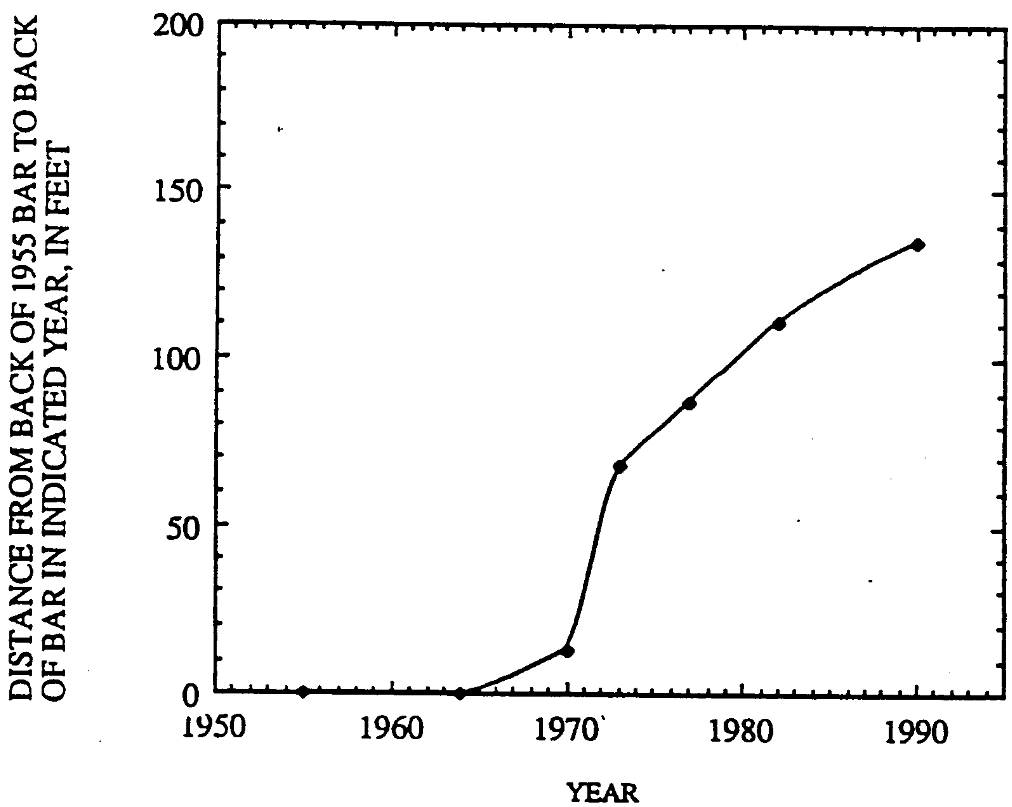


A) 1955
11,000 ft^3/s

B) 1964
12,500 ft^3/s

C) 1970
11,900 ft^3/s

Figure 27. -- Erosion of High terrace at Salt Creek Bar, 1955 - 1990.



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John Anderson

with the following dimensions: average cutbank retreat of 130 ft, average elevation difference between bar platform and top of the cutbank of 16 ft, and a bar length of 330 ft. The estimated volume lost is 340,000 ft^3.

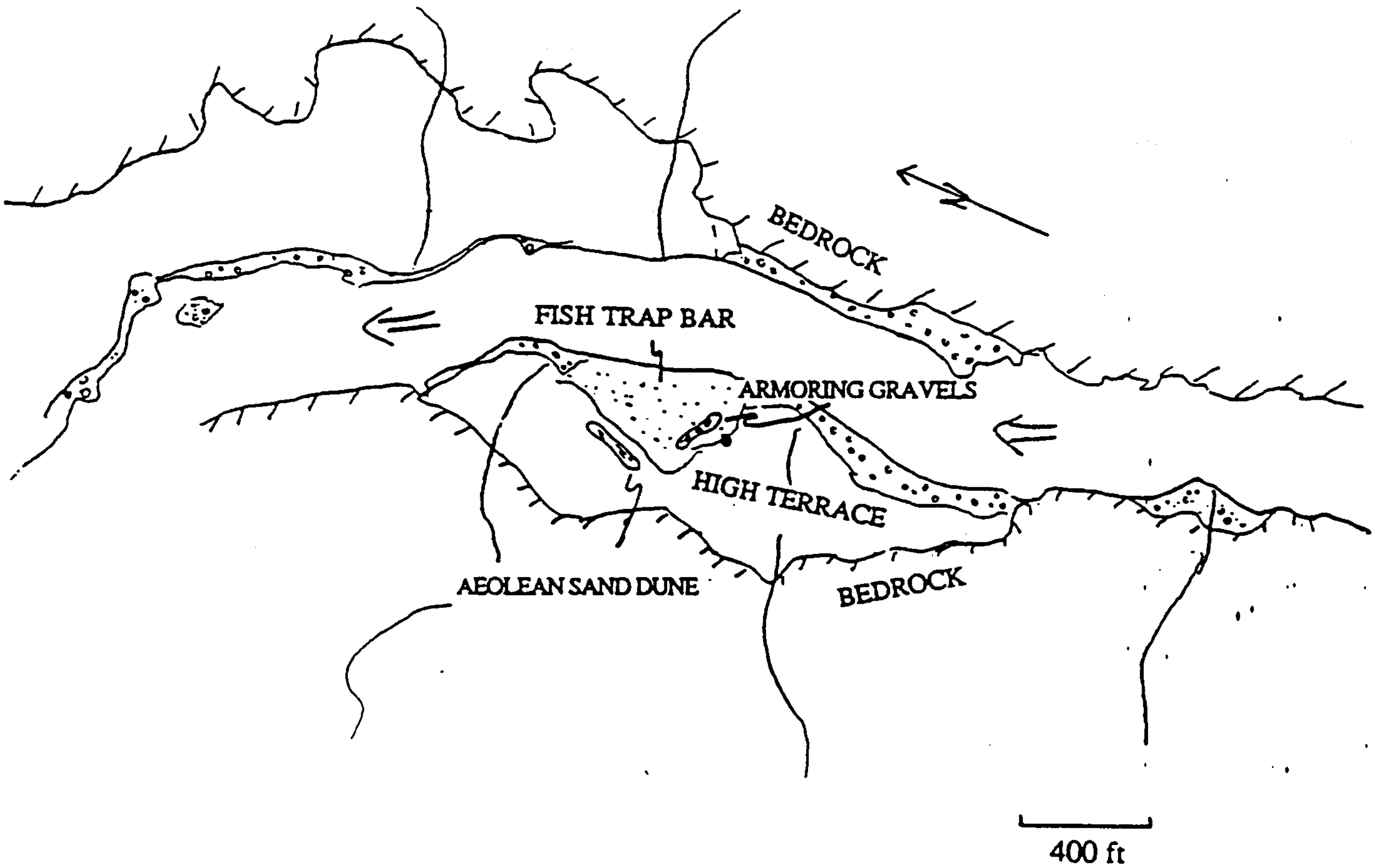
The area of sand at Salt Creek Bar has remained fairly constant since 1964. The sand bar itself, however, has migrated shore-ward, following the retreating cutbank, a distance about equal to the width of the sand bar. Whether erosion of the high terraces has an effect upon sand bar erosion is uncertain. The flow necessary to erode the terrace would certainly submerge the sand bar. Differences in material size between the sand bar and the terrace indicates that the sand eroded from the terrace has not been redeposited on the sand bar.

Fish Trap Bar

The sand bar at river-mi 216.4 on river left is a frequently used campsite and is identified in the U.S. Forest Service river guide as Fish Trap Bar. The bar is nested between two tributary fans, the larger of which forms a constriction upstream of the beach. Figure 28 is a surficial geologic map of the reach including Fish Trap Bar. The bar is located in an area of the canyon where the river emerges from a narrow section of the canyon. The geometry of the debris fan upstream of the bar and the expansion of the bedrock on the opposite bank likely cause the constriction-ratio to increase at large discharges creating a larger and more powerful eddy. The deposit was classified as a reattachment bar because it is located in a zone of recirculating flow and contains typical reattachment bar features such as a bar-crest and return-channel.

The crest of the bar runs parallel to the river and was, at the time of the topographic survey, about 9 ft above water level when discharge is about 7,000 ft^3/s. On the shore-ward side of the crest is a depression which is the eddy return channel, that runs nearly the entire length of the bar. At the rear of the beach is a very steep scarp; the top of which is 11 to 16 ft above the bottom of the return channel. The cutbank is steepest on the downstream half of the beach. Below the scarp and behind the channel, for approximately the upper

Figure 28. -- Surficial geology of the reach including Fish Trap Bar.



two-thirds of the beach, the surface material consists of sub-angular gravel. Figure 29 is a photograph of Salt Creek Bar taken July 1990, view is downstream. The cutbank is in the background and the gravel is visible to the left. Figure 30 is a close-up of the the gravel-covered return channel.

Mapping from the aerial photographs (Figure 31 A-F) shows that the scarp has cut-back significantly since 1955. The locations of four trees (A,B,C, and D) on the high terrace provide a common reference for comparison between each air photo map and the topographic map. Rates of cutbank retreat were measured along two baselines, using the trees as end-points. The top of the scarp has migrated-back as-much-as 50 ft on the downstream end of the beach and as-much-as 20 ft upstream. The rear of the beach, at its deepest point, has cut-back 30 ft since 1955 (Figure 32). Volume of bank material lost was estimated by dividing the beach into two segments which exhibited to different rates of erosion. The estimated volume of terrace material eroded is 30,000 ft^3 on the upper segment and 55,000 ft^3 on the lower segment, where the cutbank has retreated the most. Cutbank erosion was extremely rapid between 1970 and 1973 and has not occurred significantly since 1973.

The sub-angular gravels that lie at the base of the cutbank are likely uncovered hill-slope or debris fan material. They now armor the upstream two-thirds of the beach below the scarp, and have therefore probably helped to check the rate of erosion since 1973. Gravels are not present on the downstream one-third of the beach where the scarp is steepest.

China Bar

China bar is a large sand bar on the left bank at river-mi 192.4. It lies below a constriction created by a debris fan and is confined on its downstream end by a bedrock cliff. Figure 36 shows the surficial geology of the reach containing China Bar. About one-half of the back of the beach is also confined by a bedrock wall. The other half of the bar is backed by a high terrace. From that terrace there is a steep slope down to the bar surface.

Figure 29. – Photograp' f Fish Trap Bar looking downstream, ımer 1990.

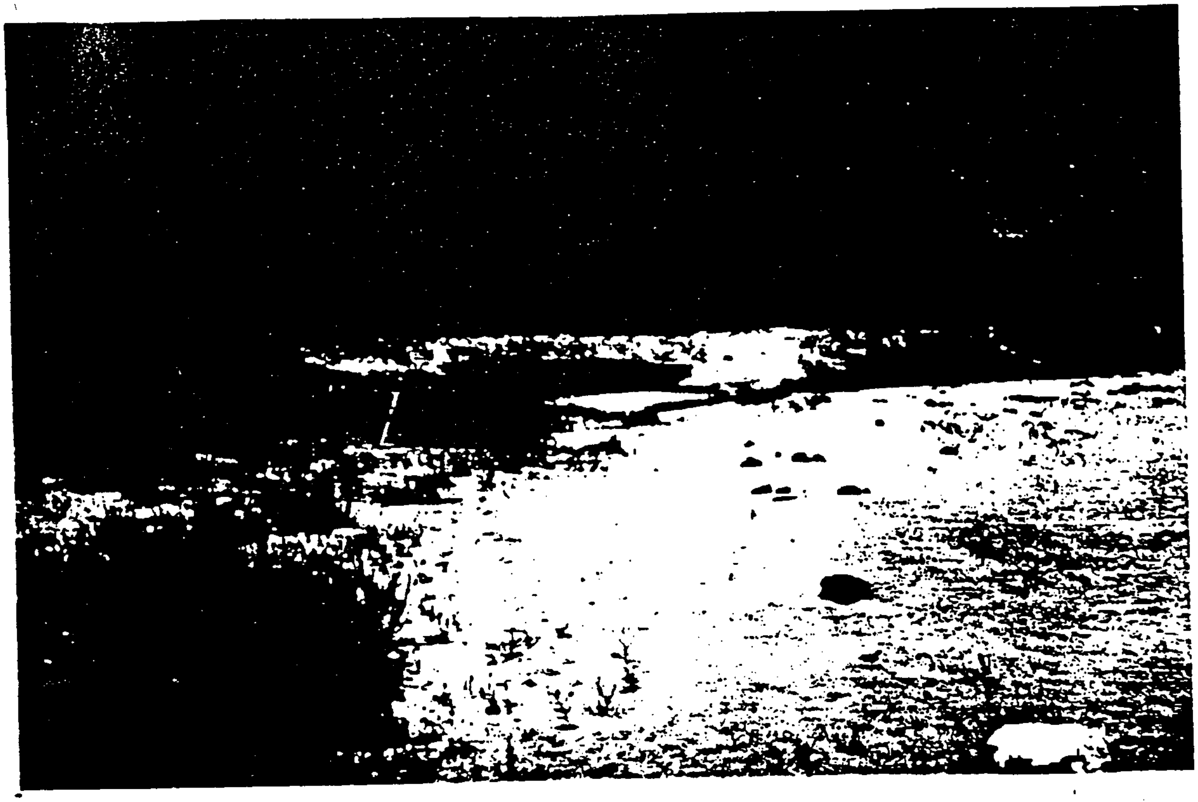


Figure 30. – Photograph of the return channel and armoring gravels at Fish Trap Bar.

Figure 31. A-F – Fish ·p Bar from each year of photographic /erage showing erosion of high terrace relative to reference points A, B, C, and D. Year and discharge at time of photograph are given for each diagram.

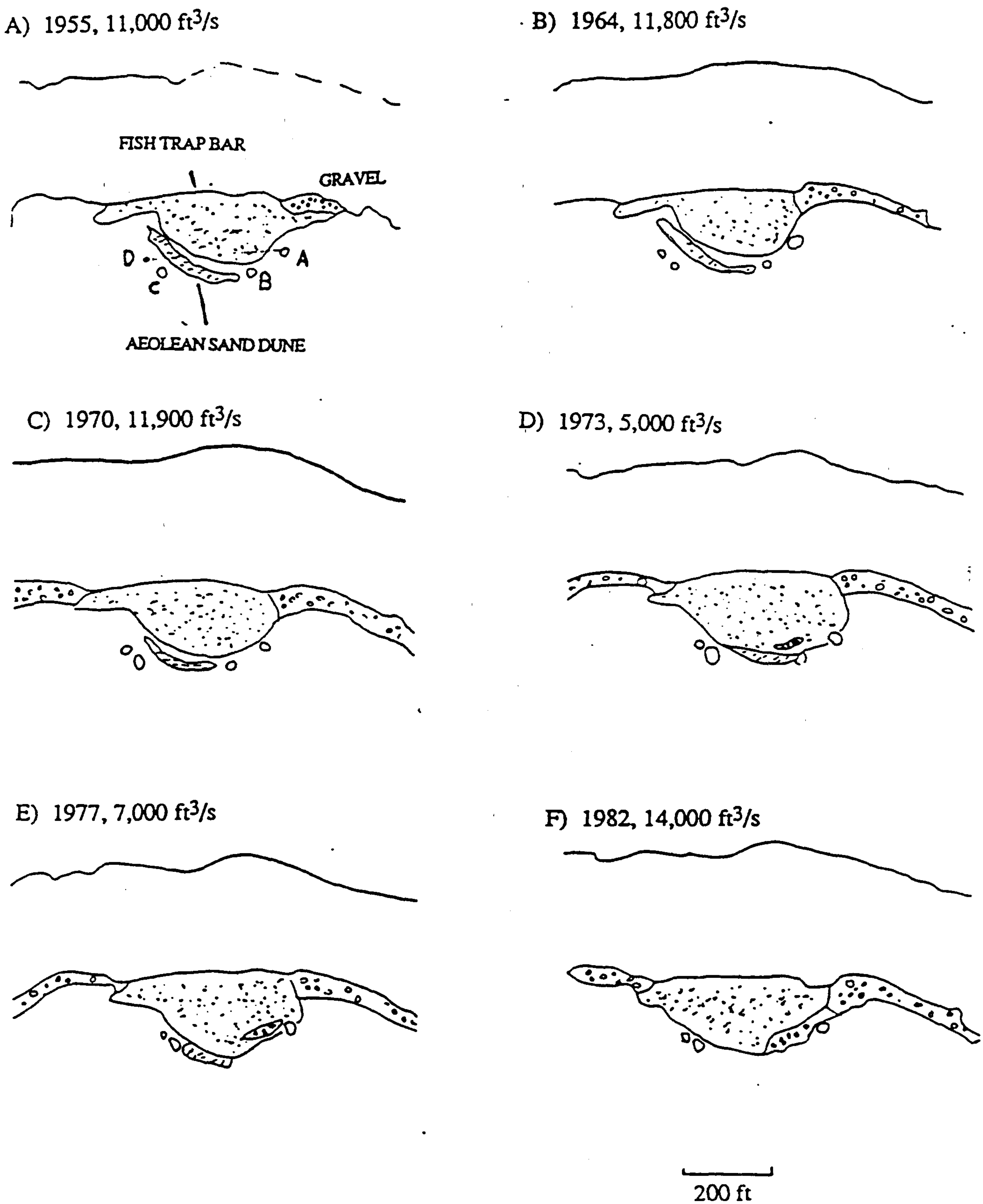
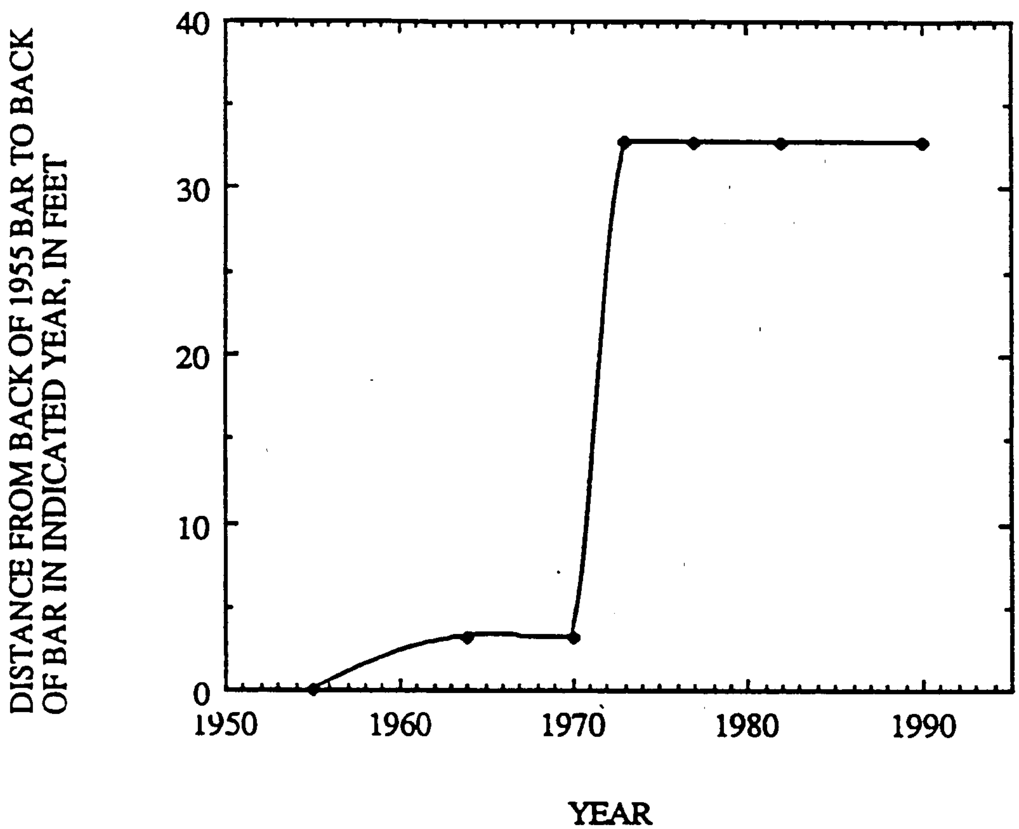


Figure 32. -- Erosion of high terrace at Fish Trap Bar, 1955 - 1990.



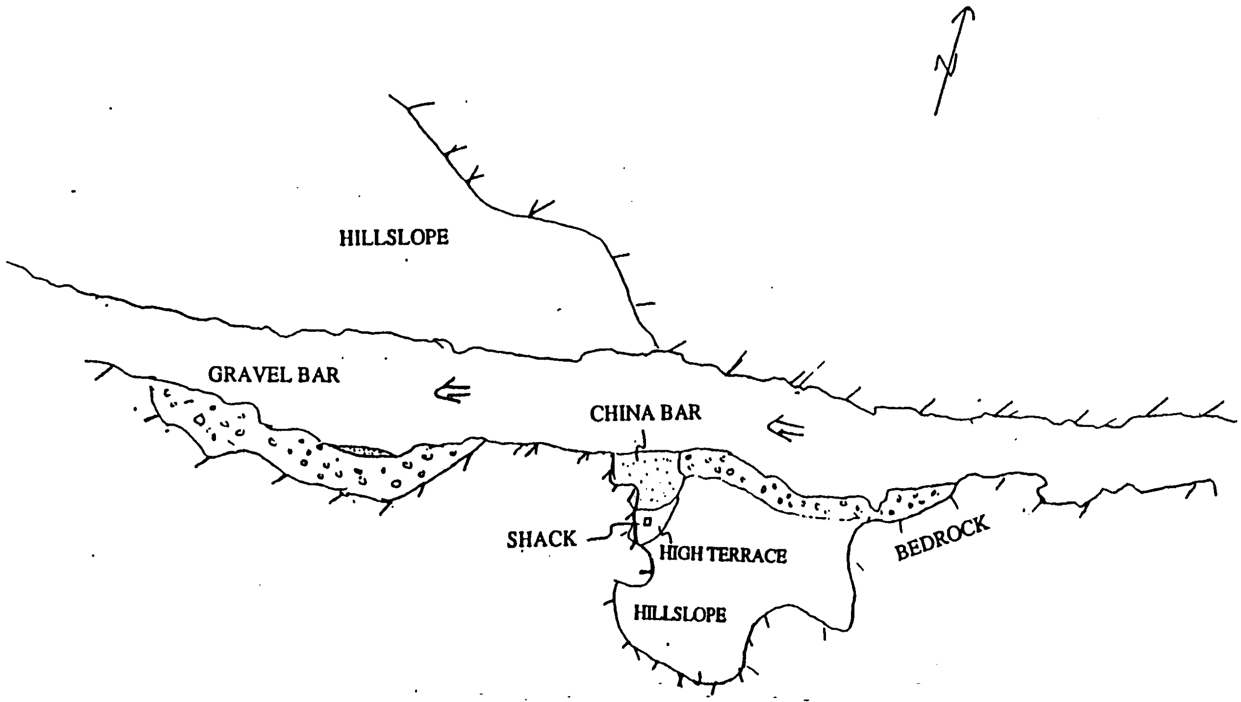


Figure 33. -- Surficial geology of the reach including China Bar.

Between the bar-crest and the bedrock wall is a channel. Water in this channel would flow into the river at the downstream end of the bar. Figure 34 is a photograph taken July, 1990 looking upstream at the bar. The channel is in the foreground and behind it is the bar crest. In the background is the debris fan, upstream of the bar. It is uncertain whether the channel is an actual return channel because it appears to drain in a direction counter to the expected circulation pattern were this a typical reattachment bar. The channel may be an erosional feature formed by runoff flowing onto the beach from the high by way of the gully in the cutbank.

Sedimentary structures exposed in trenches along the bar-crest and into the channel reveals a surface layer of trough, cross-bedded dunes overlying an inner-core of finer sediment. Dune migration directions indicate that the crest of the bar migrates towards the back channel. This deposit was classified as a reattachment bar, even though it is not a typical example of a reattachment bar.

Sand bar changes and erosion of the adjacent high terrace have been minor at this site and no significant changes can be determined. The details of the changes are within the margin of error associated with scale transformations. The only point that can be consistently located on all photographs is a small shack on the high terrace. Using this as a reference point there may have been a slight back-migration of the scarp at the rear of the beach between 1955 and 1964. There is insufficient survey control of reference points to place a scale on the photographs which would allow quantification of these changes.

<u>Initial Distribution of Sand Bars</u>

The initial condition of sand bars was evaluated using data from the 1955 and 1964 air photographs. In the 1955 photographs 207 sand bars were identified. In comparison, 220 sand bars were identified in the 1964 photographs. The total estimated area of sand bars, as determined from the 1964 photographs is 2,040,000 ft^2. The complete sand bar inventory is included as an appendix. There is one site which contained sand in 1955 and did not in 1964, while three sites empty of sand in 1955

Figure 34. -- Photograph of China Bar looking upstream, summer 1990. The bar crest is in the center of the photograph, the return channel is in the foreground.

contained sand in 1964. At 11 sites which contained sand in 1964 the presence of sand in 1955 was uncertain, either because the deposits were very small or they were in shadow. Because the scale of the 1955 photographs does not permit detailed analysis and because the 1955 and 1964 conditions are similar the 1964 photographs are also used to describe the initial, or pre-regulation, condition of sand bars.

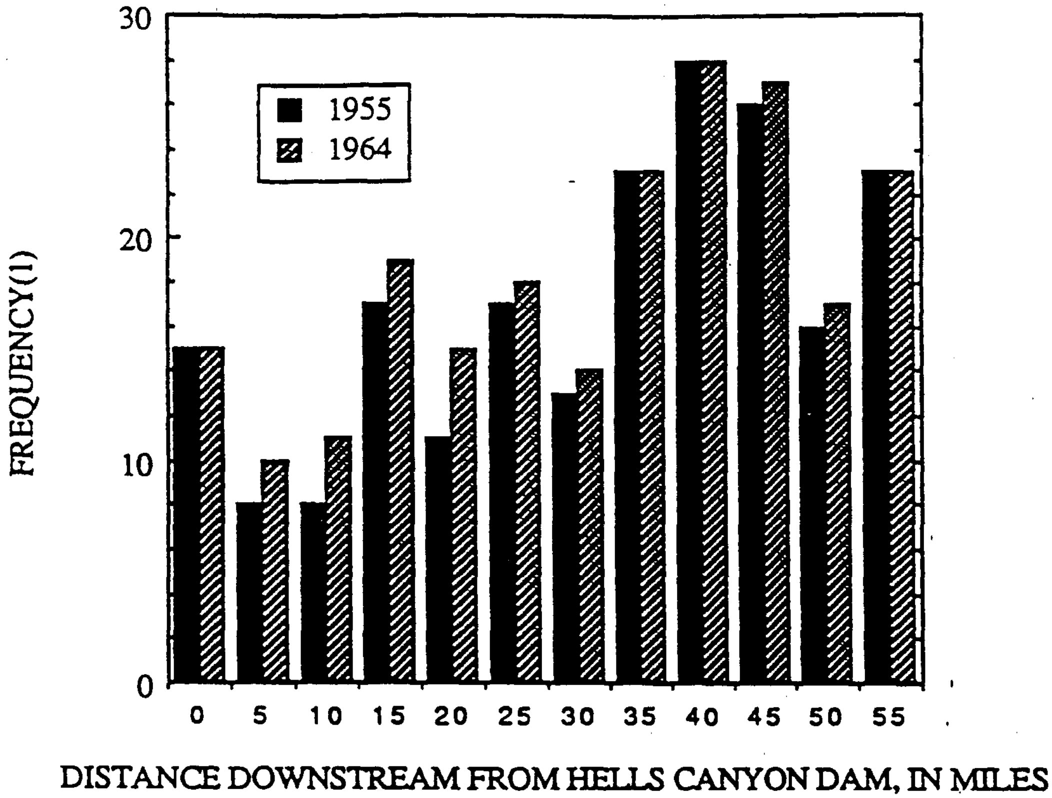
Figure 35 shows the sand bar frequency as a function of distance downstream from Hells Canyon Dam in 1955 and in 1964. There are generally more bars in the second 30 river mi below the dam than in the first. This pattern is also demonstrated in figures 36 and 37 which show frequency and area of bar types in relation to their distribution downstream from Hells Canyon Dam. Reattachment and separation bars are distributed rather evenly throughout the 60 mi reach in comparison to the channel margin bars which concentrate in the lower half of the canyon. This may be due to a greater abundance of channel irregularities, often formed by bedrock, which trap small areas of sand. These figures also demonstrate that channel margin bars far outnumber and occupy a much greater percentage of area in all reaches than the other deposit types. The greatest concentrations of reattachment bars are in the middle segments of the canyon.

Reattachment bars tend to be significantly larger than both separation and channel margin bars. The average area of a reattachment bar in 1964 was about 17,000 ft^2 while the areas of channel margin and separation bars averaged around 8,000 to 10,000 ft^2. Thus, it is the increase in the frequency of channel margin bars further downstream that establishes the general trend of higher bar frequency and greater area of exposed sand downstream.

<u>Changes in Sand Bar Frequency and Area</u>

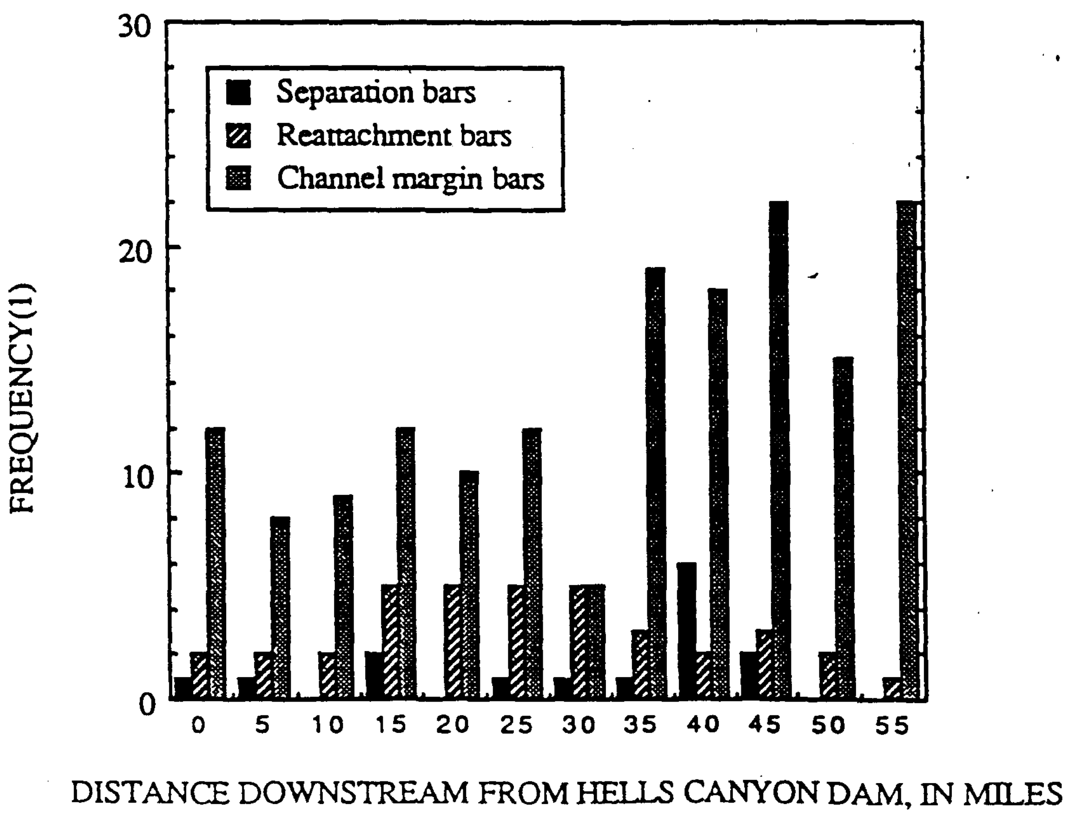
The number of sand bars in Hells Canyon decreased exponentially between 1964 and 1982. The number of sand bars identified from air photographs in the 59.2 river-mi between Hells Canyon Dam and the Salmon River confluence decreased from 220 in 1964 to 43 in 1982 (Figure 38). Between 1955 and 1964 slight aggradation possibly occurred.

Figure 35. -- Frequency of sand bars by 5-mile reach, 1955 and 1964.



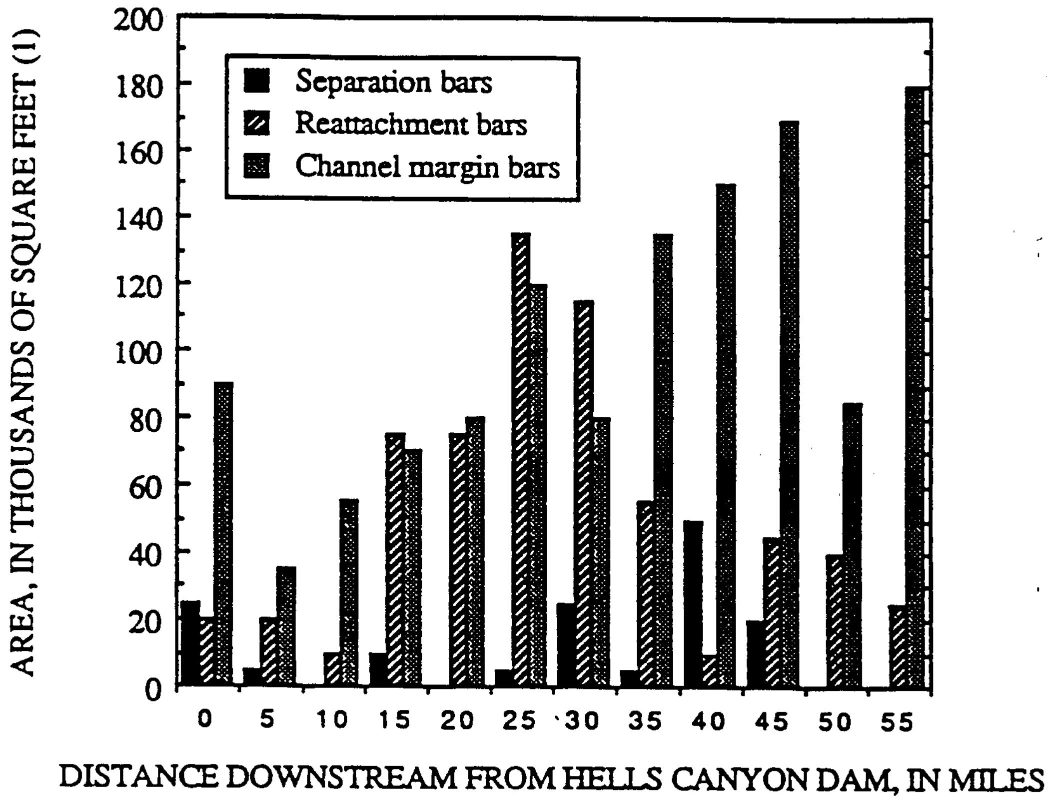
(1) Number of sand bars in 5-mile reach below indicated mile.

Figure 36. -- Frequency of sand bars by 5-mile reach and bar type, 1964.



(1) Number of sand bars in 5-mile reach below indicated mile.

Figure 37. – Area of sand bars by 5-mile reach and bar type, 1964.



(1) Area of exposed sand in 5-mile reach below indicated mile.

Figure 38. -- Frequency of sand bars in Hells Canyon, 1955 - 1982.

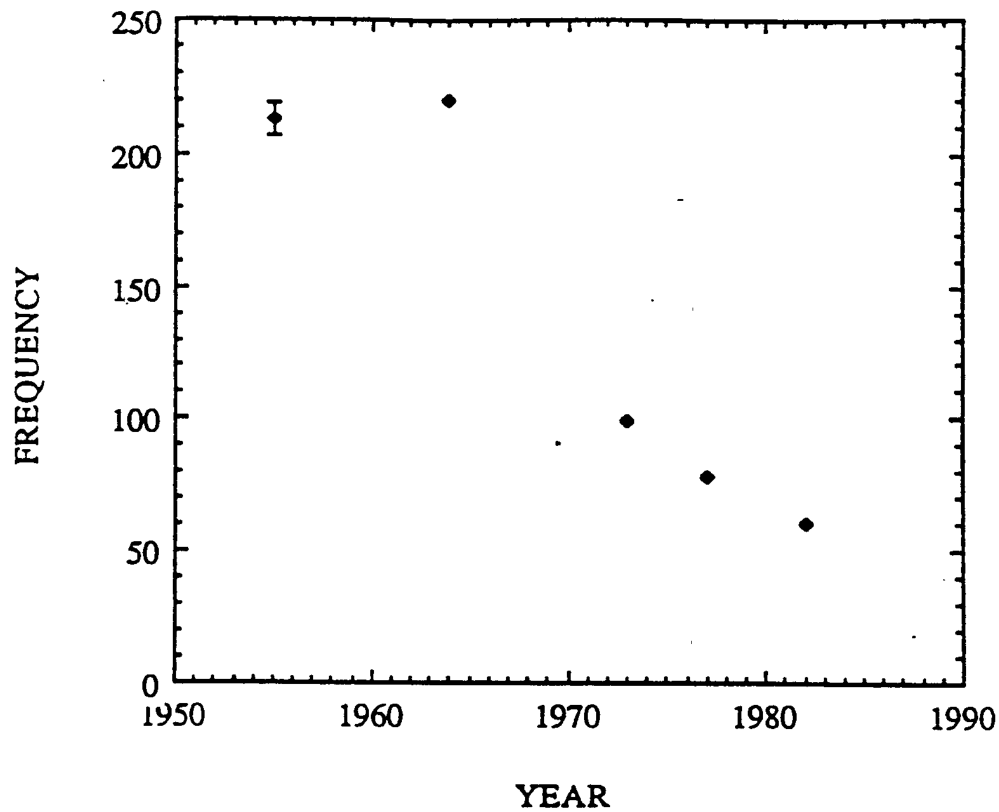
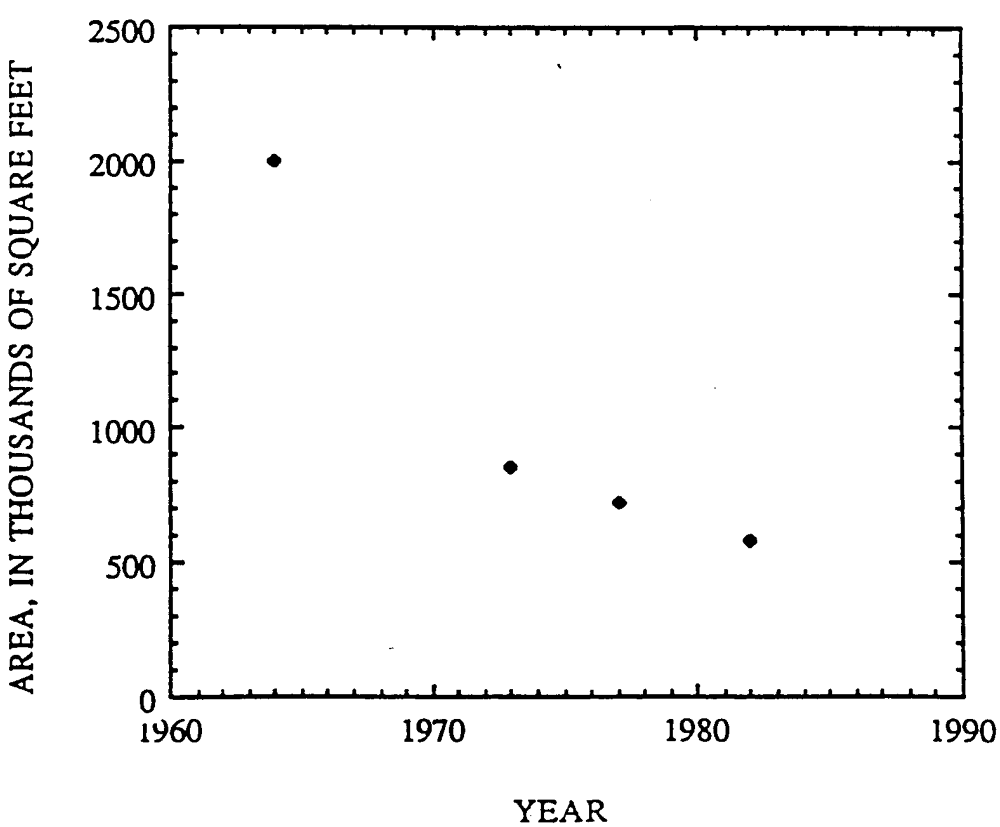


Figure 39. -- Total area of exposed sand in Hells Canyon, 1964 - 1982.



The error bars used on the 1955 value represent the bars where presence of sand in the photograph was questionable. Greatest change occurred between 1964 and 1973 when the number of bars declined by 128. Changes in total area of sand bars between 1964 and 1982 match the pattern of frequency change (Figure 39). The greatest change in area also occurred between 1964 and 1973.

Figure 40 shows how the changes in sand-bar frequency have been distributed among the four bar-size categories. The single category which exhibited the most change was small bars which have an average area of 5,000 ft^2. Between 1964 and 1973 the number of bars in that category dropped by 47 percent. These small bars, which eroded away completely, account for about 71 percent of the cumulative change in bar frequency that took place in the 1964 - 1973 interval. The frequency of larger bars in the 25,000 ft^2. category increased slightly between 1973 and 1977. This is likely a result of bars shifting size classes as they decrease in area. In the larger size categories, which have progressively fewer bars to begin with, the changes are also progressively less in the 1964 - 1973 interval. Average area of the existing bars has increased over the same period (Figure 41) This has occurred because there is a selective elimination of the smaller bars. Figure 42 shows the proportion of the change in total area of exposed sand that is a result of elimination of sand bars.

Although there have been changes in the frequency and total area of all bar types, channel margin bars have undergone the greatest amount of change as shown in Figure 43. The largest decrease of both channel margin and reattachment bars occurred between 1964 and 1973. Decline of area of the separation bars, however, is much less dramatic and more consistent over the entire period. In 1964 channel margin bars composed 62 percent, and reattachment bars 31 percent of the total area of sand bars. By 1982 channel margin bars covered only 53 percent of the area of exposed sand relative to reattachment and separation bars. The average area of each bar type has remained relatively constant (Figure 44). The slight increase in average size of channel margin and reattachment bars is

Figure 40. -- Frequenc) . sand bars for each bar size category, 1. 4 - 1982.

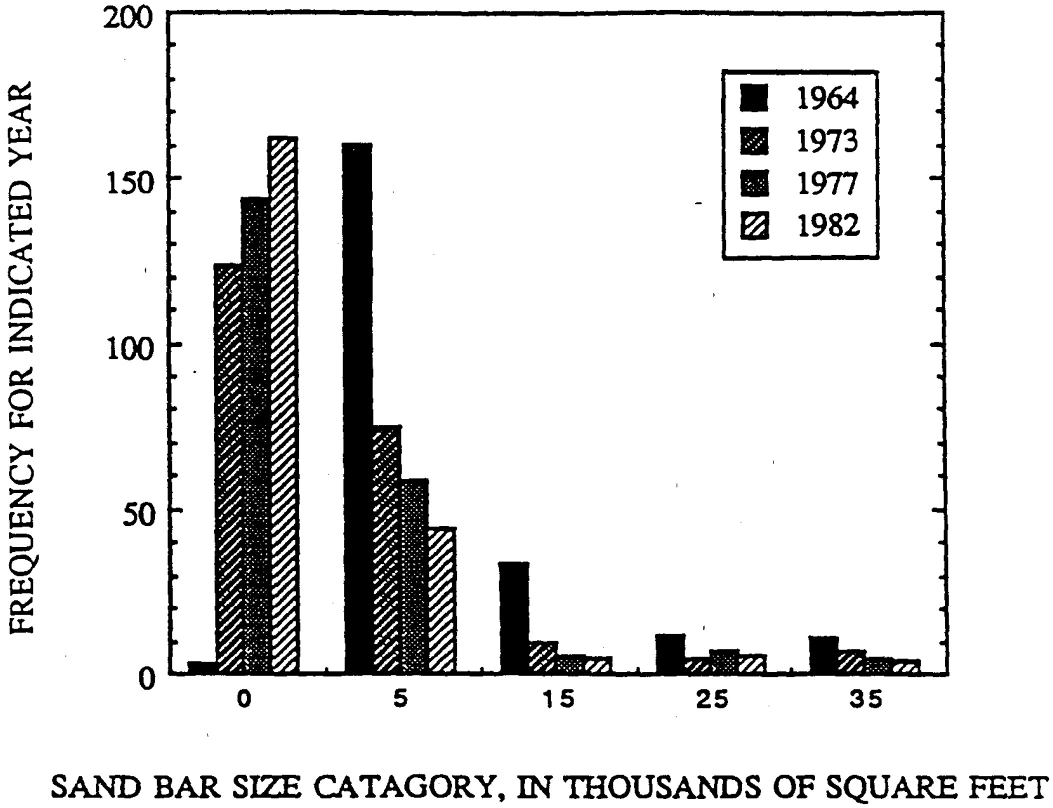


Figure 41. -- Average sand bar area, 1964 - 1982.

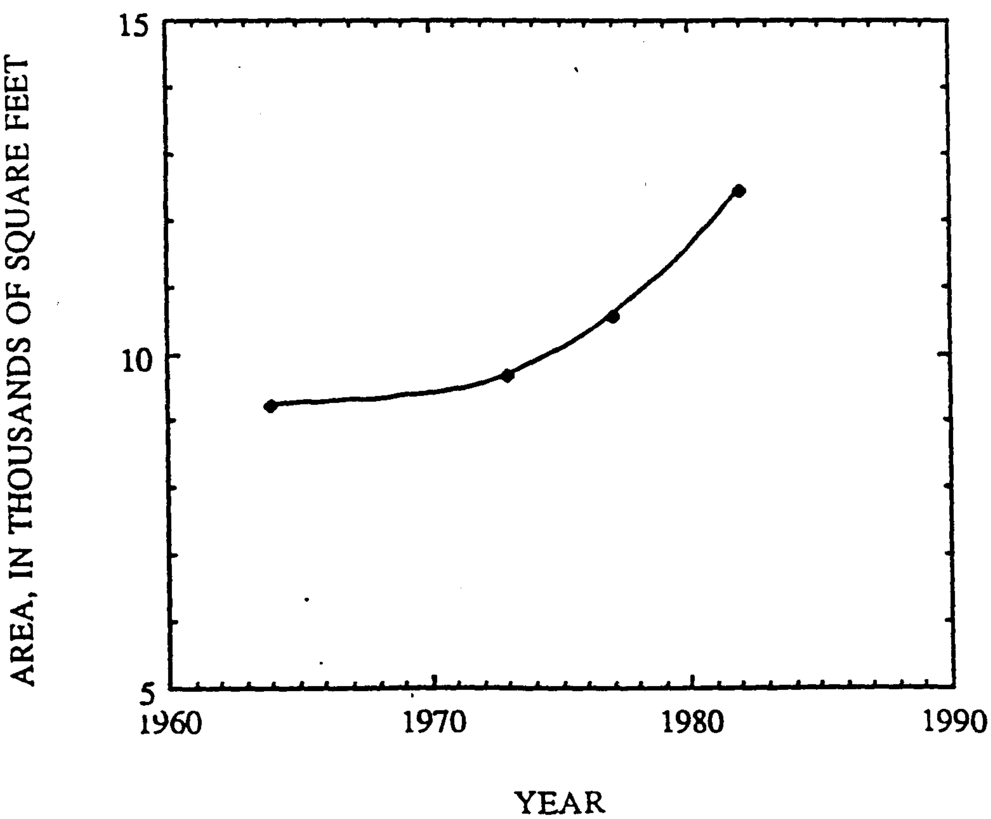


Figure 42. -- Pe nt of total area change, 1964 - 1973, w h was accomplished by elimination of exposed sand.

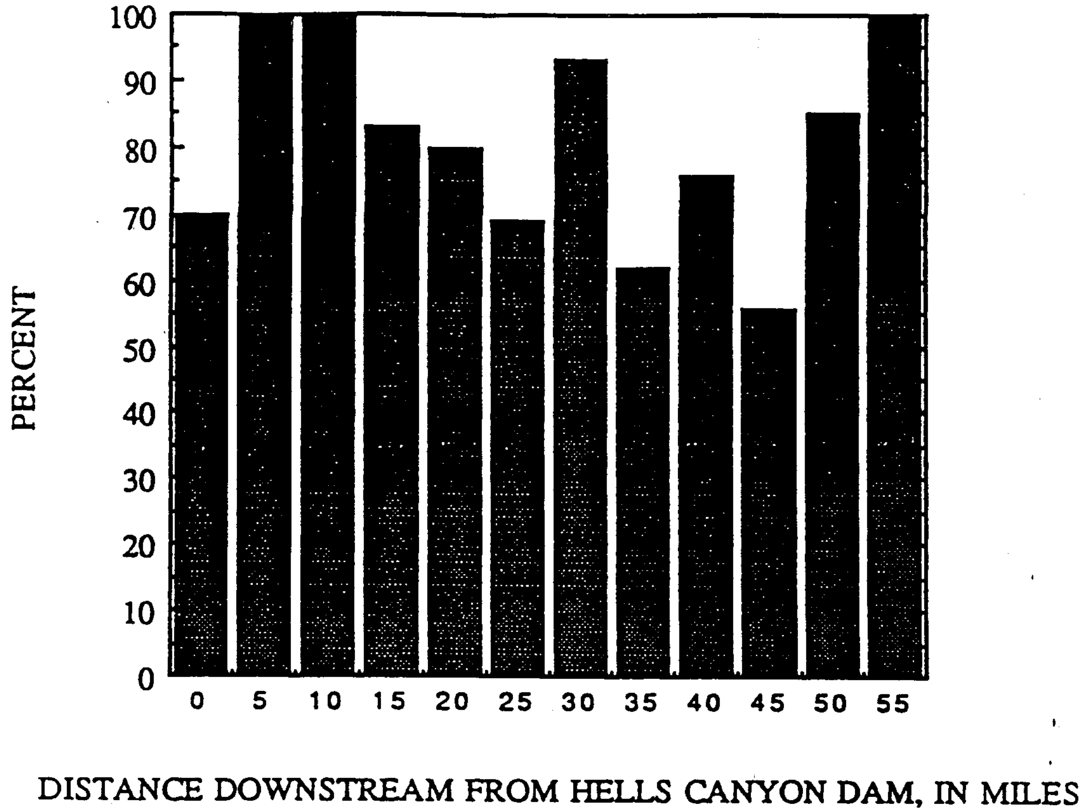


Figure 43. -- Change in area of exposed sand for each bar type, 1964 - 1982.

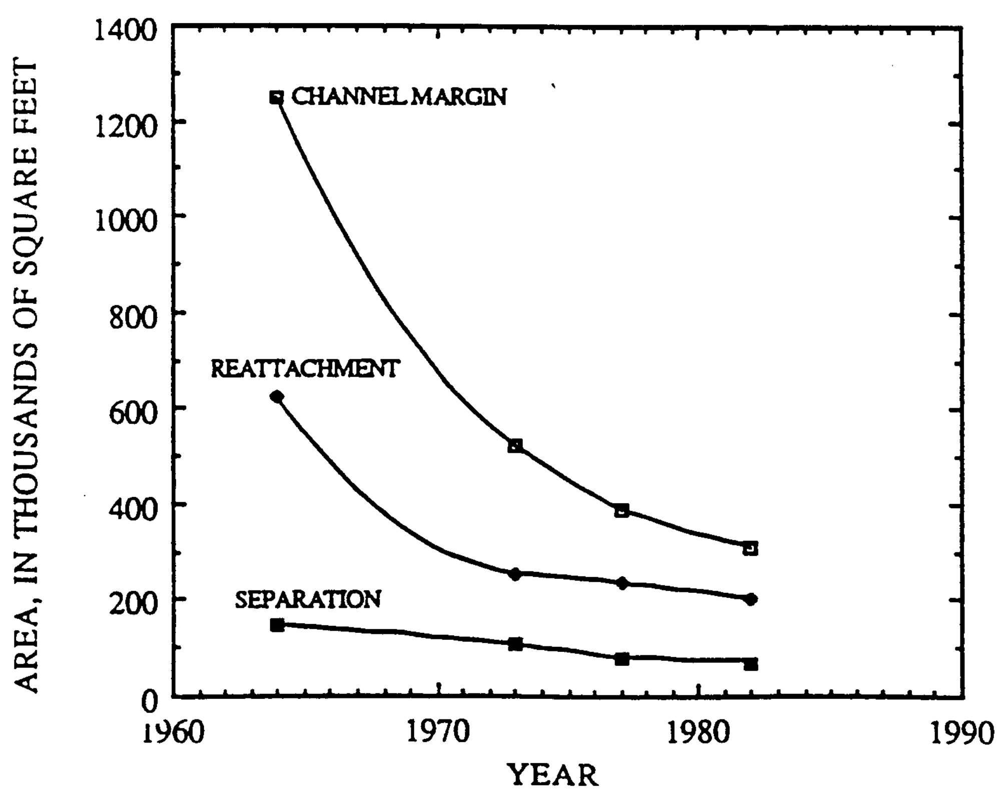


Figure 44. -- Average area of sand bars of each bar type, 1964 - 1982.

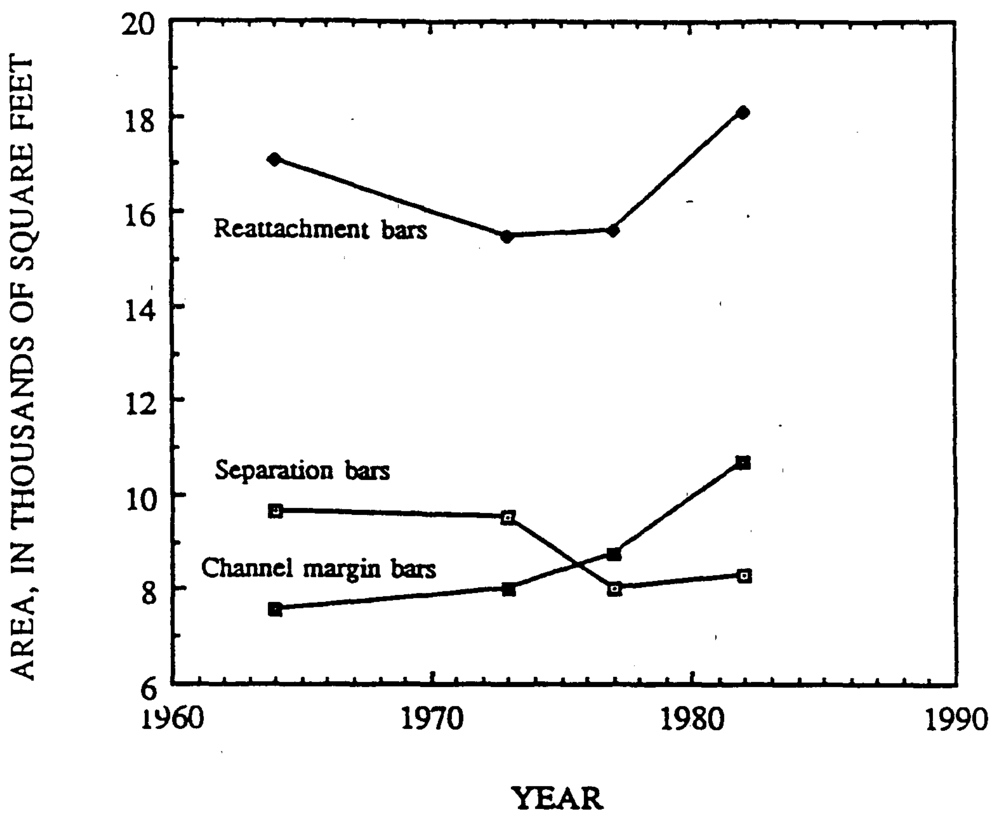
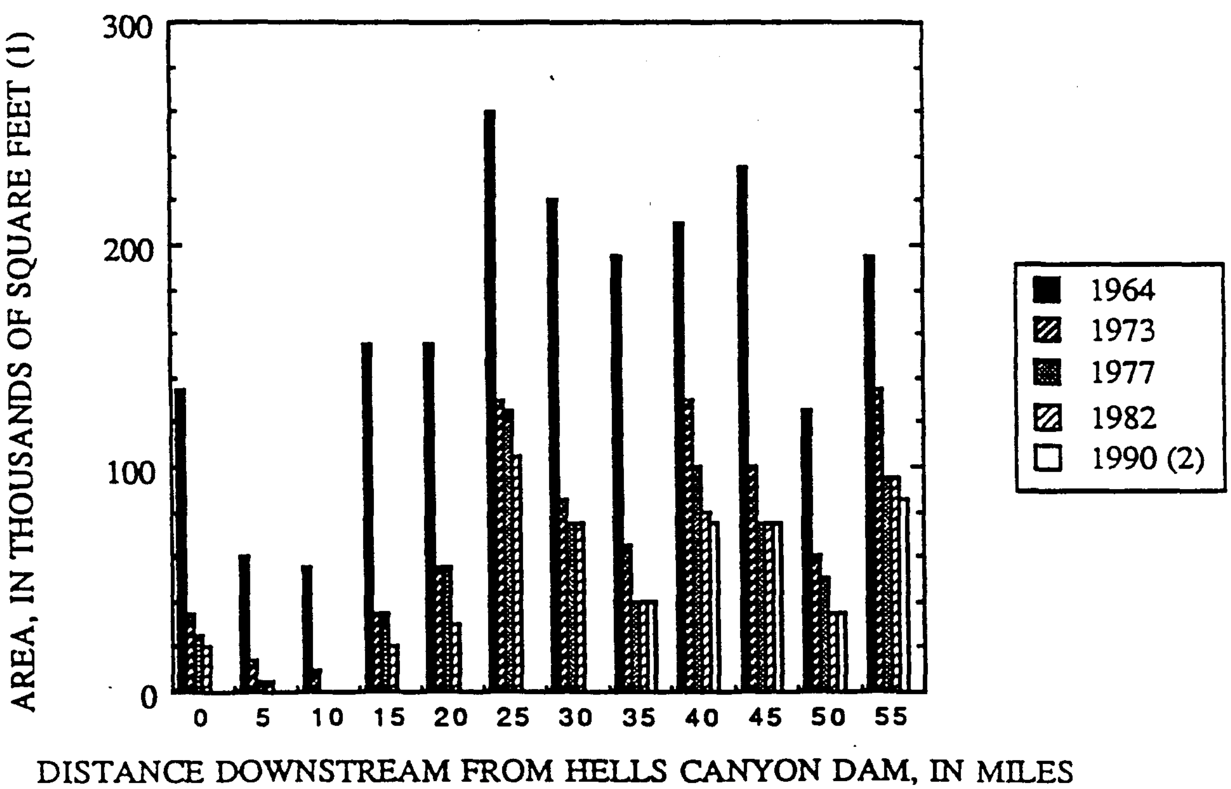


Figure 45. -- Change in area of exposed sand by 5-mile reach, 1964 - 1990.



(1) For 5-mile reach downstream of indicated mile. (2) Applies only to reaches 35 - 55.

caused by the selective erosion of small bars, discussed above. Relative to the 1964 and 1982 photographs, the discharge at the time of the 1973 and 1977 photographs was low. Therefore average area increases between 1964 and 1973 could be due to differences in river stage. However, since discharge is higher in 1982 the changes between 1977 and 1982 shown in Figure 44 likely represents actual change.

Downstream Changes in Distribution of Sand Bars

The pattern of change was very similar in each 5-mi segment of the study reach. Figure 45 shows the change in total area of sand bars for each of these segments between 1964 and 1982; 1990 values are given for segments 35 - 60. In all reaches there was a large decrease in area of exposed sand between 1964 and 1973 followed by less dramatic change or no change. Segments 25, 30, 35, and 45 exhibited the most change between 1964 and 1973. Area of sand in each of these reaches decreased by about 140,000 ft^2. Reach 25 shows the greatest change between 1964 and 1982, and reach 45 shows a similar amount of change for the entire 1964 - 1990 period. Viewed as a sequence, figures 18 and 46 A-C show how the downstream distribution of sand-bar types has changed as the area of sand decreases. Although the areas are much less, the distribution remains similar in 1982. Channel margin bars cover more area in the downstream half of the canyon and reattachment bars are concentrated in the middle segments of the canyon. Although certain types appear to be more stable in some reaches, there is no reach in which all bar types are stable. The area of exposed separation bars is completely stable in reaches 0 and 30. Reattachment bars are most stable, reduced by about 50 percent in reaches 25, 30, and 45. Channel margin bars are most stable, reduced by about 60 percent, in reaches 40, 50, and 55. Every bar type has been eliminated in at least one reach.

The 1990 condition of sand bars along the Snake River between Pittsburg Landing and the Salmon River confluence is similar to the condition of the bars in 1982. Figure 47 shows frequency of bars below Pittsburg Landing for 1955, 1964, 1973, 1977, 1982, and

Figure 46 A. -- Exposed area of sand bars of indicated type by 5-mile reach, 1973.

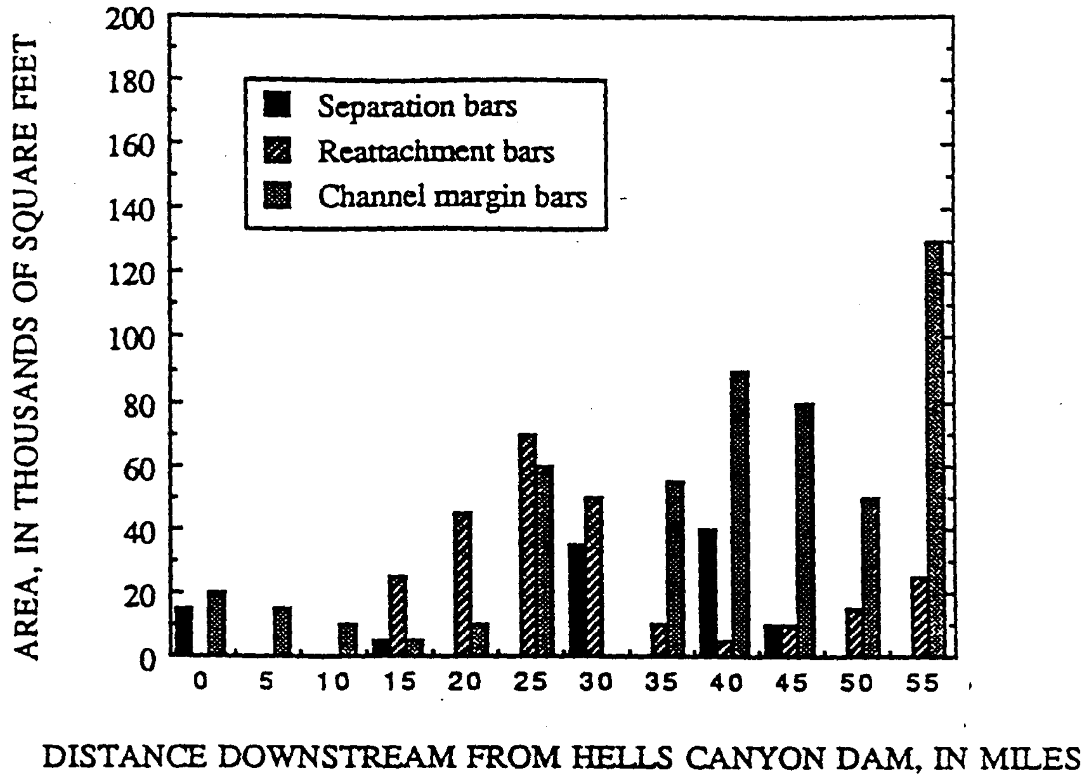


Figure 46 B. -- Exposed area of sand bars of indicated type by 5-mile reach, 1977.

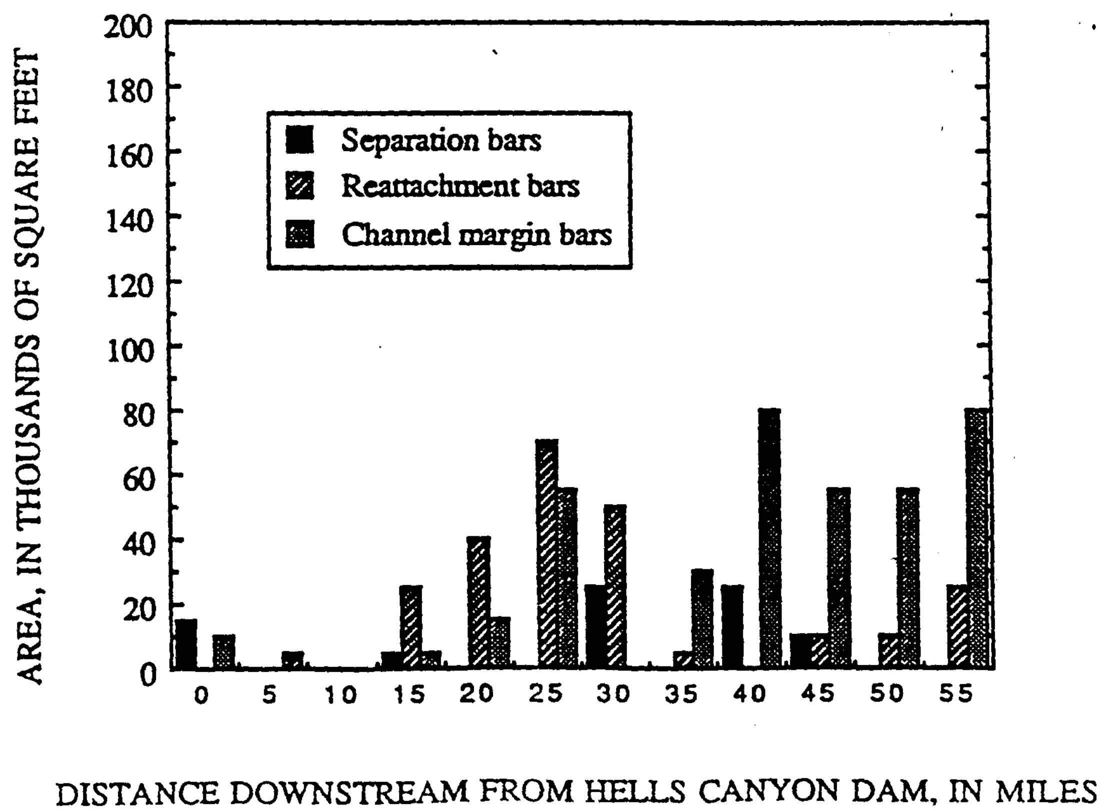


Figure 46 C. -- Exposed area of sand bars of indicated type by 5-mile reach, 1982.

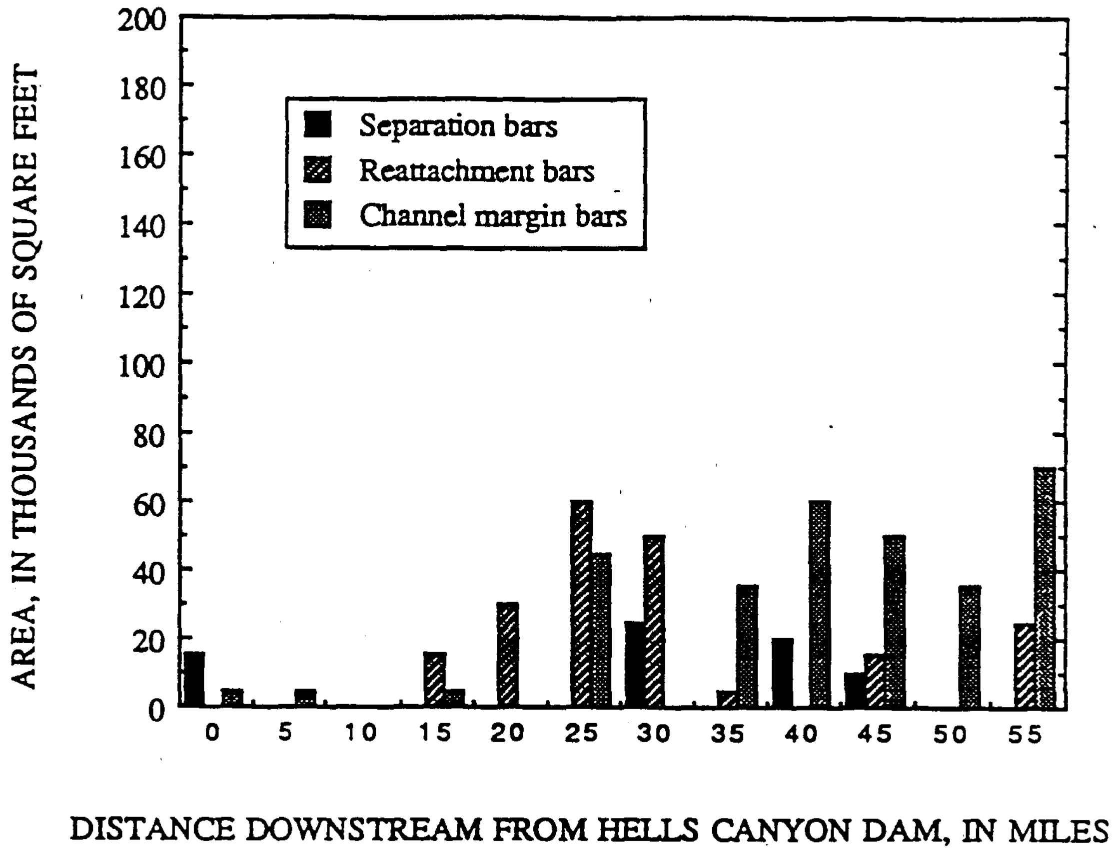
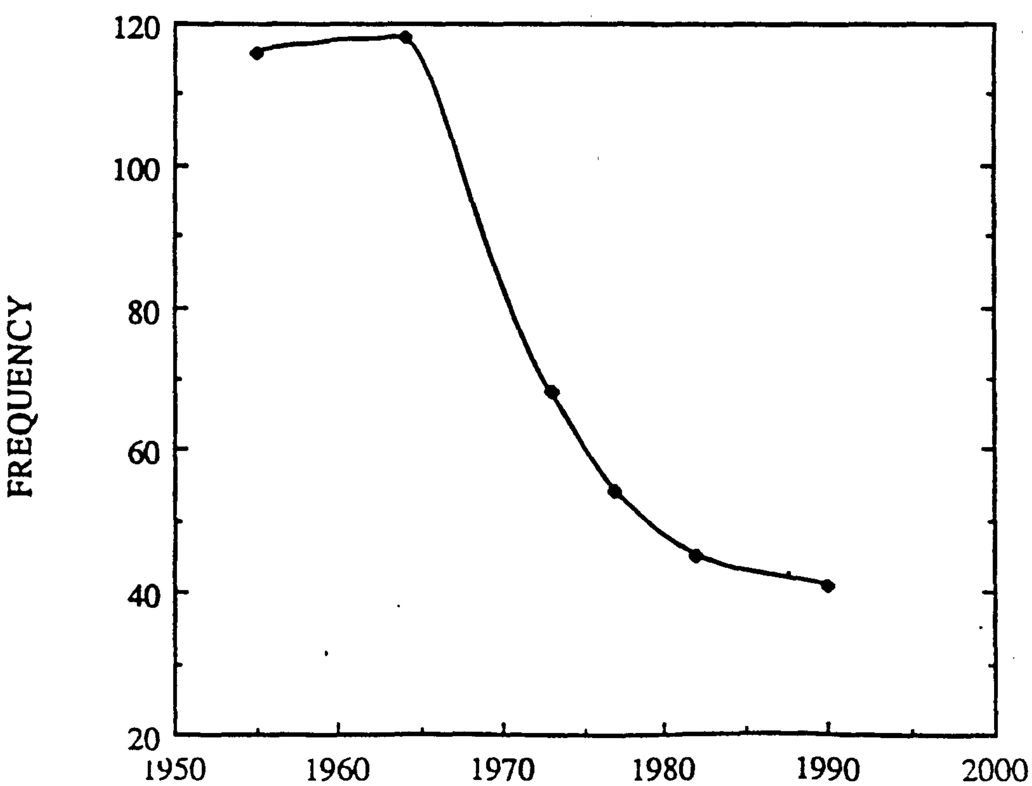


Figure 47. -- Frequency of sand bars below Pittsburg Landing, 1955 - 1990.



1990. The change between 1982 and 1990 is relatively minor. Figure 48 shows the total area of sand below Pittsburg Landing.

7. DISCUSSION

Flows Associated with Sand Bar Change

Most of the change in the frequency and extent of sand bars took place between 1964 and 1973. In this period three high peak annual flows occurred which were significantly larger than the mean annual peak flow. The highest of these floods occurred in 1965 and the others in 1971 and 1972 (Figure 9). These were the largest floods to occur subsequent to the filling of Brownlee Reservoir in 1958, and before 1982. Thus, they were the first clear-water, or sediment-starved, floods to flow through Hells Canyon. Schmidt (1990) proposed that sand bars in Grand Canyon are the most susceptible to significant change during high discharges. The changes in extent of sand bars in Hells Canyon between 1964 and 1973 are most likely a result of the highest flows in that interval. The distribution of mean daily flows during this period was similar to other time intervals as shown on the flow duration curves. The high peak floods which occurred during this interval are therefore a characteristic which distinguish it from the preceding post-Brownlee Reservoir interval. Several flows of similar and greater magnitude have occurred since 1973, yet the rate of change in extent of sand bars has substantially decreased. This suggests that recovery does not occur between destructive events, and therefore, that each subsequent destructive event will be of less geomorphic significance to the sand deposits.

There is no evidence visible in the air photographs to suggest building of sand bars took place between 1964 and 1982. Sand bar recovery is inhibited by the blocking of sediment input by the Hells Canyon Complex. A flood similar in magnitude to the 1971 and 1972 floods also occurred in 1957, prior to the closing of Brownlee Dam. In the interval between the 1955 and 1964 photographs there was no significant change and possible aggradation of sand bars. It therefore seems possible that a destructive event and recovery can both occur within a relatively short time interval. As described by Schmidt and Graf (1990) degradation and aggradation may occur during the same flood at different moments. In the Grand Canyon a sand bar was observed to erode in the early stages of a flood then aggrade during peak flow recession.

Erosion of high terraces observed at the detailed study sites was most pronounced between 1970-1973. Although at one site erosion of the high terrace has been continuous up to 1990. The discharge required to erode a high terrace and the discharge required to submerge most of the sand bars is similar. Therefore, the rate of erosion of the terraces may parallel the rate of sand bar erosion. This would suggest that most erosion occurred between 1970 - 1973. This could be investigated by completing a detailed analysis of the 1970 air photographs. If most of the change did occur during 1970 - 1973 the 1965 high flood did not have a large erosive impact on the sand bars. During the high floods in the 1960's the river may have scoured sediment from the channel, postponing large scale erosion of the bars until after that source was depleted. It is also possible that the effects on the sand bars are related to Hells Canyon Dam specifically, which began filling its reservoir in October, 1967. Because the dams were constructed beginning upstream and moving downstream, sand eroded from the reaches which are now submerged by the Oxbow and Hells Canyon reservoirs may have supplied sufficient sediment to minimize the downstream changes until Oxbow Dam and Hells Canyon Dam were built.

Models of Sand Bar Change

The decrease in sand bar frequency can be described using an exponential curve-fit, shown in Figure 48. The exponential decay function describes the change between 1964 - 1982 exceptionally well and therefore deserves consideration as a model for sand bar change. The 1955 bar frequency is similar to 1964 and does not fit the exponential relation fro reasons described above. Also, as shown in Figure 49 which considers the downstream half of Hells Canyon, the agreement of the exponential relation decreases

Figure 48. -- Fr ency of sand bars below Pittsburg La ıg showing exponential decay relations.

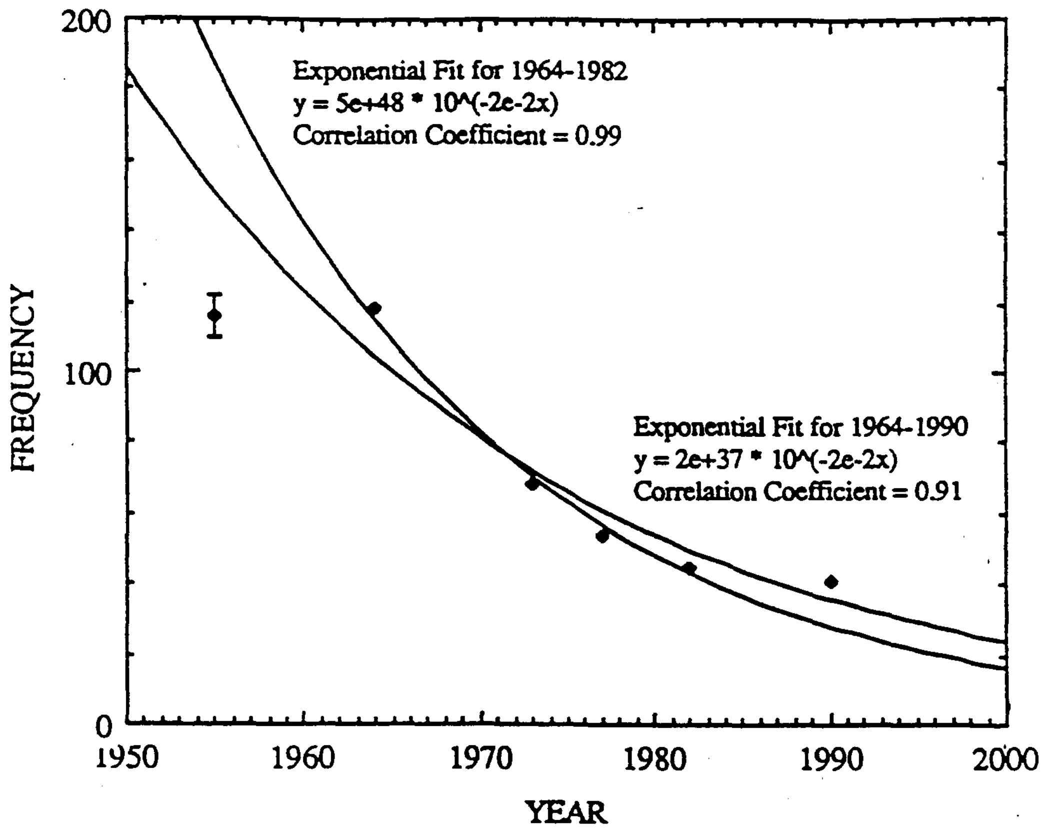
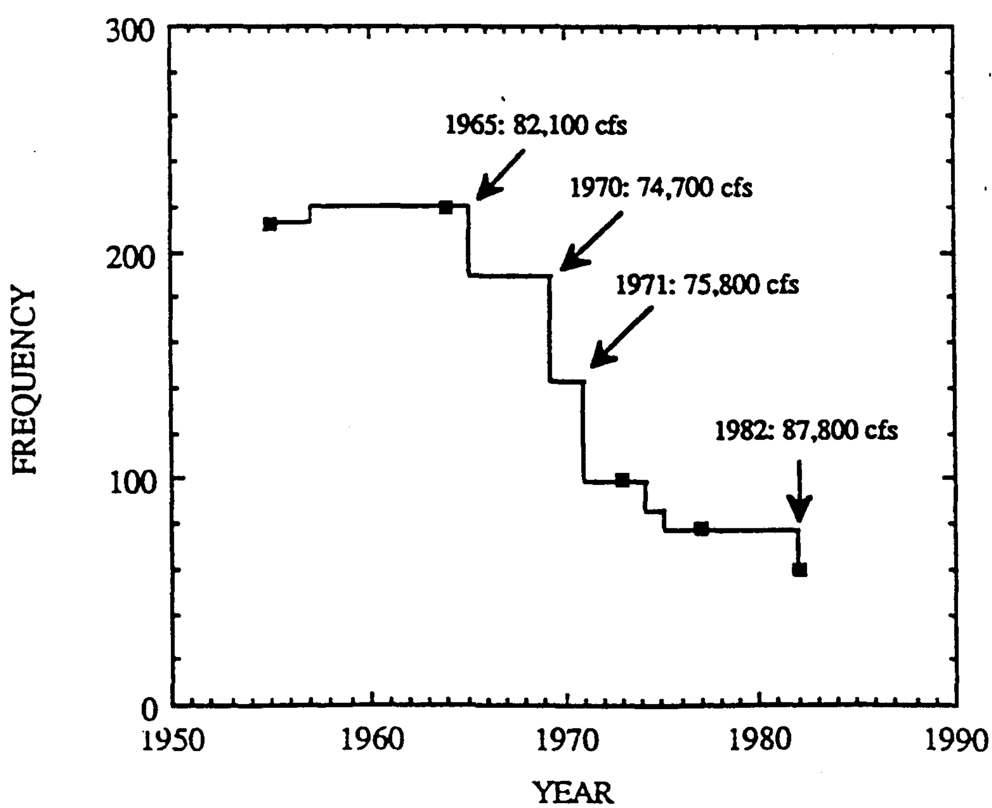


Figure 49. -- Sand bar frequency, 1955 - 1982, showing step model of sand bar change.

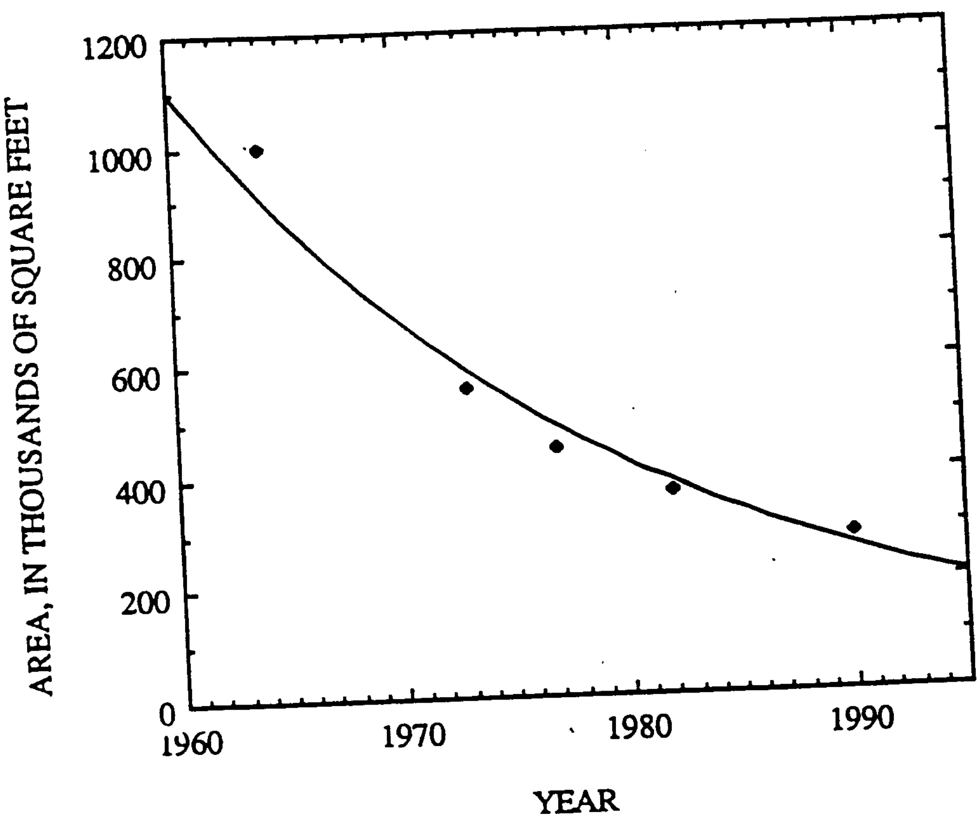


when the 1990 bar frequency is added to the curve. This suggests that the use of the exponential decay function to describe sand bar change is limited to the interval during which erosion progresses most rapidly. This interval does not necessarily begin immediately after the beginning of dam operations. The decay begins after some initial resistance to erosion, such as an in-channel sediment supply, breaks down.

The exponential decay model ceases to apply once the quantity of sediment stored in sand bars and available for erosion is depleted to an extant that a continued high-rate of erosion is no longer possible. This is similar to the models of geomorphic change discussed by Wolman and Gerson (1978) and Kochel (1988). Potentially destructive flow events, such as those which occurred in the 1980's, can not have a destructive impact if there has been insufficient time for the land forms to recover. Sand bars, however, may have a very rapid recovery time. Their recovery is therefore dependant upon the simultaneous occurrence of suitable conditions for deposition. These conditions are first, sufficiently high flow to activate the recirculation zone or other depositional environment, and second, an abundant supply of sediment in transport. Since there is no sediment supply below the dams in Hells Canyon, there is essentially no possibility for recovery. High floods have been destructive forces, though with diminished impact, or geomorphic effectiveness, as the supply of sand decreased.

Above, I suggested the possibility that most change occurred between 1970 - 1973 based upon the analysis of the detailed study sites. If the change did occur in this sequence the exponential decay model would be even less likely to be significant. Even if 1970 - 1973 was not the interval of most change another model of change which incorporates individual flow events may be more applicable. Because floods are catastrophic events of relatively short duration, changes effected by floods occur very rapidly, perhaps in a number of hours or a few days. As a result change, on a time-scale of years, would occur in steps rather than in a smooth and continuous decline. Figure 50 shows this model

Figure 50.--Total area of exposed sand below Pittsburg Landing, 1964 - 1990, with exponential curve-fit applied.



applied to sand bar change in Hells Canyon. The steps were placed to coincide with the highest discharges during the intervals between the bar frequency data points.

The effects of fluctuating flows have not been included because detailed data on fluctuating flows are not available at this time. Fluctuating flows have been shown to erode bar surfaces in the Grand Canyon (Schmidt and Graf, 1990). It has not been demonstrated, however, that fluctuating flows cause large scale changes which require that the sand bar be submerged. The discharge required to erode high terraces in Hells Canyon is above the range of power plant operations and fluctuating flow. It was observed during summer 1990 that the elevation of eroded bar surfaces was typically in the vicinity of a ubiquitous high water mark. This water-mark represents a discharge of about 45,000 ft^3/s according to experienced Hells Canyon river-runners. Thus, much of the sand that has been removed from the bars in Hells Canyon was likely not typically affected by fluctuating flow. However, once bar elevations are reduced by high flows the bars may then be more susceptible to erosion by fluctuating flows.

Sand Bar Change 1982 - 1990

Between 1982 and 1990 there has been little change in the total number of sand bars or in the total area of exposed sand in Hells Canyon below Pittsburg Landing. This reach of Hells Canyon, which extends from 35 - 60 mi below Hells Canyon Dam, initially contained a slightly larger average area of exposed sand per 5-mi reach than the first 35 mi below the dam. However, this stretch contains relatively more channel margin bars in comparison with reaches 15 - 30 which contain more reattachment bars. The rate of sand bar erosion between 1955 and 1982 has been similar in all reaches (Figure 45). Therefore the change below Pittsburg Landing is likely indicative of the pattern of change throughout the entire canyon.

The number of sand bars between Pittsburg Landing and the Salmon River confluence decreased only by 2 percent between 1982 and 1990; and the area of exposed sand in the same reach decreased by about 4 percent. This rate of change is likely a characteristic rate of change for the entire 60-mi reach below Hells Canyon Dam. However, the magnitude of these changes is small and lies within the margin of error for frequency and areal analysis. The actual area of exposed sand in 1990 is similar but slightly greater than the area suggested by exponential decay (Figure 51). The most likely explanation for the large decrease in the rate of change is that as erosion proceeds less erodible material is exposed along the banks.

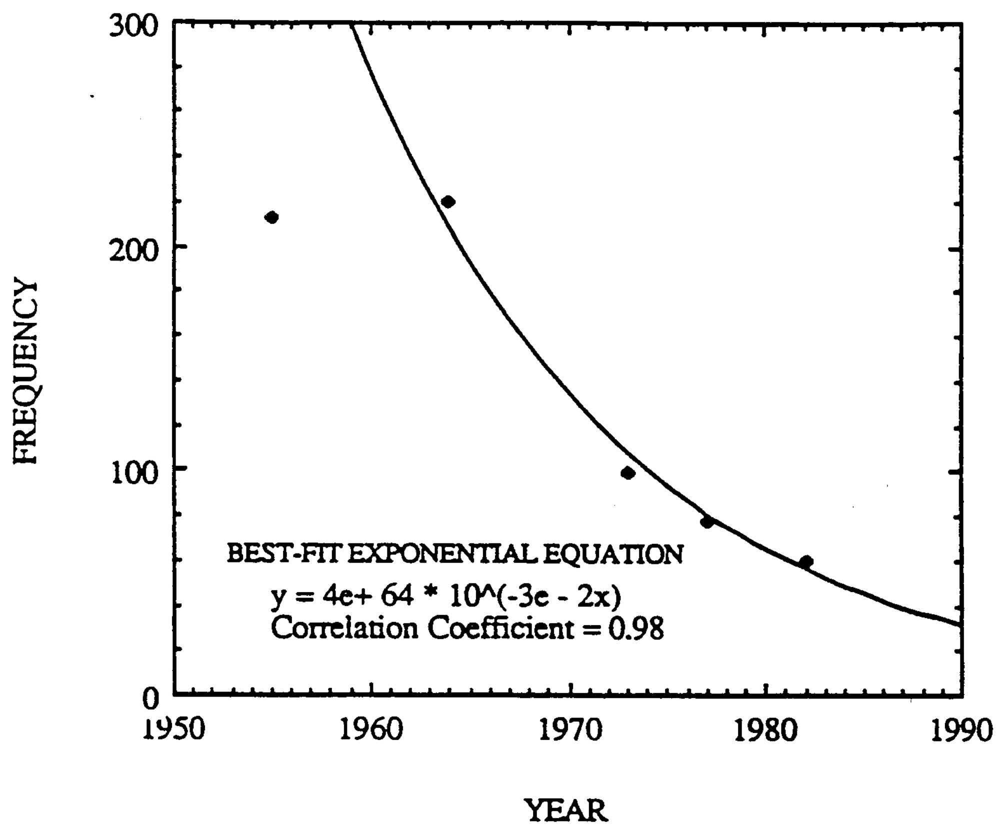
Erosion of the high terraces between 1982 and 1990 has been variable at the different detailed study sites. At Salt Creek Bar, erosion of the high terrace occurred between 1982 and 1990, during which time it was cut back about 30 ft. At Pine Bar, Fish Trap Bar, and China Bar there has been no significant change. Armoring gravels, such as occur at Fish Trap Bar, have likely checked further cutbank retreat. Local conditions are, therefore, important factors capable of significantly affecting continued erosion. Armoring may arrest erosion of cutbanks that otherwise would continue to erode.

Further erosion of the high terraces can be expected at sites where the bar is not armored with gravels. The terraces are likely subject to erosion only at high flows. The minimum required flow would be similar in magnitude to the flow that would submerge the associated sand bar. Thus, cutbank erosion and sand bar re-working may occur simultaneously. Cutbank retreat effectively increases the size of channel expansions and the resulting eddy. A larger eddy is, theoretically, more likely to develop a large sand bar. However, in the absence of a sediment supply, eddy size may not be significant since bars are not aggrading. Sand from bars may be less likely to be entrained during events in which the cutbanks are eroding and filling the eddy with sediment sufficient to meet the local transport-capacity of the river. It is also possible for a bar to migrate onshore after a retreating cutbank, as has occurred at Salt Creek Bar.

Sand Bars in Bedrock Canyons

The Colorado River in Grand Canyon is similar to the Snake River in Hells Canyon in that it is a large river flowing through a bedrock canyon below a large hydro-electric

Figure 51. -- Sand bar frequency, 1955 - 1982, with exponential curve fit applied to 1964 - 1982 data.



dam. Both rivers encompass in their drainage basins mountainous regions , and arid to semi-arid regions. The Grand Canyon extends from 17 mi to about 240 mi below Glen Canyon Dam. Because Hells Canyon is relatively short it was possible to include every bar in the first 60 mi below the dam in the study. The Hells Canyon National Recreation Area extends only another 8-mi downstream from this point. In Grand Canyon such a study including every sand bar would be more difficult and has not been done. Workers in Grand Canyon have concentrated on documenting temporal change in area and elevation of the large separation and reattachment bars. The channel margin bars, which do occur in Grand Canyon, have not been studied closely. A closer study of channel margin bars in Grand Canyon might reveal that more erosion is occurring than is presently believed. It is also possible that a continued study of reattachment deposits in Hells Canyon, including re-surveys of bars would show vertical components of change in bars that have not changed significantly in size.

The two systems differ significantly in basin characteristics and the nature of sand bar change. In the Colorado River below Glen Canyon Dam the tributaries do not add significantly to the annual water budget. They do, however, provide an important sediment source for the Colorado River. Floods in tributary basins can cause the Colorado River to be brown or red with sediment for several days. The Paria River which flows into the Colorado River above Grand Canyon, and the Little Colorado River which joins the Colorado in the upper reaches of the Grand Canyon are examples of tributaries with large drainage basins that flood regularly. These floods typically transport large amounts of sediment. In Hells Canyon above the Salmon River confluence there are no tributaries with large drainage basins capable of delivering a significant sediment supply. One and one-half miles upstream from the Salmon River confluence the Imnaha River, which may be large enough to be a significant sediment source, flows into the Snake River. Sand bars below the Salmon River confluence were not inventoried. However, field observations made in summer 1990 indicate that sand bars along the Snake River are, in fact, more frequent below this point. Thus, while tributaries in Grand Canyon may provide large amounts of sediment, there is very little to no sediment influx in the Snake River between Hells Canyon Dam and the Salmon River.

The reservoirs above Hells Canyon and Grand Canyon also differ in their effectiveness in regulating flow. The ratio of reservoir storage to annual runoff is 2.32 in the Colorado River basin above Grand Canyon and is 0.26 for the entire Columbia River basin (Hirsh and others, 1990). Since these values tend to increase downstream, the ratio of reservoir storage to runoff in the Snake River above Hells Canyon is likely less than 0.26. This means Glen Canyon Dam is better able to regulate the flow in Grand Canyon than is the Hells Canyon Complex able to regulate flow in Hells Canyon. Only in 1983 did a clear-water flood below Glen Canyon Dam equal the magnitude of the pre-dam mean annual flood. Otherwise the largest post-dam floods have been about one-half the magnitude of the pre-dam average annual flood. The highest peaks in Hells Canyon post-Brownlee dam are similar to the pre-Brownlee dam peaks and the mean annual peak has not been affected. However, changes in the sand bars in Hells Canyon have been far more dramatic than in the Grand Canyon. Although lack of sediment supply may be considered the primary cause of sand bar degradation in Hells Canyon, the relative stability of the annual hydrograph in Hells Canyon has likely been an equally significant contributing factor. More precisely, the high flows and lack of sediment, in conjunction, is the likely cause of the sand bar instability. Empirical studies have related sediment transport to the cube of stream power, which is proportional to mean velocity (Colby, 1964). Thus, during a peak flow event when discharge and velocity are very high, the rate of sediment transport may be expected to be high as well. Theoretically, a sediment-poor flood should entrain sediment from the bed and banks until an equilibrium between sediment transport and transport capacity is reached. The annual floods associated with spring snowmelt that are released into Hells Canyon through the dam complex have been empty of sediment since the dams were constructed.

In bedrock gorges such as Hells Canyon and Grand Canyon, sand bars are generally the most erodible material along the river bank (although in Hells Canyon the high terraces have also exhibited erosion). Floods, therefore, tend to be destructive events when there is an interruption of the sediment supply. In the Grand Canyon, erosion has not been as dramatic because high flows have not occurred frequently. Moreover, in the Grand Canyon sediment input from tributaries is likely to enable aggradation of sand bars to occur. Glen Canyon Dam has not created a system as completely unable to recover as have the dams above Hells Canyon. Figure 52 compares the relative effects of different dams on streamflow and sediment transport . The results from this study of sand-bar change in Hells Canyon suggest that most erosion will occur in systems where change in sediment delivery is large and change in peak floods in small.

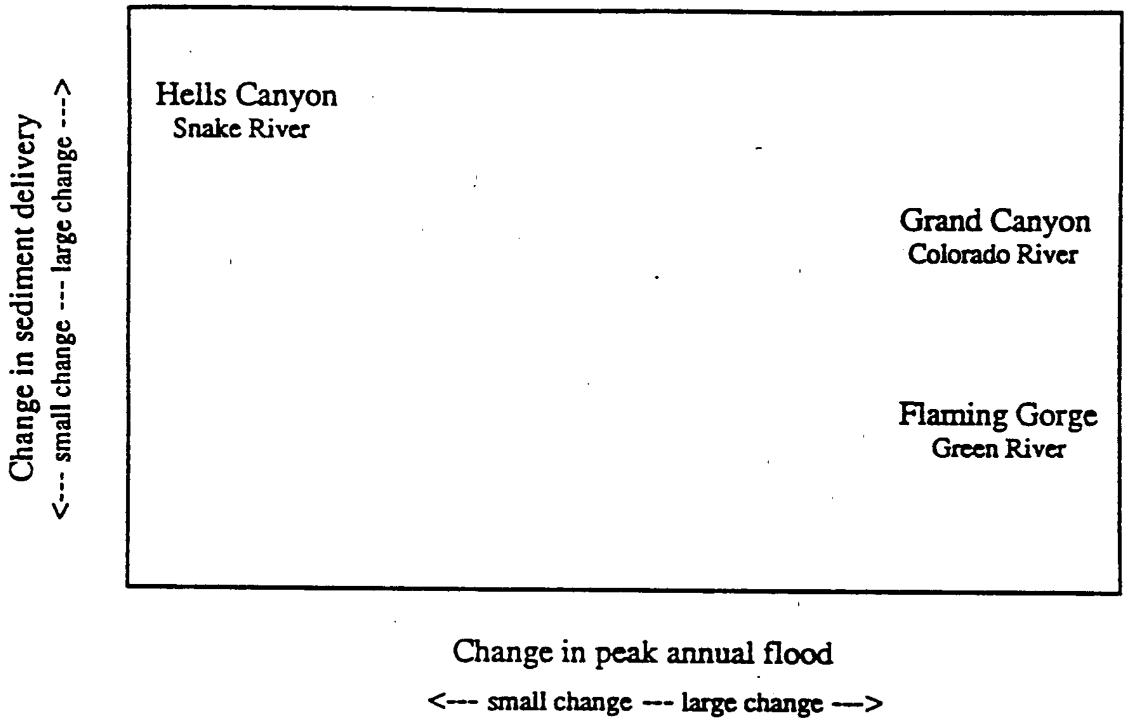
8. CONCLUSIONS

The dams of the Hells Canyon Complex have not significantly altered the frequency or the magnitude of peak flows in Hells Canyon. The character of flow duration curves and peak-flood recurrence intervals are very similar pre- and post-regulation of flow. The dams are, however, an effective barrier preventing sediment from entering Hells Canyon. Therefore only clear-water flows are released into Hells Canyon.

Erosion of sand bars and alluvial terraces occurred between 1964-90. The frequency and area of sand bars decreased by over 75 percent between 1964-73. The pattern of change was similar over the entire 60-mi reach between Hells Canyon Dam and the Salmon River confluence. Separation bars, reattachment bars, and channel margin bars all experienced some erosion. However, channel margin bars, which far outnumber the other bar types, were eroded the most.

Erosion of the sand bars began after 1964, over 6-yrs after Brownlee Dam began flow regulation in Hells Canyon. By 1973 a large amount of change had occurred. Between 1973-77 rapid erosion continued. Between 1977-82 and 1982-90 erosion

Figure 52.– Effects of dams on sediment delivery and peak annual floods.



continued at a decreasing rate. The rate of erosion of sand from high terraces was similar to the rate of sand bar change in that erosion began after 1964 at a rapid rate. Erosion decreased and halted at sites where the eroding cutbank became armored with coarse material. Erosion of high terraces has continued to present at some sites. The initial period of change, 1964-73, is associated with the first series of large clear-water floods released from the dams. Decreased rates of erosion are due to a decreasing availability of erodible material as sand bars are only eroding and not rebuilding.

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APPENDIX

Index of Sand Bars in Hells Canyon

Sand Bar Identification (1)		River Mile(2)	Site (3)	Sand Bar Size Category(4)					Area
				1964	1973	1977	1982	1990	1990 (5)
18-17	CM/L-1	246.91	HCD-Launch	5	0	0	0		
18-17	CM/L-2	246.9	HCD-Launch	5	0	0	0		
18-17	CF/L	246.81	HCD-Launch	5	0	0	0		
18-18	CM/L	245.8		15	5	0	0		
18-18	CM/R	245.7	Lamont Spr.	15	0	0	0		
18-245	CM/R	245.3	Square Beach	15	5	5	5		
18-245	S/R	244.7	Brush Cr.	25	15	15	15		
18-245	CM/R	244.6		5	5	0	0		
18-246	CM/R	244.2		5	0	0	0		
18-246	CM/R-2	244		5	5	5	0		
18-247	CM/R	243.4		5	0	0	0		
18-247	R/R	243.3		15	0	0	0		
18-248	CM/R-1	243.1	Warm Spr.	5	0	0	0		
18-248	CM/R-2	242.91		5	0	0	0		
18-248	R/L	242.9		5	0	0	0		
18-249	CM/R	242.5		5	5	5	5		
18-249	R/L	242.2	Battle Cr.	15	0	0	0		
18-250	CM/L	241.9	Sand Dunes	5	0	0	0		
18-250	CM/R	241.6	Birch Spr.	0	5	0	0		
18-250	R/L	241.3		5	0	0	0		
18-251	CM/L-1	241		5	0	0	0		
18-251	CM/L-2	240.7		5	5	0	0		
18-240	S/R	240		5	0	0	0		
18-238	CM/R-1	238.7		5	0	0	0		
18-238	CM/R-2	238.5		5	0	0	0		
18-238	CM/R-3	238.3		5	0	0	0		
18-262	CM/R	237	Dry Gulch	5	0	0	0		
18-262	R/R	236.6	Hastings	5	0	0	0		
18-263	CM/R	236.4		5	0	0	0		
18-263	CF/L	236.3		5	5	0	0		
18-264	CM/R	236		5	0	0	0		
18-264	R/L	235.8		5	0	0	0		
18-264	CM/R	235.5		5	0	0	0		
18-147	CM/R	235.1	Bernard Cr.	5	5	0	0		
18-149	CM/R-1	234.02		5	0	0	0		
18-149	CM/R-2	234.01		5	0	0	0		
18-149	CM/R-3	234		5	0	0	0		
19-224	CM/L	231.3	Rush Cr.	5	0	0	0		
19-225	CM/L	230.9		5	0	0	0		
19-225	CM/R	230.5		5	0	0	0		
19-294	R/R	229.8	Johnson Bar	35	25	25	15		
19-294	CM/L	229.7		5	0	0	0		
19-293	CF/L	229.3		5	0	0	0		
19-293	S/R	229.2		5	0	0	0		
19-293	R/R	229.1		5	0	0	0		

19-293	S/R	229		5	5	5	0		
19-293	R/R	228.8		15	0	0	0		
19-293	CF/L	228.7		15	5	5	5		
19-293	CM/L	228.6	Yreka Bar	5	0	0	0		
19-293	CM/R	228.5		5	0	0	0		
19-292	CM/R	228.4		5	0	0	0		
19-292	R/L	228.1		15	0	0	0		
19-292	CM/R	228.01		5	0	0	0		
19-292	CM/L	228		5	0	0	0		
19-292	CF/R	227.9		5	0	0	0		
19-292	R/L	227.8		5	0	0	0		
19-291	CM/R	227.6		5	5	5	0		
19-291	R/R	227.5	Pine Bar	35	35	35	25		
19-291	CF/L	227.4		5	0	0	0		
19-291	CF/L	227.3		5	0	0	0		
19-291	R/R	226.8		5	0	0	0		
19-290	R/R	226		15	5	5	5		
19-290	CM/R	225.9		5	0	0	0		
20-5	R/L	224.6		5	0	0	0		
20-5	R/L	224.4		15	5	0	0		
20-5	CM/R	224.3	Big Bar	5	5	5	0		
20-6	CM/L	223.6		5	0	0	0		
20-7	CM/L-1	223.1		5	0	0	0		
20-7	CF/R	223		5	0	5	0		
20-7	CM/L-2	222.9		25	0	0	0		
20-7	CF/L	222.8		15	0	0	0		
24-169	R/L	222.4	Salt Creek	35	35	35	35		
24-169	CM/L-1	222.2	Two Corral	25	0	0	0		
24-169	R/R	222.1		15	5	5	0		
24-169	CM/L-2	222		5	5	5	0		
24-170	CM/R	221.7		5	5	5	5		
24-170	S/R	221.6		5	0	0	0		
24-170	R/R	221.5	Half Moon Bar	25	5	5	0		
24-170	R/L	220.8		35	25	25	25		
24-170	CM/R	220.6		5	0	0	0		
24-163	CM/L	220	Yankee Bar	5	5	5	5		
24-163	R/L	219.9		25	0	0	0		
24-162	CM/R	218.8	Kirby Cr.	35	35	35	35		
24-162	CM/L-1	218.6		15	0	0	0		
24-162	CM/L-2	218.5		5	0	0	0		
24-190	CM/R-1	218.3		5	0	0	0		
24-190	CM/R-2	218.2		5	5	5	0		
24-190	CM/L	218.1		5	0	0	0		
24-190	CM/R-3	217.9		5	5	0	0		
24-189	CM/R	217.4		15	0	0	0		
24-189	R/R	216.9		25	0	0	0		
24-188	R/L	216.4	Fish Trap	35	35	35	35		
24-188	R/R	216.3	Up.Pittsburg	15	0	0	0		
24-188	R/L	215.7		5	0	0	0		
24-188	CM/L	215.6		15	0	0	0		
24-187	CM/L	215.3		15	0	0	0		

24-158	S/L	214.71	Pittsburg Adm	25	35	25	25		
24-158	R/L	214.7	Pittsburg Adm	35	15	15	15	25	28800
24-157	MC/M	213.91		5	0	0	0	0	0
24-157	CM/L	213.9		15	15	5	5	5	2700
24-156	CM/L-1	213.2		5	0	0	0	0	0
24-156	CM/R	213.11		5	0	0	0	0	0
24-156	CM/L-2	213.1		5	0	0	0	0	0
24-156	CM/L-3	212.6		5	5	5	5	5	2100
24-156	S/R	212.5		5	0	0	0	0	0
24-156	R/R	212.4		15	5	5	0	0	0
24-156	CM/R-2	212.3		5	0	0	0	0	0
24-181	CF/R	211.91		5	5	5	5	5	T
24-181	CM/L	211.9	McCarty Cr.	25	15	15	5	5	2700
24-181	CF/L	211.8		5	0	0	0	0	0
20-20	CM/R-1	211.7		5	0	0	0	0	0
20-20	CM/L-1	211.6		5	0	0	0	0	0
20-20	CF/L-1	211.4		5	5	5	5	5	1200
20-20	CM/L-2	211.2		5	5	5	0	0	0
20-20	CM/L-3	210.7		5	0	0	0	0	0
20-20	CM/L-4	210.6		5	0	0	0	0	0
20-20	CF/L-2	210.51		5	5	0	0	0	0
20-20	CM/L-5	210.5		5	5	5	0	0	0
20-20	CM/L-6	210.4	Somers Range	5	5	5	5	5	T
20-20	CM/R-2	210.3		15	5	5	5	5	1400
20-21	CM/L-1	209.9	Camp Cr.	15	5	5	0	0	0
20-21	CM/L-2	209.7		5	0	0	0	0	0
20-22	CF/R	209.2		5	5	5	5	5	T
20-23	R/R	208.3	Jones Cr. **	15	5	5	5	5	T
20-23	R/L	208.2	Lookout Cr	25	0	0	0	0	0
20-24	CM/R	207.8		5	5	0	0	0	0
20-24	S/R-1	207.5	Marlboro B.**	5	5	5	5	5	T
20-24	CF/R	207.4		5	0	0	0	0	0
20-24	S/R	207.3		5	5	5	5	5	T
20-25	CM/L-1	206.9		5	0	0	0	0	0
20-25	CM/L-2	206.8		5	0	0	0	0	0
20-25	S/R	206.7		5	5	5	5	5	T
20-26	R/R	206.3	High Range**	25	0	0	0	0	0
20-26	CF/R	206		5	5	0	0	0	0
20-26	CM/L	205.9		5	0	0	0	0	0
20-26	CF/R	205.8		5	5	5	5		
20-27	R/R	205.7		5	5	0	0	0	0
20-27	CF/L	205.51		5	5	0	0	0	0
20-27	CM/L	205.5		5	5	5	0	0	0
19-267	R/L	205.3		15	0	0	0	0	0
19-267	CF/R-1	205.1		25	15	15	15	15	S
19-267	CM/R	204.81		35	35	35	25		
19-267	CF/L	204.8		5	5	5	0	0	0
19-267	CM/L-1	204.6		5	0	0	0	0	0
19-267	CM/L-2	204.5	Bob Cr.	5	5	5	5	5	T
19-267	CF/R-2	204.4		5	0	0	0	0	0
19-267	S/R	204.2		15	15	0	0	0	0

19-257	S/R	203.9		15	5	5	5	5	4500
19-257	CM/R	203.5		5	5	5	5	5	2800
19-257	CF/L	203.4		15	0	0	0	0	0
19-257	CM/L	203.1		5	0	0	0	0	0
19-258	CM/R-1	202.9	Wolf Cr. Camp	5	0	0	0	0	0
19-258	R/L	202.81		5	0	0	0	0	0
19-258	S/R	202.8		5	5	5	5	5	120
19-258	CM/R-2	202.5		5	5	5	5	5	1800
19-258	CM/L	202.41		5	5	0	0	0	0
19-258	CM/R-3	202.4		5	5	0	0	0	0
18-187	S/L	201.9	Bar Cr.	15	5	5	5	5	9000
19-14	CM/R-1	201.61		5	0	0	0	0	0
19-14	CM/R-1B	201.6		5	0	0	0	0	0
19-14	R/R-1	201.5		15	5	5	5	5	5400
19-14	CM/R-2	201.2		35	25	25	25	25	28000
19-14	CM/R-3	201.1		15	15	15	5	5	5000
19-14	R/R-2	201		15	5	5	5	5	2500
19-14	R/R-3	200.9	Dry Cr. Camp	15	0	0	5	5	200
19-14	CM/L	200.7		5	0	0	0	0	0
19-14	CM/R-4	200.3		5	5	5	5	5	2400
18-192	CM/L-1	200.1		5	5	5	5	5	800
18-192	CF/L-1	199.5		5	0	0	0	0	0
18-192	CF/R-1	199.4		5	0	0	0	0	0
18-192	CF/R-2	199.3		5	0	0	0	0	0
18-192	CF/R-3	199.21		5	0	0	0	0	0
18-192	CM/L-2	199.2		5	0	0	0	0	0
18-192	CF/R-4	199.13		5	0	0	0	0	0
18-192	CF/R-5	199.12		5	0	0	0	0	0
18-192	CF/L-2	199.1		5	0	0	0	0	0
18-83	S/L	199	Deep Cr. Camp	5	5	5	5	5	5600
18-83	CM/R	198.7		15	5	0	0	0	0
18-83	CM/L	198.5	Robinson Gulch	5	5	5	5	5	4800
18-83	CF/L-1	198.3	Dug Cr.	15	5	0	0	0	0
18-83	CF/L-2	197.7		5	0	0	0	0	0
31-248	R/L	197.4		15	0	5	0	0	0
31-248	CM/R	197.3		5	0	0	0	0	0
31-247	CM/R	195.3	Warm Spring	15	15	25	15	15	12600
19-20	CM/R-1	195		5	5	5	5	5	T
19-20	CM/L-1	194.9		5	0	0	0	0	0
19-20	CM/R-2	194.7		5	0	0	0	0	0
19-20	CM/R-2A	194.31		5	0	0	0	0	0
19-20	CM/R-2B	194.3		5	0	0	0	0	0
19-20	CM/R-2C	194.2		5	0	0	0	0	0
19-20	CM/R-3	194.11	Zig Zag	5	5	5	5	5	T
19-20	CM/L-2	194.1		5	0	0	0	0	0
19-20	CM/R-4	194.01		5	5	5	5	5	T
19-20	CM/L-3	194		5	5	5	5	5	T
19-20	R/L	193.8		25	15	5	0	0	0
19-20	CM/R-5	193.5		5	5	5	0	0	0
19-20	CM/R-6	193.3		5	5	0	0	0	0
19-178	CM/L-1	192.7		5	0	0	0	0	0

9-178	R/L	192.4	China Bar	15	15	15	15	15	13400
19-178	CM/R	192.21		5	5	0	0	0	0
19-178	CM/L-2	192.2		5	5	5	5	5	600
19-178	CM/L-3	192.1		5	5	5	5	5	300
21-233	CM/L	190.9		35	25	15	5	15	14000
21-233	CM/R-1	190.8		5	5	0	0	0	0
21-233	CF/L-1	190.3		5	0	0	0	0	0
21-233	CF/L-2	190.2		5	0	0	0	0	0
21-233	CM/R-2	190		5	5	5	5	5	1200
21-235	CM/R-1	189.8		5	0	0	0	0	0
21-235	CM/R-2	189.7		5	0	0	0	0	0
21-235	CM/L-1	189.6		5	5	5	5	5	T
21-235	CM/R-3	189.3		5	5	5	0	0	0
21-235	CF/L-1	189.2		5	0	0	0	0	0
21-235	CM/L-2	188.7		5	0	0	0	0	0
21-235	CM/L-3	188.61		5	0	0	0	0	0
21-235	CR/R-1	188.6		5	0	0	0	0	0
21-235	CF/L-2	188.5		5	5	5	5	5	2000
21-235	CF/R-2	188.4		5	0	0	0	0	0
21-235	CM/L-4	188.31		5	0	0	0	0	0
21-235	PB/R	188.3		5	5	0	0	0	0
21-235	CM/R-4	188.2		5	15	5	5	5	T
21-235	CM/R-5	188		35	35	25	35	15	17500

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.
"T" signifies sites which contained a small area of sand (less than 5,000 square feet) not measured precisely.