Review of existing studies and literature on the geomorphology, hydrology and sediment transport related to Hells Canyon, Snake River, Idaho

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Background and Scope

This report was requested by the Region 6 Regional Hydropower Assistance Team (RHAT) of the U.S. Forest Service to synthesize available information on the status of current scientific understanding of geomorphic, sediment transport, and hydrologic processes of the Snake River through Hells Canyon. Its purpose is to provide information relevant to developing and evaluating studies conducted under the Federal Energy Regulatory Commission (FERC) relicensing process for the Hells Canyon Dam Complex.

Hells Canyon is a spectacular, popular recreation area that has grown in use and interest in the public eye over the past decade. Many stakeholders are interested in the operation of the dams from federal agencies to private landowners to public citizens. The Hells Canyon reach of the river carries a federal Wild and Scenic River designation and is within a National Recreation Area. Both designations occurred in 1975, sixteen years after the completion of Brownlee Reservoir. The United States Forest Service (USFS) manages the river below the dams and is responsible for administering and protecting both the Wild and Scenic and National Recreation Area designations. FERC relicensing is providing a forum to evaluate and discuss dam-induced impacts, current and future studies, and future dam operations.

The Hells Canyon Complex, which is owned and operated by Idaho Power Company, is scheduled for relicensing in the year 2005. The Hells Canyon Complex consists of three dams within a 35-mile stretch of the Snake River. Brownlee Dam, the most upstream dam was completed in 1958, Oxbow Dam in 1961, and the farthest downstream, Hells Canyon Dam, was completed in 1968. The combined storage of the Hells Canyon Complex was one million acre-feet of water when the gates first closed, with 90 percent of that storage in Brownlee Reservoir. Total storage represents only 7% of the river's average annual flow as measured at Hells Canyon (Collier and others, 1996).

As the largest tributary of the Columbia River, the Snake drains over 93,000 mi^2 of Idaho, Montana, Wyoming, Washington, Nevada and Utah. The three dams of the Hells Canyon Complex constitute only 12% of the dams on the Snake River; twenty-five dams lie between its headwaters in Yellowstone National Park and confluence with the Columbia River, 1,000 miles downstream. The river below the Hells Canyon Complex is thus only a small stretch of a heavily regulated river. While this document focuses on the section of the Snake downstream from Hells Canyon Dam to Lewiston, Idaho, we have also included relevant information upstream from Swan Falls Dam to the Columbia River where appropriate.

Dams and reservoirs interrupt the movement of water, sediment, wood and organisms through a river system. Because they typically alter the supply of water and sediment to downstream reaches, they can cause a range of changes to the physical structure of the channel. Dams commonly trap up to 99% of all incoming bedload sediment and most or all of the suspended load. Flows released from dams are typically clear water flows devoid of sediment, so that downstream sediment loads are derived almost exclusively from tributaries and the channel bed and banks. While this can often lead to bed degradation, channel widening, and/or coarsening of bed textures, channel response downstream from dams is complex and does not always follow a predictable course (Petts, 1979). Many field studies have documented the effects of dams on alluvial rivers; however, the direction, time scales, and location of geomorphic changes are neither well understood nor possible to predict in advance (Williams and Wolman, 1984). Key factors determining the response include the relation between pre- and post-dam hydrologic and sediment transport regimes, which are, in turn, influenced by factors such as regional geology and geomorphology, drainage network structure, and rules governing dam operations (Grant and others, 1999).

Several studies have suggested that presence and operation of the Hells Canyon dams have resulted in altered flows and reduced sediment transport downstream. Changes in flow and sediment regime can affect beach and terrace erosion, aquatic and riparian habitat, recreational opportunities, and cultural resources. Because of their management responsibilities for multiple downstream resources, the USFS is concerned with many issues and impacts concerning the operation of the Hells Canyon Complex. This report only focuses on the sediment, geomorphic, and hydrologic issues of the area of interest and is not intended to be a completely comprehensive report of all existing information produced about the Hells Canyon region of the Snake River. Its intent is to serve as a synthesis of major, pertinent, readily available technical reports about the area to assist in and inform the FERC relicensing process.

Sources of Information and Methods

Numerous books have been published about Hells Canyon of the Snake River, from descriptions of its discovery and exploration, history of dam construction, designation as a National Recreation Area (Ashworth,), and boaters' guides to the river corridor (US Forest Service, 1997). Despite this wealth of information about Hells Canyon and its popularity as a recreation destination, there are few published scientific studies that focus on the geomorphic, sediment transport, and hydrologic characteristics of the canyon.

Through the Oregon State University library, we conducted a thorough library and Internet search of library catalogs and resources for all reports, publications, and published data that could be used to characterize the current and historical geomorphic and hydrologic regimes of the Snake. State and federal agencies and private individuals were contacted for any other known reports or sources of information. Table 1 consists of a list of individuals contacted who sent information pertaining to the study area. Inevitably, not all relevant individuals or reports were discovered during this information gathering stage. In particular we may have overlooked unpublished theses, dissertations, or agency reports that have not made it into the general literature. We believe, however, that we have identified most of the primary sources.

Some work was intentionally omitted. Because of our focus on the geomorphic, hydrologic, and sediment characteristics of Hells Canyon, we excluded the extensive work currently being conducted on native and non-native fish species, their life history requirements, and population status. Also, although a limited number of water quality studies are included in this report, they are not emphasized because they do not contain information specific to the geomorphic characteristics of the study area. Issues focusing on the impacts of agriculture and irrigation on the Snake River Plain are also not addressed, because of the large regional extent of such impacts. Finally, the current public interest in salmon recovery and dam breaching proposals for the lower Snake River dams are also not considered.

Organization of the Report

The information collected has been organized as a main *Findings* section and a series of Appendices. The findings section summarizes the results of the primary studies, discusses their strengths and limitations and concludes with a discussion of implications for future work. Five appendices attached to this report list and summarize a wider range of studies relevant to both the Snake River and the broader issues of effects of dams on fluvial systems. Location of studies cited in Appendices A to C are keyed to the attached map, using a numeric and colored dot reference system. Appendix A (red dots) includes all reports with specific information on the Snake River proper while Appendix B (red dots) includes reports specific to the larger Snake River Basin, emphasizing sediment and geomorphic issues. Appendix C (green dots) includes reports of studies in the greater Columbia River basin that are relevant to Snake River issues. Appendix D is a partially annotated bibliography of literature focusing on geomorphic impacts of dams on alluvial river systems, and Appendix E is a non-annotated reference list of geomorphic studies useful for evaluating dam impacts.

Findings

This part of the report summarizes and critically examines some of the findings from the most important studies on the Snake River, commenting on the content and quality of existing information. Beginning with a brief description of the Hells Canyon region to better place the existing information into context, it is organized into three main sections by type of information: geomorphic, hydrologic, and sediment. Each of these sections analyzes the major reports, summarizing their breadth and depth of issue coverage, geographic scope, and time period of study. Key findings are reported and adequacy and limitations of the information reported where appropriate. Following the findings section is an overall review of the adequacy of existing information and implications for the FERC relicensing process.

<u>Description of Hells Canyon and Lower Snake River Basin</u>

The Snake River flows through a diverse geologic and geomorphic setting over its entire course from Wyoming to Washington. The Hells Canyon region of the Snake River, located along the Idaho-Oregon and Idaho-Washington borders, is characterized by deep, narrow gorges and remote and rugged terrain. This 200-mile stretch of river from Farewell Bend to Lewiston, Idaho is primarily semiarid steep highlands, a part of the Rocky Mountain Forest Province. Hells Canyon is characterized by a narrow valley bottom, generally less than 0.5 mi wide, and deeply dissects steep mountainous terrain that rises from both sides to altitudes of several thousand feet. A comprehensive description of the geology of Hells Canyon can be found in Vallier (1998), which incorporates both an overview and background information about the geology of the region with a detailed description of the geology as seen from the river. This report summarizes many previous reports of the geology of the region (Galtieri and Simons, 1978; Vallier, 1973; Vallier, 1977; Vallier, 1978; Vallier and Hooper, 1976; Vallier and Miller, 1974; Walker, 1977).

Information Summary: Existing Geomorphic Information

Overall, little geomorphic work has been conducted in Hells Canyon. With the exception of the Grams and Schmidt (1991) study, most work on the Snake has been conducted either upstream or downstream of the Hells Canyon section. There is no overall geomorphic characterization of the channel and its environment. A multi-year effort on the part of the Forest Service to develop its water rights claims for the Snake River has resulted in extensive channel and bedload data for the upper Snake River and tributaries; however this data is either unpublished or sealed as court documents.

Probably the most useful long-term geomorphic information is contained within the extensive aerial photo record (a table of available aerial photograph series is listed in Table 2 and Appendix B). Historic aerial photographs can be compared with recent photos to determine magnitude of channel change, changes in land use, vegetation, and other aspects of the river corridor. Using a series of photos taken at incremental years can be analyzed to observe increments of change and bracket timing of major change. This can be extremely useful in determining the impacts of the Hells Canyon Complex on geomorphic and sediment resources in the canyon. Only limited analysis of the air photo record has been accomplished to date, mostly by Grams and Schmidt (1991), discussed below.

Grams and Schmidt study: Gram***s*** and Schmidt (1991) conducted the most extensive study on sand bar degradation below the Hells Canyon Complex. Frequency, aerial extent and volume of sandbars in the Snake River between 1955 and 1990 were evaluated from river-mile 247.6 to 188.3, from Hells Canyon Dam to the confluence of the Snake and Salmon Rivers. Aerial photography taken in 1955, 1964, 1970, 1973, 1977, and 1982 were combined with field observations conducted in 1990.

For the air photo analysis, 1964 photos were used for initial classification of sandbars because they show more detail than 1995 photos. Sandbars were classified as separation, reattachment, and channel margin. Sandbars were divided into 5 size classes based on surface area: no sand cover, < 10,000 ft^2, < 20,000 ft^2, < 30,000 ft^2, and < 40,000 ft^2 (the mid point of each size class was used for the class value for statistical purposes). Difficulties with air photo analysis include: differentiating between sand and gravel, error due to river stage differences, and error in accuracy of the zoom transfer scope. Air photo analysis tends to slightly underestimate bar size for small bars (Grams and Schmidt, 1991).

Field inventory of sandbars was conducted in 1990 from Johnson Bar to China Bar and from Pittsburg Landing to the mouth of Grande Ronde River. Beach dimensions were measured on site, and detailed topographic surveys using a laser theodolite were made of three of the sandbars. Digging shallow trenches determined the sedimentology of two sites and the surficial geology was mapped (Grams and Schmidt, 1991).

Aerial photo analysis and field data suggest that frequency, aerial extent and volume of sandbars along the Snake River through Hells Canyon have decreased by over 75% since dam closure. Comparison of the 1964 and 1955 photos show that generally more sandbars are found in the second 30 miles below the dam than in the first. Reattachment and separation bars were distributed rather evenly throughout 60 miles, while channel margin bars were concentrated in the lower half of the canyon. Channel margin bars, however, outnumbered and occupied a greater percentage of area in all reaches. The number of sandbars decreased exponentially from 220 in 1964 to 43 in 1982. Greatest change occurred from 1964 to 1973, with the total number of bars declining by 128. Most change occurred in small bars with an average area of 5,000 ft^2 (Grams and Schmidt, 1991). Channel margin bars, underwent the greatest amount of change. In all reaches, a large decrease in area of exposed sand occurred between 1964 and 1973 followed by less dramatic change or no change in subsequent years. No reach where all bar types are stable was observed (Grams and Schmidt, 1991).

Three high flows in 1965, 1971, and 1972 occurred subsequent to filling of Brownlee Reservoir. Changes in extent of sandbars were interpreted as resulting from these high flows, and there was no photo evidence of bar rebuilding between 1964 and 1982. Erosion of high terraces was most pronounced between 1970 to 1973 (Grams and Schmidt, 1991). The change below Pittsburg Landing shows only a 2-4% decrease from 1982-1990. This rate of change may be characteristic for the entire reach, while erosion of high terraces is variable between 1982-1990. Further erosion of high terraces can be expected at sites where the bar is not armored with gravels (Grams and Schmidt, 1991).

Study adequacy and limitations: This study represents the most deliberate effort to date to evaluate the downstream effects of the Hells Canyon Dam Complex. Methods and approaches used were pioneered by Schmidt and others in their work on the effects of the Glen Canyon Dam on the Colorado River (e.g., Schmidt and Graf, 1990), and are generally considered to be scientifically credible and defensible. The study's primary finding that beach loss is concentrated in the first decade following dam closure, with only limited erosion since then needs validation; repeat sandbar surveys conducted in 1997-98 by Grams and Schmidt will extend the timescale of the analysis by almost a decade and help answer this question. A detailed and updated sandbar inventory of the entire river would provide a useful monitoring tool to evaluate future trends and flow regimes. The study's major focus is on beach erosion; a more detailed analysis of terrace erosion processes and rates would be needed to validate the observed rates of terrace erosion. The study does not attempt an overall geomorphic characterization of the channel, so it is not clear to what extent the detailed sandbar measurements can be extended to other sites.

O'Connor study: O'Connor (1987) studied the effects and estimated the hydraulics of the Pleistocene Bonneville Flood. This study encompasses a much larger geographic scope, from the initial break-out point of the Bonneville Flood at Red Rock Pass, through the Snake River Plain in Southern Idaho, and into Hells Canyon to the confluence with the Columbia. Lake Bonneville was the largest of numerous lakes within the closed basins of the Basin and Range province, southeast of Hells Canyon. Approximately 14,500 years ago, Lake Bonneville discharged 4,750 km^3 of water over the divide between the Bonneville basin and the watershed of the Snake River (O'Connor, 1987). Little impact of the Bonneville Flood can be seen through the Hells Canyon stretch of the Snake because of the high gradient and relief, and resistant bedrock along the Snake River between Farewell Bend (near Weiser, Idaho) and Lewiston, Idaho. Narrow valleys and active hillslope processes also contributed to the few preserved and exposed flood deposits within Hells Canyon. Only isolated deposits were found where the canyon was wide enough to allow for substantial deposition along the valley bottom.

O'Connor (1987) also offers a very detailed description of the impact of the flood and its hydraulics on the Snake River Plain east of the Hells Canyon area.

Study adequacy and limitations: While only marginally relevant to the issue of the dam and its effects, this study provides insight into canyon-shaping processes and landforms, and suggests why abundant quantities of sediment may be limited in reaches of the Snake River. It also provides a measure of the scale of flood events that have occurred in the Snake River as a reference point for evaluating the current flow regime.

Osterkamp study: Impacts of the Bonneville Flood were also studied by Osterkamp, (1998) who described the origin and stability of fluvial islands located in the Deer Flat Wildlife Refuge upstream from Brownlee Reservoir. Fluvial islands in the Snake River result in part from the Bonneville Flood. Where post-flood inputs of sediment by tributaries have not altered the Snake River bottomland, geomorphic features are described as: (1) an incised, locally divided Snake River channel; (2) extensive reaches of channel that have been essentially static, both vertically and laterally since the Bonneville Flood; (3) large areas of fluvial terrace in the Snake River Valley, but only a very narrow modern flood plain; and (4) numerous relict islands, generally elongate, lacking well-developed teardrop morphology, capped by up to 2 m of slackwater deposits, and having xeric, upper surfaces that may not have been overtopped by flood flows (or significantly eroded by water) since formation. These islands are termed as relict islands, which are unusually stable and typically found upstream from the confluence of the Boise River. Regime islands differ from relict islands and are of the fluvial deltaic type, formed by tributary inputs of coarse sediment to a confluence reach of lower gradient and energy conditions than of the tributary supplying the sediment. Aerial photographs of the river above the confluence reach with the Owyhee and Boise Rivers show no indication of lateral channel migration, but indicate a stable, stationary channel position through an extended time period. In the reach downstream of these confluences, regime islands are highly irregular in size and shape and most are unstable, subject to erosion by channel migration and floods.

Study adequacy and limitations: Because this study was conducted in alluvial reaches above Hells Canyon with a very different geomorphic character, it may have only limited applicability to the Hells Canyon reach. Only some of the geomorphic forms described here are found further downstream. In particular, Hells Canyon is likely to exhibit behavior more characteristic of the bedrock-constrained reaches further upstream than the more alluvial sections. A key distinction developed in this study between `relict' and `regime' features could usefully be applied to islands, terraces, rapids, and other landforms found in Hells Canyon.

Other geomorphic studies: An evaluation of habitat and passage requirements for salmonid species prompted a geomorphic study of the Lower Snake River from Lower Granite Dam upriver to the confluence with the Clearwater River (Hanrahan and others, 1998). The purpose of this project was to assess the river conditions resulting from ``permanent natural river drawdown'' of the lower Snake River and the effects of drawdown on anadromous salmonids. Geomorphic changes resulting from the drawdown were assessed using Geographic Information Systems (GIS) to evaluate cause-effect-result relationships between desirable attributes of alluvial rivers and overarching controlling factors. Controlling factors were defined as climate, temperature, geology and physiography, hydrologic regime, channel morphology, substrate, hydraulics, water quality, and sediment transport (Hanrahan and others, 1998).

In this study desirable attributes of an alluvial river system were considered to include complex channel morphology, natural variability in flows and water quality, frequently mobilized channel bed surface, periodic channel bed scour and fill, periodic channel migration, balanced fine and coarse sediment budgets, functional floodplains, infrequent channel-resetting floods, self-sustaining diverse riparian plant communities, and a naturally fluctuating groundwater table. These concepts were only broadly defined. The purpose of this analysis was not to restore the lower Snake River to its historical, pre-dam conditions, but suggest how more normative habitat conditions (*sensu* Stanford and others, 1996) could be restored through flow regulation to produce more natural seasonality of flow and temperature. The GIS framework was used to assess this habitat restoration strategy (Hanrahan and others, 1998).

Important data layers used in this GIS analysis consisted of substrate, channel morphology, hydraulics and sediment transport. Substrate evaluation indicated that sand/fines is the dominant substrate at most locations followed by large gravel. This bivariate dominant/sub-dominant substrate composition for each individual sample point did not exhibit any apparent spatial patterns. The substrate data can be used to characterize existing substrate conditions in narrowly defined areas for current reservoir operations, but are less useful for assessing substrate conditions under drawdown configurations. Channel morphologic analysis was conducted to determine the pre-dam channel morphology to serve as a target for post-dam morphology. River maps compiled in 1934-1935 from the US Army Corps of Engineers were used in this analysis. Hydraulics were simulated using a one-dimensional unsteady flow model to estimate sediment transport rates (Hanrahan and others, 1998).

GIS analysis and sediment transport estimates revealed that based on historical flow conditions most of the sediment deposited in the Lower Snake River since dam completion would be transported out of the study area under drawdown scenarios. Based on the sediment transport rate that is exceeded 50% of the time, the estimated time for sediments to be removed from Lower Granite Reservoir was less than 5 years. It is likely that the transported sediment would start to deposit downriver of Ice Harbor Dam where velocities are reduced by backwater from the McNary pool. The impacts of fine sediment removal from the study area on salmonid species is not discussed in detail because the habitat requirements of each species vary spatially and temporally as they complete their life cycle. Alterations to physical habitat from fine sediment accumulation can adversely affect their migration, spawning, incubation, emergence, and rearing. The extent of these effects are complex and depend on many interacting factors, such as species, duration of freshwater rearing, availability of spawning and rearing habitats, lateral and longitudinal slope of the channel bed, channel morphology, and hydrologic regime. Estimating sediment transport rates and removal of fine sediments from the study area is needed to assess availability of future possible habitat for salmonid species (Hanrahan and others, 1998).

Study adequacy and limitations: Because of its geographical and topical focus, this study has only limited applicability to the Hells Canyon reach; it does, however, provide some information on the type and quantities of sediment being produced and transported through the lower Snake River. Some of this information may be useful for analyzing the consequences of alternative operating strategies for the Hells Canyon Dam complex.

Historical information on channel conditions can offer valuable information for assessing current conditions and change over time. A series of reports by McIntosh and others (1989) provide a summary of fish habitat surveys conducted from 1934 to 1942. The surveys were conducted by the Bureau of Fisheries on many streams and rivers in the Pacific Northwest. The rivers in the Snake River basin that were surveyed include the Clearwater, Salmon, Weiser, Payette, and Grande Ronde Rivers (McIntosh and others, 1989a; c); reports on other rivers surveyed can also be found (McIntosh and others, 1989b; c; d, c). Surveys of river basins typically began at the mouth of the river and moved upstream to the first total fish barrier or where the stream was too small to sustain fish. Measurement stations were selected at intervals of several miles at important landmarks or channel changes. Information collected included: channel width (measured with a measuring tape), average channel depth, flow discharge in cubic feet per second (using average width and depth and velocity measured using floats), and temperature. General conditions of the stream were described between stations. These descriptions included the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley type, and number and species of fish observed. The height and length of obstructions to flow, both natural and artificial were also described. We provide some brief description of the type of historical information contained on various Snake River tributaries:

The Clearwater River flows through high plateau lands supporting extensive wheat fields. Forest covers the watershed east of the river above the confluence with the North Fork Clearwater. Fluctuations in flows are primarily caused by rapid runoff from the Bitterroot Mountains during spring snowmelt. Large placer gold dredging operations on the South Fork of Clearwater River contribute silt and chemicals (McIntosh and others, 1989a). In 1938, the Payette River was heavily diverted with dams at Black Canyon, Deadwood, Payette Lakes, and on the North Fork Payette. The survey describes the channel up and downstream of Black Canyon dam (McIntosh and others, 1989a). During the spring and summer, much of the water was diverted for irrigation. All sewage from Payette and Emmett, Idaho was dumped into the river; flows, however, were able to dilute it rapidly.

A 19.2-mile stretch of the Salmon River from the mouth of Valley Creek in the town of Stanley to the wooden bridge opposite the Sawtooth Valley Range Station was surveyed. Channel descriptions and available fish habitat are described (McIntosh and others, 1989a).

The Grande Ronde River was surveyed in 1941 and was subjected to numerous diversions and obstructions both natural and man made. Descriptions of diversions and obstructions are given as well as opportunity for fish passage at low flows (McIntosh and others, 1989c).

Study adequacy and limitations: These historical surveys do not cover the mainstem Snake River but provide an historical snapshot useful for comparing the relative conditions of tributaries over 60 years ago. As such, they provide a reference point for evaluating current channel conditions. Quality of measurements, including precision and accuracy are not easily determined, and may be quite variable from observer to observer. Given the large numbers of rivers surveyed and paucity of other channel descriptions for this time period, however, these represent an important data set for evaluating gross changes in channels during the latter half of this century.

Information Summary: Existing Hydrologic Information

The two largest sources of high quality historical data for the Hells Canyon region lie in its aerial photography and stream gage records. A table of U.S. Geological Survey gaging stations along the mainstem of the Snake, and the first gage upstream from the confluence along gaged tributaries is listed in Table 2.

Stream gaging station records are an excellent source of long term information about the channel because they are often located in stable reaches and provide much more than just discharge data. Stream gage records can be analyzed for mean annual flow, flood frequency, peak flows, seasonal variation, bankfull flow, channel change at a cross-section, and sediment input or output of the reach. Table 2 lists the gages along the mainstem of the Snake from Ice Harbor Dam in Washington upstream to Milner Dam, Idaho that could be used for such analyses for the mainstem Snake. Little of this data has actually been analyzed, however; we report on the more prominent studies here.

Grams and Schmidt study: In their study on changes in sandbar size through time, Grams and Schmidt (1991) conducted the most extensive hydrologic analysis. Their streamflow analysis compared gaging station records taken from representative years pre- and post- Brownlee Reservoir and suggested that Brownlee has not had a large impact on the distribution of annual flows. Post-dam annual variation of daily was similar to pre-reservoir flows, although weekly and daily variations were greater. Flow duration curves indicated that total post-reservoir flows were greater (presumably due to climatic differences), but normalized curves showed similar shapes. Peak flows were slightly higher in the pre-reservoir period, while low flows were slightly less post-reservoir.

Grams and Schmidt (1991) also analyzed the annual hydrographs from gaging station records for the Snake River at Hells Canyon Dam and the discontinued gage at Oxbow, Oregon for the period of record from 1926 to 1988. Comparison of annual hydrographs taken from representative years pre-and post-Brownlee Reservoir suggest that the Hells Canyon dams have not had a large impact on the intra-annual flow distribution. Effects of regulation can be seen in the loss of two distinct peaks, likely associated with snowmelt originating in different parts of the drainage basin, that are apparent in the pre-reservoir hydrographs. Another effect is the removal of peak flows spikes, especially above the 30,000-cfs level, which is the upper-end of the range of power plant capacity at Hells Canyon Dam. Flow is held as long as possible at this level to avoid spilling water in an effort to store it for future power generation. Annual distributions of daily flows are very similar between pre- and post-reservoir time periods, although day-to-day or week-to-week variations are greater. Analysis of the distribution of mean daily flows pre- and post-reservoir shows that while regulation has not significantly changed the shape of the flow duration curves, it has effectively lowered both the highest and lowest flows (Grams and Schmidt, 1991).

Study adequacy and limitations: Although not a comprehensive analysis of the entire range of changes in the pre- and post-dam hydrographs, this study addresses the general direction and magnitude of flow changes imposed by the Hells Canyon Dams. A more detailed analysis, focusing on overall hydrograph shape and timing, may be more diagnostic.

Pacific Northwest River Basins Commission study: Travel time of water through a reach can be important information for evaluating flow regulation and modeling sediment transport. The stage wave travel time (time for a flow fluctuation to propagate downstream) was estimated using three methods during an intensive study to determine minimum streamflow in 1973 (Pacific Northwest River Basins Commission, 1974). Although there are many swift rapids in the canyon, the average velocity of a mass of water is relatively slow when compared to the stage wave. According to the measured data, the stage wave travels at an average 12.9 feet per second (fps) at 7,700 cfs and 11.4 fps at 5,000 cfs. Data indicate that water mass time of travel varies within a relatively narrow range between 10,000 and 14,200 cfs with an appreciable increase to 3.5 fps at 23,400 cfs. The data also show no significant increase in velocity between the 5,000 cfs flow and the 14,200 cfs flow. It would appear that the breaking point for increasing velocities of the water mass would be somewhere between 14,2000 and 23,400 cfs.

Study adequacy and limitations: This study does not address the overall river hydrology but is useful for estimating or modeling the effects of flow fluctuations. The range of values considered in this study would need to be evaluated against any proposed operating regime.

Other hydrologic studies: In his expert witness report for his geomorphic work on the islands of the Deer Flat National Wildlife Refuge (DFNWR), Osterkamp (1998) describes the hydrology of the tributaries that enter the lower portion of DFNWR, upstream from Brownlee Reservoir. These tributaries primarily drain granitic and volcanic rocks of the Sawtooth and Owyhee Rivers, and are dominated by spring snowmelt. Relative to that of the upper Snake River basin, geologic conditions in the tributary basins result in faster runoff and higher flow magnitudes covering two to three orders of magnitude as compared with tributaries in the upper Snake River basin. Mean elevations of the more downstream tributary basins are lower than those of the upper Snake River Basin, therefore lower tributary peak flows ordinarily precede those of the upper and mainstem Snake River (Osterkamp, 1998).

Most streamflow originates from snowmelt in mountainous areas and provides direct runoff to river and indirect runoff to groundwater. Snowmelt as well as runoff from summer convectional storms, readily infiltrates the fractured, highly permeable, and extensive basalts of the Snake River Plain basins, and ultimately discharges to the Snake River as springflow, mostly in the incised canyon reaches of the river (Osterkamp, 1998).

Study adequacy and limitations: This study emphasizes the hydrology of the upper Snake above Brownlee Reservoir. A more comprehensive hydrologic analysis of the relative magnitudes and timings of tributary flows below the Hells Canyon Dam would be useful to develop a picture of where water in the river is coming from and what the timing of tributary relative to mainstem flows is for different dam scenarios.

In addition to hydrologic data, a few water quality reports were collected. Water quality issues extend beyond the scope of this report, but the following water quality reports are referenced in the appendices (Clark and Maret, 1998; Clark and others, 1998; Clark and Bauer, 1983; Harrison and Anderson, 1997; Kingery and Harrison, 1997; Myers and others, 1998; Myers and Stute, 1997; Myers, 1997; Myers and Stute, 1998; US Geological Survey, 1997; Worth and Braun, 1993).

Information Summary: Existing Sediment Information

Sediment data in most drainage basins is rather sparse because of the expense and time required for collection. Although water quality studies typically collect some sort of suspended sediment data, this is often measured in concentration and usually is taken as a grab sample in one or two locations in the reach of interest. Suspended or bedload transport data is more useful from a geomorphic perspective, since it can be analyzed for particle size distribution and used to calculate entrainment thresholds and average load.

The longest record of suspended and bedload transport data on the Snake and Clearwater Rivers was collected from 1972-1979 in conjunction with the building of Little Granite Dam. The US Geological Survey gage station Snake River near Anatone, Washington was used as the sediment collection site because of the availability of stream flow data and access. Bedload ranged from about 200,000 tons per year in 1972 and 1974 to about 10,000 tons per year in 1973. Bedload was too low for determination in 1977 due to the low flows. Suspended sediment load ranged from about 5,000,000 tons per year in 1974 to about 50,000 tons per year in 1977. Bedload ranged from about 2 to 10 percent of suspended load and averaged about 5 percent. Bedload particle size was bimodal. Modes were in the medium- to coarse-sand range and in the very coarse-gravel range. Suspended sediment particle size was generally finer than sand (Jones and Seitz, 1980). Jones and Seitz (1980) summarized the data collected in the following reports (Emmett, 1976; Emmett and Seitz, 1973; Emmett and Seitz, 1974; Jones and Seitz, 1979; Seitz, 1975; Seitz, 1976).

Study adequacy and limitations: This high-quality and widely used data set represents some of the best bedload data available for large rivers. It represents an excellent validation data set for testing and constraining sediment transport models used for the lower river. Because the study site is located below the confluence with the Salmon River where large quantities of sand are introduced into the river, conclusions from this study are not necessarily applicable to defining bedload transport in the upper river below Hells Canyon.

Extensive bedload measurements were made during spring-runoff seasons, 1994 and 1995, for 9 unregulated streams of Snake River Basin: Boise River near Twin Springs, Idaho; South Fork Payette River at Lowmann, Idaho; Valley Creek at Stanley, Idaho; Yankee Fork Salmon River near Clayton, Idaho; South Fork Salmon River near Krassal Ranger Station, Idaho; Johnson Creek at Yellow Pine, Idaho; Selway River near Lowell, Idaho; Lochsa River near Lowell, Idaho; and North Fork Clearwater near Canyon Ranger Station, Idaho. Data was also collected in 1996 and 1997, but were not contained in some of these reports. These data were collected by the US Forest Service in conjunction with their Organic Act Claims for channel maintenance flows. These data are summarized in the expert witness reports available on the Snake River Adjudication web site (http://www.fs.fed.us/r4/water/srba/tech_rep.htm). Measurements show virtually no movement of particle sizes greater than 32 mm. Less than 5% by weight of bedload was in a size range of 8 to 32 mm, median particle size typically 1 mm. Suspended sediment in the nine streams averages roughly 40% silt and clay and 60% sand.

Study adequacy and limitations: This data could provide valuable information on the caliber and frequency of tributary input to the Snake River; however, since much of it is unanalyzed, unpublished, and being used in an active court case, it would require some effort to take full advantage of it. It seems likely that more and more of this data will be coming out in the next few years as the court case moves forward and the evidentiary rules are relaxed.

Sediment data for upstream from the Hells Canyon complex, i.e., sediment entering Brownlee Reservoir, comes from numerous sources with a long and diverse land use history. Suspended-sediment loads of tributaries to Snake River in and upstream from the Deer Flat National Wildlife Refuge (located in the reach upstream from Brownlee Reservoir extending upstream to the mouths of the Owyhee and Boise Rivers) are low relative to many other drainage basins of similar size and climate (Osterkamp, 1998). Suspended-sediment loads prior to development and streamflow regulation upstream from DFNWR were probably lower than at present because of lack of soil disturbance by agriculture and other land-use practices. The DFNWR reach itself is low in suspended sediment, owing in part to storage of sediment upstream in reservoirs on mainstem and major tributaries. Suspended sediment loads are mostly silt-clay size. A limited supply of sand is available as bedload transport. Sources of suspended-sediment load and sand-size bedload in DFNWR reach are tributary inflow, sediment stored in channel, and erosion and mass wasting of channel banks (Osterkamp, 1998).

Study adequacy and limitations: This study gives insight into the caliber and volumes of material reaching the upper Hells Canyon reservoirs, notably Brownlee.

Numerous studies have documented land use impacts, particularly logging, on the granitic soils of the Idaho batholith, some of which are tributaries of the Snake (Megahan, 1992; Megahan and Nowlin, 1976; Megahan and others, 1992; Platts and others, 1989). The South Fork Salmon River was studied for changes in salmon spawning and rearing habitat from increased delivery of fine sediment (Platts and others, 1989). This study was conducted over a 20-year period from 1965 to 1985. Between 1950 and 1965, logging and road construction, in combination with large storm events in 1964 and 1965, resulted in delivery of increased amounts of fine sediments to the river channel. Transects were established at five spawning areas in the upper 50 km of the river and a moratorium was enacted on logging activity in 1965. Spawning areas typically act as aggradational zones due to their low gradient. Visual estimates of channel surface materials were conducted and core samples of subsurface materials were collected. Both surface and subsurface fine sediment decreased form 1965 to 1985, with the largest percentage of decrease occurring in 1974. Reduced sediment supply from logging and road-induced landslides was interpreted as the primary cause.

Implications of Current Status of Studies on the Snake River

This literature review has pointed up both strengths and weaknesses of current scientific understanding of physical processes in the Snake River Canyon near Hells Canyon. For a river of its size and stature, which is also the most extensively dammed river in the country, comparatively little is known about the Snake relative to other big canyon rivers, such as the Colorado (Collier and others, 1996). The FERC relicensing process for the Hells Canyon complex offers a significant learning opportunity, which if seized upon, will advance understanding and stewardship of the canyon and its resources.

The Grams and Schmidt (1991) study represents the most detailed look at the effects of the dams on the downstream geomorphology of the river. The follow up work to this study now being conducted will help extend the timeframe for interpreting changes to sandbars and terraces. Changes to the latter are particularly critical in light of the cultural resources that either are on or buried in the terraces. The flow intensities, timing, and processes involved in terrace erosion remain some of the most pressing unknowns with respect to evaluating the effects of the dams.

While this study provides a sound framework and insight into some of the downstream effects of the dam on a decadal timescale, it is not a comprehensive analysis of the geomorphic setting and behavior of the river with respect to dam operation. A more detailed look would focus on the historical (i.e., pre-dam), current (post-dam) and potential future relations, under different operating scenarios, among flow regime, sediment transport, and channel morphology and change. A rough sediment budget to evaluate the rate, volume, and caliber of sediment supplied from tributaries relative to that deposited in the reservoirs would provide a useful context for analyzing likely future changes to key morphologic features (i.e., sandbars, terraces, gravel deposits). Such morphologic features should be mapped and geo-referenced to provide a basis for longer term monitoring of dam and other environmental effects. A geomorphic analysis of this type could usefully provide a physical framework for stratifying both physical and biological sampling.

Augmenting supply and/or bypassing sediment around the dams has been suggested as a means of potentially mitigating the already documented effects of the dams to sediment supply and downstream (Collier and others, 1996). There is virtually no literature on this subject because such practices have never been attempted at the scale of the Snake River. Supplying sediment to rivers below dams has been attempted in Japan and elsewhere, primarily to forestall or reduce seacoast erosion, but there are no published accounts in English that we were able to find. With growing interest in mitigating dam effects worldwide, it seems likely that such practices may be expanded in the future. At present, however, there are no guidelines and each case must be viewed as an experiment without replication.

The other studies cited here provide valuable information and context to the Hells Canyon complex. The many studies planned by Idaho Power as part of the dam relicensing should complement and expand on this work to paint a coherent picture of how the river and dams are functioning.

Table 1. List of individuals and agencies contacted during this study, in alphabetical order

Bailey, Rick, Hells Canyon Preservation Council
Barret, Cindy, Idaho Division of Environmental Quality, Lewiston, ID
Bowling, John, Idaho Power Company, Boise, ID
Burch, Susan, US Fish and Wildlife Service, Boise, ID
Carlson, Terry, US Forest Service Hydrologist, Enterprise, OR
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Clark, Greg, US Geological Survey, Boise, ID
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Garcia, Aaron, US Fish and Wildlife, Boise, ID
Grafe, Cindy, ID Division Environmental Quality, Boise, ID
Gram, Greg, US Army Corps of Engineers
Grams, Paul, Utah State University
Graves, Ritchie, National Marine Fisheries Service
Ingham, Mike, ID Division of Environmental Quality
Lee, Danny, US Forest Service, Boise, ID
Lipscombe, Steve, US Geological Survey, Boise, ID
McFadden, Linda, US Forest Service River Ranger
McIntosh, Bruce, US Forest Service, Corvallis, OR
Myers, Ralph, Idaho Power Company, Boise, ID
O'Conner, Jim, US Geological Survey, Portland, OR
Osterkamp, Waite, US Geological Survey, Tucson, AZ
Parkinson, Shaun, Idaho Power Company, Boise, ID
Pinney, Chris, US Army Corps of Engineers
Rea, Matt, Army Corps of Engineers Project Manager
Schuld, Bruce, ID Division of Environmental Quality, Boise, ID
Schinke, Paul, ID Division of Environmental Quality
Schmidt, Jack, Utah State University
Sedell, Jim, US Forest Service, Corvallis, OR
Vallier, Tracy, US Geological Survey, retired
Wilson, Monte, Boise State University, retired

Table 2. General information on aerial photographs

Photography date		Approximate scale	Mean daily discharge at Hells Canyon Dam, in cfs	Discharge variability for preceding 6 hrs, in cfs
1955	8/20	1:20,000	10,900	500
	8/21		11,000	500
	9/3		10,800	250
	9/4		11,100	250
1964	8/17	1:12,000	10,800	
	8/		11,000	--

	18			
	8/24		10,300	--
1965	8/6		14,000	--
1970	7/31	1:14,000	11,900	11,950 - 12,070
	8/10		10,300	10,106 - 10,736
1971	7/15		17,100	--

1973	3/22	1:12,000	18,000	NA
1973	3/23	1:12,000	12,000	NA
1973	3/24	1:12,000	7,700	NA
1973	3/25	1:12,000	5,000	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.

Table 3. List of U. S. Geological Survey Gaging Stations

Gaging	Gaging Station Name	Drainag	Period of
13353000	Snake R below Ice Harbor Dam, WA	108500	1910-1990
13343600	Snake R blw Lower Granite Dam, WA	N/A	1979-1985
13343500	Snake R nr Clarkston, WA	103200	1894-1972
13334300	Snake R nr Anatone, WA	92960	1959-present
13290460	Snake R at Johnson Bar nr Riggins, ID	73400	1959-present
13290450	Snake R at Hells Canyon Dam, ID-OR	73300	1965-present
13290000	Snake R at Oxbow Cr	72800	1923-1971
13269000	Snake R at Weiser, ID	69200	1910-present

13213100	Snake River at Nyssa, OR	58700	1974-1986; 1989-present
13087995	Snake R at Milner, ID	17180	1992-present

Bibliography

Clark, G. M., and T. R. Maret, 1998, Organochlorine compounds and trace elements in fish tissue and bed sediments in the Lower Snake River Basin, Idaho and Oregon: US Geological Survey and Idaho Power Company, Water-Resources Investigations Report 98-4103, 35 p.

Clark, G. M., T. R. Maret, M. G. Rupert, M. A. Maupin, W. H. Low, and D. S. Ott, 1998, Water quality in the Upper Snake River Basin Idaho and Wyoming, 1992-95: US Geological Survey Circular 1160, 35 p.

Clark, W. H., and S. B. Bauer, 1983, Water quality status report Lower Boise River drains Canyon County, Idaho, Boise, Idaho, Idaho Department of Health and Welfare, 101 p.

Collier, M., R. H. Webb, and J.C. Schmidt, 1996, Dams and Rivers: Primer on the downstream effects of dams, US Geological Survey Circular 1126.

Emmett, W. W., 1976, Bedload transport in two large, gravel-bed rivers, Idaho and Washington: Proceedings, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado.

Emmett, W. W., and H. R. Seitz, 1973, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: March 1972 through June 1973, Boise, Idaho, US Geological Survey Basic-Data Report, 78 p.

Emmett, W. W., and H. R. Seitz, 1974, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: July 1973 through July 1974, Boise, Idaho, US Geological Survey Second Annual Basic-Data Report, 76 p.

Grams, P. E., and J. C. Schmidt, 1991, Degradation of alluvial sand bars along the Snake River below Hells Canyon Dam, Hells Canyon National Recreation Area, Idaho: Senior thesis, Middlebury College, Middlebury, Vermont, 98 p.

Grant, G.E., H. Fassnacht, E.M. McClure, and P.C. Klingeman, 1999, Downstream effects of the Pelton Round Butte Hydroelectric Project on bedload transport, channel morphology, and channel-bed texture, Deschutes River, Oregon. Portland General Electric, FERC Project No. 2030, Portland, Oregon, 111 p.

Gualtieri, J. L., and G. C. Simons, 1978, Preliminary geologic map of the Hells Canyon area, Adams and Idaho counties, Idaho and Wallowa county, Oregon: US Geological Survey Open File Report 78-805.

Hanrahan, T. P., D. A. Neitzel, M. C. Richmond, and K. A. Hoover, 1998, Assessment of drawdown from a geomorphic perspective using geographic information systems: Lower Snake River, Washington, Richland, WA, Pacific Northwest National Laboratory, 87 p.

Harrison, J., and K. Anderson, 1997, Brownlee Reservoir water quality model response to nutrient and algae inflow concentration, Boise, Idaho, Idaho Power Company, 19 p.

Jones, M. L., and H. R. Seitz, 1979, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: August 1976 through July 1978, Boise, Idaho, US Geological Survey Fifth Basic-Data Report, 87 p.

Jones, M. L., and H. R. Seitz, 1980, Sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho: US Geological Survey Water Resources Investigations Open-File Report 80-690, 179 p.

Kingery, D., and J. Harrison, 1997, Brownlee reservoir: water quality model development, Boise, Idaho, Idaho Power, 26 p.

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989a, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Clearwater, Salmon, Weiser, and Payette River Basins, 1934-1942, 406 p.

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989b, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Cowlitz River Basin, 1934-1942, 390 p.

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989c, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Umatilla Tucannon, Asotin, and Grande Ronde River Basins, 1934-1942, 153 p.

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989d, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Willamette River Basin, 1934-1942, 476 p.

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989e, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Yakima River Basin, 1934-1942, 297 p.

Megahan, W. F., 1992, An overview of erosion and sedimentation processes on granitic soils: Proceedings of Decomposed Granitic Soils Conference: 11-39.

Megahan, W. F., and R. A. Nowlin, 1976, Sediment storage in channels draining small forested watersheds in the mountains of central Idaho: Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 4:115-126.

Megahan, W. F., J. P. Potyondy, and K. A. Seyedragheri, 1992, Best management practices and cumulative effects from sedimentation in the South Fork Salmon River: an Idaho case study, *in* R. J. Naiman, ed., Watershed management: balancing sustainability and environmental change, New York, Springer-Verlag: 401-414.

Myers, R., S. Parkinson, and J. Harrison, 1998, Tributary nutrient loadings to the Snake River Swan Falls to Farewell Bend, March through October 1995, Boise, Idaho, Idaho Power, 27 p.

Myers, R., and M. H. Stute, 1997, Oxbow bypassed reach study, Boise, Idaho, Idaho Power Environmental Affairs.

Myers, R. E., 1997, Pollutant transport and processing in the Hells Canyon Complex, Boise, Idaho, Idaho Power Environmental Affairs, 65 p.

Myers, R. E., and M. H. Stute, 1998, Hell's Canyon Complex total dissolved gas study, Boise, Idaho, Idaho Power Environmental Affairs.

Osterkamp, W. R., 1998, Processes of fluvial island formation, with examples from Plum Creek, Colorado and Snake River, Idaho, Wetlands, 18:530-545.

Pacific Northwest River Basins Commission, 1974, Anatomy of a river: an evaluation of water requirements for the Hell's Canyon Reach of the Snake River, Vancouver, Washington, Pacific Northwest River Basins Commission, 203+ p.

Petts, G. E., 1979, Complex response of river channel morphology subsequent to reservoir construction, Progress in Physical Geography: 3:329-362.

Platts, W. S., R. J. Torquemada, M. L. M. Henry, and C. K. Graham, 1989, Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to

the South Fork Salmon River, Idaho, Transactions of the American Fisheries Society: 118:2274-283.
Seitz, H. R., 1975, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: August 1974 through July 1975, Boise, Idaho, US Geological Survey Third Annual Basic-Data Report, 70 p.
Seitz, H. R., 1976, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: August 1975 through July 1976, Boise, Idaho, US Geological Survey Fourth Annual Basic-Data Report, 77 p.
Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissel, R. N. Williams, J. A. Lichatowich, and C. C. Coutant, 1996, A general protocol for restoration of regulated rivers, Regulated Rivers: Research and Management: 12:391-413.
US Forest Service, 1997, The wild and scenic Snake River boater's guide: Hells Canyon National Recreation Area, Wallowa-Whitman National Forest.
US Geological Survey, 1997, Water quality data for locations on and near Boise River.
Vallier, T. L., 1973, Geologic map of the Snake River Canyon, Oregon and Idaho, Oregon Department of Geology and Mineral Industry.
Vallier, T. L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, *in* D. G. Howell, and K. A. McDougall, eds., Mesozoic paleogeography of western United States, Pacific Coast Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists.
Vallier, T. L., 1977, The permian and triassic Seven Devils Group, western Idaho and northeastern Oregon, US Geological Survey Bulletin 1437.
Vallier, T. L., and P. R. Hooper, 1976, Geologic guide to Hells Canyon, Snake River, Field Guide No. 5, 72nd Annual Meeting, Geological Society of America, Geology Department, Washington State University.
Vallier, T. L., and V. C. Miller, 1974, Landslides in the Snake River Canyon along the Oregon and Idaho boundary, Department of Geography and Geology Professional Paper No. 5.
Walker, G. W., 1977, Geologic map of Oregon east of the 121st meridian, US Geological Survey Miscellaneous Investigation Series Map I-902.
Williams, G. P., and M. G. Wolman, 1984, Downstream effects of dams on alluvial rivers, US Geological Survey Professional Paper 1286, 83 p.
Worth, D., and K. Braun, 1993, Water quality conditions in the lower Snake River during low river flows, Boise, Idaho, Idaho Division of Environmental Quality, 33 p.

Appendix A
Reports specific to the Snake River - Yellow Dots

Y101 Brusven, M. A., D. J. Walker, K. M. Painter, and R. C. Biggam, 1995, Ecological-economic assessment of a sediment producing stream behind Lower Granite Dam on the Lower Snake River, USA, Regulated Rivers, Research and Management: 10:373-387.

Y102 Carrey, J., C. Conley, and A. Barton, 1979, Snake River of Hells Canyon, Cambridge, Idaho, Backeddy Books, 399 p.

Y103 Cotton, J. S., 1953, Comparison of Hells Canyon multiple purpose scheme (US Bureau of Reclamation) and Snake River development schemes (Idaho Power Company), 88 p.

Y104 Emmett, W. W., 1976, Bedload transport in two large, gravel-bed rivers, Idaho and Washington: Proceedings, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado.

Y105 Emmett, W. W., and H. R. Seitz, 1973, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho: March 1972 through June 1973, Boise, Idaho, US Geological Survey Basic-Data Report, 78 p.

Y106 Emmett, W. W., and H. R. Seitz, 1974, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho: July 1973 through July 1974, Boise, Idaho, US Geological Survey Second Annual Basic-Data Report, 76 p.

Y107 Emmett, W. W., and W. A. Thomas, 1978, Scour and deposition in Lower Granite Reservoir, Snake and Clearwater Rivers near Lewiston, Idaho, U.S.A., Journal of Hydraulic Research 16(4):327-345.

Y108 Grams, P. E., and J. C. Schmidt, 1991, Degradation of alluvial sandbars along the Snake River below Hells Canyon Dam, Hells Canyon National Recreation Area, Idaho, Senior thesis, Middlebury College, Middlebury, Vermont, 98 p.

Number and area of sandbars along the Snake River in Hells Canyon has decreased by over 75% following closure of 3 large upstream dams constructed between 1957-1967. Aerial photograph series and field work document these changes. Greatest amount of 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%. The rate of sand bar erosion decreased after 1973 and decreased further after 1982. Erosion of alluvial terraces backing sandbars was also documented. Erosion of these terraces still continues at some sites.

The erosion of sandbars in Hells Canyon greatly exceeds the erosion of similar eddy-system bars in Grand Canyon downstream from Glen Canyon Dam. Ratio of total reservoir storage to mean annual flow is much lower on the Snake River. Therefore, 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.

Frequency, areal extent, and volume of sandbars in the Snake River between 1955 and 1990 were evaluated from river-mile 247.6 to 188.4, the confluence of Snake and Salmon Rivers. Aerial photography taken in 1955, 1964, 1970, 1973, 1977, and 1982 were used in this analysis and field observations were made in summer 1990. 1964 photos were used for initial classification because they show more detail than

1955 photos. Sandbars were classified as separation, reattachment, and channel margin (and or cove-fill bars). Sandbars divided into 5 size classes, no sand cover, less than 10000 ft^2, less than 20,000 ft^2, less than 30,000 ft^2, and less than 40,000 ft^2, the mid-point in each size class was used for the class value for statistical purposes. Difficulties with air photo analysis: differentiating between sand and gravel; error due to river stage differences; and error in accuracy of zoom transfer scope of scale. Air photo analysis tends to slightly underestimate bar size for small bars

Field inventory of sandbars was conducted in 1990 in the field from Johnson Bar to China Bar and from Pittsburg Landing to mouth of Grande Ronde River. Beach dimensions were measured on site, and topographic surveys using a laser theodolite were made on three of sandbars. Sedimentology of 2 sites was determined by digging shallow trenches and surficial geology maps were made.

Streamflow analysis through comparison of gaging station records taken from representative years pre-and post Brownlee Reservoir suggest that dams have not had a large impact on yearly flow distribution. Variation of daily flows over one year is similar to pre-reservoir, although weekly or daily variations are greater. Flow duration curves, indicate that post-reservoir has more water (presumably due to climatic differences), but normalized curves show similar shapes. Highest peak flows were slightly higher in the pre-reservoir period. Low flows are slightly less post-reservoir

Comparison of the 1964 and 1955 photos show that generally more sandbars are found in the second 30 miles below the dam than in the first. Reattachment and separation bars are distributed rather evenly throughout 60 miles, while channel margin deposits concentrate in the lower half of the canyon. Channel margin bars outnumber and occupy greater percentage of area in all reaches. Number of sandbars decreased exponentially between 1964 and 1982 from 220 in 1964 to 43 in 1982. Greatest change occurred from 1964 to 1973, as total number of bars declined by 128. Most change in small bars, average area of 5,000 ft^2.

Channel margin bars underwent greatest amount of change. In all reaches, large decrease in area of exposed sand occurred between 1964 and 1973 followed by less dramatic change or no change in subsequent years. There is no reach in which all bar types are stable

Three high peak annual flows occurred in 1965, 1971, and 1972 occurred subsequent to filling of Brownlee Reservoir. Changes in extent of sandbars are most likely a result of highest flows. Recovery does not occur between destructive events. No evidence in air photos to suggest building of sandbars between 1964 and 1982. Erosion of high terraces most pronounced between 1970 - 1973.

Change below Pittsburg Landing, only 2-4% decrease from 1982-1990. This rate of change may be characteristic for entire reach, while erosion of high terraces is variable between 1982-1990. Further erosion of high terraces can be expected at sites where the bar is not armored with gravels.

Y109 Gualtieri, J. L., and G. C. Simons, 1978, Preliminary geologic map of the Hells Canyon area, Adams and Idaho counties, Idaho and Wallowa county, Oregon, US Geological Survey Open File Report 78-805.

Y110 Harrison, J., and K. Anderson, 1997, Brownlee Reservoir water quality model response to nutrient and algae inflow concentration, Boise, Idaho, Idaho Power Company, 19 p.

Y111 Jones, M. L., and H. R. Seitz, 1979, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho: August 1976 through July 1978, Boise, Idaho, US Geological Survey Fifth Basic-Data Report, 87 p.

Y112 Jones, M. L., and H. R. Seitz, 1980, Sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho, US Geological Survey Water Resources Investigations Open-File Report 80-690, 179 p.

This report summarizes bedload and suspended-sediment measurements collected from 1972 to 1979 in the Snake and Clearwater Rivers near Lewiston, Idaho. It contains a compilation of data previously reported in five data reports, as well as some new and previously unreported data. In some instances, review of records has necessitated modification of previously reported data. Although the modifications are minor, where discrepancies appear, values reported in this report supercede previously reported values. Bedload in the Clearwater River ranged from 50,000 tons per year in 1972 and 1974 to about 1,000 tons per year in the drought years of 1973 to 1977. Suspended load at the same location ranged from about 1,000,000 tons per year to about 50,000 tons per year for the same respective years. In the Snake River, bedload ranged from about 200,000 tons per year for 1972 and 1974 to about 10,000 tons per year in 1973. Bedload was too low for determination in 1977. Suspended sediment load ranged from about 5,000,000 tons per year in 1974 to about 50,000 tons per year in 1977. Bedload ranged from about 2 to 10 percent of suspended load and averaged about 5 percent. For either river, bedload particle size was bimodal. Modes were in the medium- to coarse-sand range and in the very coarse-gravel range. Suspended sediment particle size was generally finer than sand.

Data collection sites were established at US Geological Survey gaging stations: Snake River near Anatone, Washington (station number 13334300) and Clearwater River at Spalding, Idaho (station number 13342500). Discharge was measured in 15 minute increments with digital punch tape recorders. Stream temperatures were recorded on a continuous-trace thermograph at the Clearwater River station and on a digital-punch tape recorder at the Snake River station. Stream-channel process measurements were made from cableways.

Either P-61 or P-63 suspended sediment samplers was used to collect point- and depth-integrated water samples for analysis of suspended sediment concentration, size distribution, and spatial distribution in the cross section. Helley-Smith bedload samplers were used to determine transport rate, size distribution, and spatial distribution. A conventional 3-in square orifice, weighted to about 150-lb bedload sampler was used in 1972. A 6-in square orifice in a geometric scale-up design was used during the 1973-1979 sampling period, weighing about 165 lb., with allowed a streamlined design and increased stability. Samples were collected at least 20 equally spaced cross-channel location from 1972-1974. Sampling duration was 30 to 60 seconds at each location. During 1975-1979, samples were collected at 20 equally spaced cross-channel locations, with duration of 60 seconds. Size distribution was determined by weight percentage of each size fraction retained in sieves with incremental mesh-size openings differing by a factor of 1.414.

At-a-station hydraulic geometry curves were developed for both rivers. Snake River floods are affected by upstream flow regulation. The recurrence-interval curve for the Clearwater River is for the period prior to the construction of Dworshak Dam on the North Fork Clearwater River. Curves of water-surface slope are determined by field measurements during the 1972-1973 runoff season, show increasing values of slope with increasing discharge.

Only values of daily mean discharge for the period of January to July are included in the analysis, sediment transport rates for the remainder of the year are minimal. Question, is it assumed no sediment transport during the fall, or was this not measured.

Suspended sediment transport was computed as a function of discharge. Cross sectional variability of velocity, depth, and suspended sediment load is exhibited for a high flow on May 19, 1972. Almost all bedload transport occurs in a part of the channel occupying only about one-half the total width of channel.

K113 Kingery, D., and J. Harrison, 1997, Brownlee reservoir: water quality model development, Boise, Idaho, Idaho Power, 26 p.

M114 Myers, R., and M. H. Stute, 1997, Oxbow bypassed reach study, Boise, Idaho, Idaho Power Environmental Affairs.

The purpose of this study is to determine what flow is required for maintaining minimum water quality standards in the Oxbow Bypass reach, located along the Idaho/Oregon border on the Snake River between river mile 270 and 272.5. Currently, flow reduction in this segment of the Snake River is reduced to a minimum of 100 cfs at all times, except when flows exceed hydraulic capacity of the Oxbow Powerhouse.

Data were collected in 1994 and 1997 during periods when flow in the bypassed reach was approximately 100 cfs. In 1994 five parameters were collected biweekly at four sites. In 1997, data were collected weekly for nine water quality variables between June 10 and October 8, at three of the four sites sampled in 1994 and at RM 271.3. Vertical profile measurements were taken at all sites, except 272.4.

Field measurements were taken for all parameters except fecal coliform, ammonia nitrogen, nitrate nitrogen, and chlorophyll a. Surface grab samples were taken for these parameters. Hourly values were recorded using continuous temperature and dissolved oxygen monitoring with a Datasonde 3 loggers. Physical habitat will be assess using IFIM (Instream Flow Incremental Methodology) techniques and are not addressed in this report.

The year 1997 was not ideal for describing effects of low flow on water quality within this reach because of the unusually high flows. Maximum temperatures were warmer than the state standard for cold water biota at all sampled locations. Dissolved oxygen standards were not met at river miles 270.2 and 272.6 in 1994 and at three locations in 1997. Chlorophyll a levels never exceeded the Oregon standard for concern of 15ug/l. Oxbow Reservoir levels, however, reached 27.7 ug/l on July 7, 1994. All other state water quality criteria supporting designated beneficial uses were met at all sites during the sampling period.

Y115 Myers, R. E., 1997, Pollutant transport and processing in the Hells Canyon Complex, Boise, Idaho, Idaho Power Environmental Affairs, 65 p.

This report is the review of the first phase of a two-phase study to look at water quality indicators in the water column, its purpose is to review, compile and summarize existing, relevant data. Thirteen water quality parameters were monitored throughout the Hells Canyon Complex from July 1991 to December 1997. Samples were collected throughout the water columns of the three reservoirs, and also at points longitudinally through the reservoirs. Sampling occurred at least monthly, and mainly during months of March to November. Water temperature, dissolved oxygen, ammonia nitrogen, and phosphorus were monitored and analyzed.

Results indicate that water quality conditions are severely degraded in Brownlee Reservoir, especially the upstream half and water quality conditions in Brownlee influence those in Oxbow and Hells Canyon Reservoirs. With the exception of dissolved oxygen, water quality conditions leaving Hells Canyon Dam are improved for cold water biota over conditions of water flowing into Brownlee Reservoir.

Y116 Myers, R. E., and M. H. Stute, 1998, Hell's Canyon Complex total dissolved gas study, Boise, Idaho, Idaho Power Environmental Affairs.

The goal of this preliminary study is to assess the effects of Idaho Power Company project operations on total dissolved gas levels within and downstream of, Hells Canyon hydroelectric complex. Monitoring occurred between March and June 1997 only when spill occurred at Brownlee Dam and in April 1998 during spill periods at each project, regardless of spill conditions at Brownlee. Total dissolved gas (TDG) pressures, barometric pressure, and water temperatures were measured using a Common Sensing #TB-F gas meter probe immersed to a depth of one meter. TDG sampling was conducted near spill gates in the three reservoirs, in spilled water below the spillways and in the turbine discharge of Brownlee and Oxbow dams. TDG levels below Hells Canyon Dam were monitored from Hells Canyon Boat Launch.

Flows in 1997 saw periods of extremely high runoff, exceeding power plant capacity during most of the sampling period at Brownlee and for the entire sampling period at Oxbow and Hells Canyon dams. Flows in 1998 were considered normal, plant capacity was not exceeded by river flows at Brownlee.

TDG levels in Brownlee Reservoir averaged 100.1% of saturation in 1997 and 103.5% in 1998. No recorded levels ever exceeded the accepted state standard of 110%. Maximum TDG levels were 107.9% in 1997 and 108.1% in 1998. Average TDG in turbine outflow was 99.3% and 101.8% in 1997 and 1998, respectively. TDG levels below the spillway were significantly higher than reservoir levels and in 1997 always exceeded Idaho state standard of 110%. TDG ranged from a low of 118.9% saturation during spill of 15,500 cfs to a peak of 128.0% during spill of 49,000 cfs. 1998 TDG levels exceeded state standards during all spill levels over 3,000 cfs.

TDG levels in Oxbow reservoir ranged from 109.7% to 125.3% saturation in 1997, and ranged between 100.4% and 107.1% in 1998, a year of relatively low spill. TDG levels below Oxbow spillway increased with increasing spill levels up to 20,000 cfs, however, spills between 20,000 and 35,000 cfs levels declined with increasing flows. TDG levels below Hells Canyon Project were significantly higher than reservoir levels and exceeded 110% state standard, ranging from 123.9% to a high of 130.6%.

Y117

Pacific Northwest River Basins Commission, 1974, Anatomy of a river: an evaluation of water requirements for the Hell's Canyon Reach of the Snake River, Vancouver, Washington, Pacific Northwest River Basins Commission, 203+ p.

The purpose of this study was to establish the lower level instream flow requirements, and where possible optimum flow, for fish, wildlife, water quality, navigation and recreation through Hells Canyon of the Snake River downstream from Hells Canyon Dam to Lewiston Idaho. A series of controlled releases over a period of six days in March 1973 were released starting at 27,000 cfs and ramping down to 5,000 cfs. Various components of the river system were measured or monitored throughout the test flows. These include: time of water travel, water quality, aquatic vegetation, benthic insects, catchability and feeding habits of fish, salmonids, warm water fishes, sturgeon fishing, fish stranding surveys, wildlife, recreating, whitewater boating, navigation, and power and water supply.

Time of Travel: The stage wave travel time was estimated using three methods: calculated predictions by USGS based on USGS stage gage measurements, actual stage gage tracings during the study, and individual observations at each of the study sites throughout the reach. The water mass time of travel was estimated by three methods: calculated predictions by USGS method based on stage gage readings multiplied by a 1.2 factor. This factor is commonly used by USGS when estimating water mass travel time in rivers of uniform shape and slope. Rhodamine B dye was used to tag the water mass at the 7,700 cfs flow and the 5,000 cfs flow, a fluorometer and visual observations were used to track the dye. Oranges were used to supplement the other methods as a floating indicator. Releases were made at the 27,000 and 12,000 cfs flows.

Generally, the stage wave reacted in accordance with the calculated predictions, with some anomalies. The use of oranges as indicators was a failure, as they were trapped in rough shoreline and eddies and provided no significant data. The use of Rhodamine B dye was not a complete success, but provided a valuable insight to the nature of low flows and can be used as background information for future studies. It would appear that the breaking point for increasing velocities of the water mass would be somewhere between 14,2000 and 23,400 cfs. Whether this velocity and water volume would be sufficient to maintain a reasonably cool and clean river is open to speculation and future study.

Water Quality: Five primary water quality monitoring stations were established throughout the study reach and field observations of dissolved oxygen, temperature, pH and specific conductance were made every two hours or whenever possible from early morning until late afternoon at each regulated flows. Samples for laboratory analysis were taken at all primary stations at discharges of 27,000, 12,000, and 5,000 cfs. Samples were also taken at 8 secondary stations one or two days before the flow releases.

Field observations and laboratory analyses of Snake River water from Brownlee Dam to the mouth of the Grande Ronde River showed the water to be of high quality. The water quality data collected during the controlled flow period indicate no significant change in water quality attributable to a decrease in flow during the study.

Y118 Seitz, H. R., 1975, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: August 1974 through July 1975, Boise, Idaho, US Geological Survey Third Annual Basic-Data Report, 70 p.

Y119 Seitz, H. R., 1976, Suspended- and bedload-sediment transport in the Snake and Clearwater Rivers in the Vicinity of Lewiston, Idaho: August 1975 through July 1976, Boise, Idaho, US Geological Survey Fourth Annual Basic-Data Report, 77 p.

Y120 US Army Corps of Engineers, 1953, Review report on Columbia River and tributaries: Middle Snake River Basin Lewiston to Pittsburg Landing Idaho, Oregon, and Washington.

Y121 US Department of Energy, Bonneville Power Administration, and Office of Power and Resources Management, 1985, Final report: Hells Canyon environmental investigation, Department of Energy.

The purpose of this study is to determine the level of involvement by Idaho Power Company in the Water Budget Plan. The Water Budget Plan is intended to provide additional flows in the Columbia and Snake Rivers to mitigate the losses to fish and wildlife resulting from dams constructed in the Columbia River Basin, in particular, Lower Granite Dam. This environmental investigation evaluates three Water Budget scenarios, simulating three drawdowns of Brownlee Reservoir. A total of nine discipline areas were studies: natural features (including geology), water use, water quality, land use, historical and archeological resources, recreational resources, aesthetic resources, and fish, botanical and wildlife resources. Information used in this report comes solely from secondary sources.

Y122 US Forest Service, 1997, The wild and scenic Snake River boater's guide: Hells Canyon National Recreation Area, Wallowa-Whitman National Forest.

Y123 US Geological Survey, 1991, Hells Canyon Dam gaging station ratings tables.

Y124 Vallier, T., 1998, Islands and rapids: a geologic story of Hells Canyon, Lewiston, Idaho, Confluence Press, 151 p.

Y125 Vallier, T. L., 1973, Geologic map of the Snake River Canyon, Oregon and Idaho, Oregon Department of Geology and Mineral Industry.

Y126 Vallier, T. L., 1977, The permian and triassic Seven Devils Group, western Idaho and northeastern Oregon, US Geological Survey Bulletin 1437.

Y127 Vallier, T. L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, *in* D. G. Howell, and K. A. McDougall, eds., Mesozoic paleogeography of western United States, Pacific Coast Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists.

Y128 Vallier, T. L., and P. R. Hooper, 1976, Geologic guide to Hells Canyon, Snake River, Field Guide No. 5, 72nd Annual Meeting, Geological Society of America, Geology Department, Washington State University.

Y129 Vallier, T. L., and V. C. Miller, 1974, Landslides in the Snake River Canyon along the Oregon and Idaho boundary, Department of Geography and Geology Professional Paper No. 5.

Y130 Walker, G. W., 1977, Geologic map of Oregon east of the 121st meridian, US Geological Survey Miscellaneous Investigation Series Map I-902.

Y131 Wallowa-Whitman, N., Payette National Forests, States of Oregon and Idaho, Counties of Baker and Wallowa in Oregon, and I. a. A. i. I. Counties of Nez Perce, 1981a, Appendix for Final Environment Impact Statement Hells Canyon National Recreation Area, USDA Forest Service.

Y132 Wallowa-Whitman, N., Payette National Forests, States of Oregon and Idaho, Counties of Baker and Wallowa in Oregon I. a. A. i. I. Counties of Nez Perce, 1981b, Final Environmental Impact Statement: Hells Canyon National Recreation Area Comprehensive Management Plan, USDA Forest Service.

Y93

Worth, D., and K. Braun, 1993, Water quality conditions in the lower Snake River during low river flows, Boise, Idaho, Idaho Division of Environmental Quality, Department of Health and Welfare, Southwest Regional Office, 33 p.

The purpose of this report is to characterize a synoptic survey of water quality conditions along the Lower Snake River, between King Hill and Brownlee Dam, conducted in summer 1992. Major tributaries sampled in this study include: Bruneau River, Boise River, Payette River, and Weiser River. Physical parameters, temperature, conductivity, and dissolved oxygen, chemical parameters, nitrogen, phosphorus, solids, and turbidity, and biological parameters, chlorophyll a and phaeophytin were measured at each monitoring site using electronic field instruments and samples analyzed following approved EPA or APHA Standard Methods guidelines.

Overall, water quality declines between Swan Falls Dam and Brownlee Reservoir reflecting the cumulative impacts of tributary inflows and other contributions. Gradient increases in nitrogen, solids concentrations and chlorophyll were observed at run-of-the-river stations and reach a maximum in Brownlee Reservoir coinciding with a large algal bloom event. In contrast, total and orth-phosphorus concentrations remained relatively consistent.

Inflows from the Snake River mainstem were the single largest contributor of water and nutrient loading to the Lower Snake River. Tributary rivers accounted for less than 15% of the total water but contributed 30% of the phosphorus and 20% of nitrogen inputs in surface waters. Because of shallow depth and limited storage capacity of Swan Falls changes in water quality induced by pulse flows were not observed during the monitoring period. Periodicity and volume discharges from Swan Falls Dam subsequently influenced downstream water quality by increasing or decreasing hydraulic residence time and potential dilution of nutrients. The net influx of nutrients and algal biomass in Brownlee Reservoir significantly impacted water quality resulting in oxygen depletion due to increased oxygen demand from organic loading and promoted development of horizontal gradients of different water quality within Brownlee Reservoir.

Appendix B

Reports specific to Snake River Basin - Red Dots

R201 Clark, G. M., and T. R. Maret, 1998, Organochlorine compounds and trace elements in fish tissue and bed sediments in the Lower Snake River Basin, Idaho and Oregon, US Geological Survey and Idaho Power Company, Water-Resources Investigations Report 98-4103, 35 p.

R202 Clark, G. M., T. R. Maret, M. G. Rupert, M. A. Maupin, W. H. Low, and D. S. Ott, 1998, Water quality in the Upper Snake River Basin Idaho and Wyoming, 1992-95, US Geological Survey Circular 1160, 35 p.

R203 Clark, W. H., and S. B. Bauer, 1983, Water quality status report Lower Boise River drains Canyon County, Idaho, Boise, Idaho, Idaho Department of Health and Welfare, 101 p.

R207 Idaho Division of Environmental Quality, 1998, Lower Payette River raw water quality data October 1996 through September 1998.

R208 Ingham, M. J., 1996, Lower Payette River agriculture irrigation water return study and ground water evaluation Payette County, Idaho 1992-1993, Boise, Idaho, Idaho Division of Environmental Quality, 65 p.

R209 Johnson, W. C., M. D. Dixon, R. Simons, S. Jenson, and K. Larson, 1995, Mapping the response of riparian vegetation to possible flow reductions in the Snake River, Idaho, Geomorphology 13:159-173.

R211 Kjelstrom, L. C., 1995, Streamflow gains and losses in the Snake River and ground-water budgets for the Snake River Plain, Idaho and Eastern Oregon, US Geological Survey Professional Paper 1408-C, 47 p.

R212 McGuire, D. L., 1991, Aquatic macroinvertebrates in the Snake River: Swan Falls Dam to Weiser, November 1990, Boise, Idaho, Idaho Power Company.

During November 1990, Idaho Power collected aquatic macroinvertebrates from eight locations on the Snake River between Swan Falls Dam and Weiser. Sampling sites were located at River Miles 455.9, 424.0, 397.1, 393.2, 383.2, 368.8, 364.4, and 345.6. Samples were obtained from predominately gravel substrates. This report goes on to explain the methods of their sampling and the results of their findings. This report exclusively deals with the macroinvertebrates found in the Snake River.

R213 McGuire, D. L., 1992, Aquatic macroinvertebrate survey of nine tributaries to the Snake River between Swan Falls and Hells Canyon Dam November, 1991: a biological assessment of environmental conditions, Boise, Idaho, Idaho Power Company.

During October and November 1991, Idaho Power collected aquatic macroinvertebrates from major tributaries to the Snake River between Swan Falls Dam and Hells Canyon Dam. The streams surveyed were Pine Creek, Wildhorse, Powder, Burnt, Weiser, Payette, Malheur, Boise, and Owyhee Rivers. Samples were obtained from three different riffles near each stream's confluence with the Snake River. Samples were evaluated to provide a general assessment of environmental conditions and biological integrity in each tributary.

R214

McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989a, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Clearwater, Salmon, Weiser, and Payette River Basins, 1934-1942, 406 p.

This report provides a summary of fish habitat surveys conducted in 1934 to 1942. Surveys typically start at the mouth of the river and move upstream on foot, horse or boat to a point of total barrier or the stream was too small to be of value. Stations of measurement were selected at intervals of several miles at important landmarks or change. Station information collected included: channel width, measured with a measuring tape, average channel depth (at 10 or more measurements across the width of the channel), flow measurement in cubic feet per second using average width, average depth, and velocity using floats multiplied by 0.8 for drag), and temperature using a thermometer in a shaded portion about 1 inch deep. General conditions of the stream were described between stations. These descriptions include the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley, type and amount of cultivation and forest utilization, source and extent of pollution, and the number and species of fish observed. Obstructions of flow, both natural and artificial were described using height and length parameters. Attention to conditions and adequacy of existing fish ladders was included.

Much of the Clearwater River flows through high plateau lands surmounted by extensive wheat fields. Forest cover the watershed lying east of the river above the confluence of the North Fork. Fluctuations in flows mainly caused by rapid run off from Bitterroot Mountains during spring snow melt. Large placer gold dredging operation on the South Fork of Clearwater River, primarily contributing silt and some chemicals.

19.2 mile stretch of the Salmon River from mouth of Valley Creek in the town of Stanley to the wooden bridge opposite the Sawtooth Valley Range Station was surveyed in July 1941. Survey contains descriptions of the channel and available fish habitat.

In 1938 the Payette River was a heavily diverted and had dams at Black Canyon, Deadwood, Payette Lakes and on tributaries of the North Fork. During the spring and summer much of the water is diverted for irrigation. All sewage from Payette and Emmett, Idaho is dumped into the river, flows seem to be great enough to dilute it rapidly. Entire salmon run has been completely wiped out. Describes the channel up and downstream of Black Canyon dam.

R215 McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989b, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Umatilla Tucannon, Asotin, and Grande Ronde River Basins, 1934-1942, 153 p.

This report provides a summary of fish habitat surveys conducted in 1934 to 1942. Surveys typically start at the mouth of the river and move upstream on foot, horse or boat to a point of total barrier or the stream was too small to be of value. Stations of measurement were selected at intervals of several miles at important landmarks or change. Station information collected included: channel width, measured with a measuring tape, average channel depth (at 10 or more measurements across the width of the channel), flow measurement in cubic feet per second using average width, average depth, and velocity using floats multiplied by 0.8 for drag), and temperature using a thermometer in a shaded portion about 1 inch deep. General conditions of the stream were described between stations. These descriptions include the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley, type and amount of cultivation and forest utilization, source and extent of pollution, and the number and species of fish observed. Obstructions of flow, both natural and artificial were described using height and length parameters. Attention to conditions and adequacy of existing fish ladders was included.

The Grande Ronde River was surveyed in 1941 and was subjected to numerous diversions and obstructions both natural and man made. Descriptions of diversions and obstructions are given, as well as passability at low flows.

R216 Megahan, W. F., J. P. Potyondy, and K. A. Seyedragheri, 1992, Best management practices and cumulative effects from sedimentation in the South Fork Salmon River: an

Idaho case study, *in* R. J. Naiman, ed., Watershed management: balancing sustainability and environmental change, New York, Springer-Verlag**:** 401-414.

R219 Myers, R., S. Parkinson, and J. Harrison, 1998, Tributary nutrient loadings to the Snake River Swan Falls to Farewell Bend, March through October 1995, Boise, Idaho, Idaho Power, 27 p.

R220 Osterkamp, W. R., 1998, Processes of fluvial island formation, with examples from Plum Creek, Colorado and Snake River, Idaho, Wetlands 18(4):530-545.

A fluvial islands is a landform elevated above and surrounded by stream-channel branches or waterways, that persists sufficiently long to establish permanent vegetation. Processes, often interactive, by which islands form include avulsion, rapid and gradual channel incision, channel migration, dissection of both rapidly and slowly deposited bed sediment, and deposition of bed sediment on a vegetated surface behind a channel obstruction. Fluvial islands in the Snake River, Idaho partly result of the Pleistocene Bonneville Flood and illustrate how islands form, develop and disappear. Where post-flood inputs of sediment by tributaries have not altered the Snake River bottomland, results have been (1) an incised, locally divided Snake River channel, (2) extensive reaches of channel that have been essentially static, both vertically and laterally since the Bonneville Flood, (3) large areas of fluvial terrace in the Snake River Valley, but very narrow modern flood plain, and (4) numerous relict islands, generally elongate, lacking well-developed teardrop morphology, capped by up to 2 m of slackwater deposits, and having xeric, upper surfaces that may not have been overtopped by flood flows (or significantly eroded by water) since formation. Most relict islands of the Snake River were develop by rapid evacuation of sediment, during the Bonneville Flood. Relict islands upstream of the Boise River are unusually stable. Regime islands are of the fluvial deltaic type, formed by tributary inputs of coarse sediment to a confluence reach of lower gradient and energy conditions than of tributaries supplying the sediment. Aerial photographs of the river above the confluence reach with the Owyhee and Boise Rivers show no indication of lateral channel migration, but rather indicate a stable, stationary channel position through an extended time period. In the reach downstream, regime islands are highly irregular in size and shape and most are unstable, subject to erosion by channel migration and floods.

R221 Platts, W. S., R. J. Torquemada, M. L. M. Henry, and C. K. Graham, 1989, Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho, Transactions of the American Fisheries Society 118:2274-2283.

This study describes the effect of accelerated amounts of fine sediment delivered into the South Fork Salmon River on spawning and rearing habitat of anadromous fish over a 20-year period, from 1965 to 1985. Between 1950 and 1965, logging and road construction, in combination with large storm events in 1964 and 1965, resulted in the delivery of increased amounts of fine sediments to the river channel. A moratorium was enacted in 1965. Transects were established at five spawning areas in the upper 50 km of the river. Spawning areas are typically low gradient, which can function as areas of aggradation. Visual estimates of channel surface materials were conducted and core samples of subsurface materials were collected. Both surface and subsurface fine sediment decreased from 1965 to 1985, with the largest percentage of the decrease occurring by 1974.

R222 Raymond, H. L., 1979, Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River 1966 to 1975, Transactions of the American Fisheries Society 108(6):505-529.

R225 U.S. Engineer Office, 1946, Appendix B--Hearing Review of survey report Boise River, Idaho with a view to control floods, Portland, Oregon, U.S. Engineer Office.

R226 US Engineer Office, 1946, Review of survey report Boise River, Idaho with a view to control floods, Portland, Oregon.

R229 US Geological Survey, 1997, Water quality data for locations on and near Boise River.

Appendix C
Reports specific to Columbia River Basin -- Green Dots

G301 Collier, M., R. H. Webb, and J. C. Schmidt, 1996, Dams and Rivers: Primer on the downstream effects of dams, US Geological Survey Circular 1126.

Dams and river regulation are an integral part of society and provide many benefits while altering physical and ecological characteristics of the river. This report describes the impacts of dams on many of the large rivers in the lower 48 states, including the Snake River.

The Snake River is the most extensively dammed river in the West. Twenty-five dams lie between its headwaters in Yellowstone National Park and its confluence with the Columbia River, 1,000 miles downstream. The Snake River is one of the major tributaries of the Columbia River, which drains 259,000 mi2 of Canada and the Pacific Northwest. Hells Canyon Complex spans a 35-mile stretch of the Snake River with three dams, Brownlee completed in 1958, Oxbow Dam in 1961, and Hells Canyon dam in 1967. Combined storage of Hells Canyon Complex was one million acre-feet of water when the gates were first closed, with 90 percent held in Brownlee Reservoir. All together, that represents only seven percent of the river's average annual flow as measured at Hells Canyon. Dams have little value for flood control and are managed to maximize the potential for electricity generation. Hells Canyon Complex has the capacity to generate 1,400 megawatts when releasing 30,000 cfs from all three dams. Differences in pre-dam and post-dam high flows lie not in magnitude of flow but in their sediment content. Water released by Hells Canyon Dam is usually crystal clear and no significant sediment bearing river joins the Snake until the Salmon River comes in 60 miles downstream.

G302 Dauble, D. D., and D. G. Watson, 1997, Status of fall chinook salmon populations in the Mid-Columbia River, 1948-1992, North American Journal of Fisheries Management 17(2):283-300.

G303 Fassnacht, H., 1997, Frequency and magnitude of bedload transport downstream of the Pelton-Round Butte Dam Complex, Lower Deschutes River, Oregon, Masters thesis, Civil Engineering and Geology, Corvallis, Oregon, Oregon State University.

A first order approximation of frequency and magnitude of bedload transport downstream from a the Pelton Round Butte Hydroelectric complex on the lower Deschutes River is made. Field measurements of channel hydraulics, geometry and particle size were made and used in conjunction with a one-dimensional hydraulic and bedload transport model to determine flows capable of transporting bed material. Predicted critical discharges were equaled or exceed very infrequently during the 72-yr streamflow record, therefore predicted rates and amounts of bedload transport over the period of record are low. Flood events in 1964 and 1996, although the two largest on record, did not cause major morphological changes to the lower Deschutes River.

G305 Geist, D. R., and D. D. Dauble, 1998, Redd site selection and spawning habitat use by fall chinook salmon: the importance of geomorphic features in large rivers, Environmental Management 22(5):655-669.

This paper presents a conceptual spawning habitat model for fall chinook salmon that describes how geomorphic features of a river channel create hydraulic processes, including hyporheic flows, that influence where salmon spawn in the Hanford Reach of the Columbia River. The authors propose that traditional habitat models such as Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation model (PHABSIM), which use estimates of water depth, water velocity, and substrate size to predict available spawning habitat, be used in combination with other key hydraulic and hydrologic characteristics, particularly processes within the hyporheic zone, to predict suitable habitat spawning areas.

In the Hanford Reach of the Columbia River, fall chinook salmon redds usually aggregate in definite clusters even though suitable spawning habitat appears to be widely distributed. Redds tend to cluster in more complex channel patterns. Measurements of water velocity, depth and substrate size are not related to distribution of redds. Piezometers were installed into riverbed sediments within a major fall chinook salmon spawning area to measure interactions between surface and groundwater flows. Use of

GIS technology to evaluate substrate use and preference relative to available habitat revealed that available spawning habitat (based only on substrate) did not provide a useful predictor of spawning potential. Piezometer data and information on spawning habitat use and preference on other large rivers suggests that locations with high intragravel flow may explain spawning habitat preference and tendency to aggregate in particular locations, while ignoring others that are superficially similar.

Hanrahan, T. P., D. A. Neitzel, and others, 1998, Assessment of drawdown from a geomorphic perspective using geographic information systems: Lower Snake River, Washington. Richland, WA, Pacific Northwest National Laboratory, 87 p.

G307 Idaho Division of Environmental Quality, 1998, Large River Sites.

G308 Idaho Water Resources Research Institute, Oregon Water Resources Research Institute, and S. O. W. W. R. Center, 1975, Region Problem Analysis in the Pacific Northwest, Part A -- Instream Flow Needs, Part B -- Basalt Aquifers, Part C -- Wild and Scenic Rivers.

The purpose of this analysis was to facilitate identification of regional research needs concerned with urgent water and related land-use problems in the Pacific Northwest (the states of Idaho, Oregon, and Washington). Three areas were selected for intensive analysis in this study: (1) Instream flow needs methodology to determine how much water is required for various water uses; (2) Study of basalt aquifers; and (3) Impact of designation of Wild and Scenic Rivers on other values including social, economic, and political values and upon alternative uses for water and adjacent land resources.

G309 Ketcheson, G. L., 1986, Sediment rating equations: an evaluation for streams in the Idaho Batholith, USDA Forest Service, Intermountain Research Station, 12 p.

King, J. G., 1997, United States' expert witness report of Dr. John G. King concerning Organic Act claims - consolidated subcase No. 63-25243, USFS.

G310 McClure, E. M., 1998, Spatial and temporal trends in bed material and channel morphology below a hydroelectric dam complex, Deschutes River, Oregon, Masters thesis, Geology and Civil Engineering, Corvallis, Oregon, Oregon State University.

The lower Deschutes River, below the Pelton Round Butte Hydroelectric Project, flows through a narrow, constrained canyon on the east side of the Cascades in Oregon. Hydrological conditions in the basin have undergone relatively little change following impoundment. Mean daily flows have been higher during post-impoundment period, difference is only 3.5 percent for the 50 percent flow and the ten-year peak flow has increased by only 16 percent. Analysis of bed material reveals no longitudinal trend in particle size or armoring, and armoring ratios generally decline with distance from the hydrocomplex. Material input from tributaries does no produce abrupt shifts in mainstem grain-size distribution. The results from this study suggest that for rivers where there is minor alteration to the flow regime and sediment supply and transport rates are low over longer time scales, measurable geomorphic impacts may be subdued.

G311 McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989a, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Cowlitz River Basin, 1934-1942, 390 p.

This report provides a summary of fish habitat surveys conducted in 1934. Surveys typically start at the mouth of the river and move upstream on foot, horse or boat to a point of total barrier or the stream was too small to be of value. Stations of measurement were selected at intervals of several miles at important landmarks or change. Station information collected included: channel width, measured with a measuring tape, average channel depth (at 10 or more measurements across the width of the channel), flow measurement in cubic feet per second using average width, average depth, and velocity using floats multiplied by 0.8 for drag), and temperature using a thermometer in a shaded portion about 1 inch deep. General conditions of the stream were described between stations. These descriptions include the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley, type and amount of cultivation and forest utilization, source and extent of pollution, and the number and species of fish observed. Obstructions of flow, both natural and artificial were described using height and length parameters. Attention to conditions and adequacy of existing fish ladders was included.

G312 McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989b, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Willamette River Basin, 1934-1942, 476 p.

This report provides a summary of fish habitat surveys conducted in 1934. Surveys typically start at the mouth of the river and move upstream on foot, horse or boat to a point of total barrier or the stream was too small to be of value. Stations of measurement were selected at intervals of several miles at important landmarks or change. Station information collected included: channel width, measured with a measuring tape, average channel depth (at 10 or more measurements across the width of the channel), flow measurement in cubic feet per second using average width, average depth, and velocity using floats multiplied by 0.8 for drag), and temperature using a thermometer in a shaded portion about 1 inch deep. General conditions of the stream were described between stations. These descriptions include the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley, type and amount of cultivation and forest utilization, source and extent of pollution, and the number and species of fish observed. Obstructions of flow, both natural and artificial were described using height and length parameters. Attention to conditions and adequacy of existing fish ladders was included.

G313 McIntosh, B. A., S. E. Clarke, and J. R. Sedell, 1989c, Summary Report for Bureau of Fisheries Stream Habitat Surveys: Yakima River Basin, 1934-1942, 297 p.

This report provides a summary of fish habitat surveys conducted in 1934. Surveys typically start at the mouth of the river and move upstream on foot, horse or boat to a point of total barrier or the stream was too small to be of value. Stations of measurement were selected at intervals of several miles at important landmarks or change. Station information collected included: channel width, measured with a measuring tape, average channel depth (at 10 or more measurements across the width of the channel), flow measurement in cubic feet per second using average width, average depth, and velocity using floats multiplied by 0.8 for drag), and temperature using a thermometer in a shaded portion about 1 inch deep. General conditions of the stream were described between stations. These descriptions include the nature of marginal (riparian) vegetation, evidence of erosion and fluctuation in water level, gradient, character of valley, type and amount of cultivation and forest utilization, source and extent of pollution, and the number and species of fish observed. Obstructions of flow, both natural and artificial were described using height and length parameters. Attention to conditions and adequacy of existing fish ladders was included.

G314 Megahan, W. F., 1992, An overview of erosion and sedimentation processes on granitic soils, Proceedings of Decomposed Granitic Soils Conference: 11-39.

G315 Megahan, W. F., and G. L. Ketcheson, 1996, Predicting downslope travel of granitic sediments from forest roads in Idaho, Water Resources Bulletin 32(2):371-382.

G316 O'Connor, J. E., 1993, Hydrology, hydraulics, and geomorphology of the Bonneville Flood, US Geological Survey Special Paper 274, 83 p.

G317 US, 1997, US Expert Report disclosing methodologies for quantification of Organic Act Claims.

G318 US Army Corps of Engineers, 1939, Navigation Maps of Lower Snake River from confluence with Columbia to Pittsburg Landing.

US Army Corps of Engineers, 1995, Columbia River System Operation Review Final Environmental Impact Statement.

Summary: The goal of the Columbia River System Operation Review (SOR) is to develop a system operating strategy and a regional forum for allowing interested parties, other than these Federal agencies, a long-term role in system planning. SOR is to also provide the environmental analysis needed for the federal agencies to sign new agreements for coordinating power generation (PNCA).

The preferred alternative of this Environmental Impact Statement proposes several means to assist anadromous fish recovery: in-river migration, barge transportation, fish passage objectives, spill at projects, flow augmentation, flow targets, reservoir drawdowns, and further study of the feasibility of deep drawdowns. These measures represent key operating decisions.

The 1995 NMFS Biological Opinion establishes an 80 percent fish passage efficiency target at each mainstem project for juvenile salmon passage through the Federal Columbia and Snake River hydro system. This means 80 percent of the smolts would pass the projects through non-turbine routes, and both spill and transportation would be used to achieve this goal in the SOR Preferred Alternative. Key variables in fish recovery include spill, drawdown and flow augmentation. Spill can create a condition in the water known as gas supersaturation. Legal limits for gas supersaturation are in all four Northwest states. Passage of fish will use combination of spill and transportation.

Deep drawdowns in most cases would require massive modifications to dams before they could be implemented. Drawdown options ranged from a permanent riverbed-level drawdown of all four lower Snake River projects to a four and one-half month drawdown of Lower Granite Reservoir. The Preferred Alternative calls for the lower Snake River projects to be operated a minimum operating pool during the spring and summer. The Preferred Alternative uses sliding scale flow targets based on runoff forecasts. Reservoirs would be on minimum outflows through the winter so as much water as possible could be accumulated and held in storage. The water would be released as needed throughout spring and summer to bring flow up to their predetermined targets.

The Columbia River is the fourth largest river in North America. The river and its tributaries are the dominant water system in the Pacific Northwest. The SOR focuses on 14 Federal dams in the federal Columbia River Power System, five storage and nine run-of-river. These large-scale facilities play a key role in the multipurpose use of the Columbia River system.

Main Report: Chapter 2 Columbia River Basin: Description of the Natural Environment: The Columbia River is fourth largest river in North America. The Snake River joins the Columbia River about 330 miles upriver from its mouth. The two principal tributaries to Snake River are Salmon and Clearwater Rivers. The Snake River Plain extends from southeastern Oregon across southern Idaho and includes parts of northern Nevada and Utah. Elevations range from 3,000 ft along the Snake River to more than 10,000 feet at peaks along the basin's fringes. Blue Mountains extend from southeastern Washington to central Oregon. Peaks in the Blue Mountains and associated ranges rise form 7,000 to 9,000 feet while peaks in the Wallowa Range on the east rise to more than 10,000 ft. This area is drained by the John Day and Crooked Rivers, flowing west and north; the Umatilla and Walla Walla Rivers, flowing west to the Columbia; and the Grande Ronde, Malheur and other smaller tributary streams, draining east to the Snake River.

The Snake River and associated tributaries pass through xerophytic shrub-steppe, Ponderosa pine, and Idaho white pine vegetation zones. The white pine belt consists of white pine, grand fir, Douglas-fir, Engelmann spruce, and western red cedar. On the North Fork of Clearwater, fluctuating levels at Dworshak Reservoir have essentially precluded establishment of riparian vegetation. Some red alder occurs along the reservoir, particularly in draws and tributary deltas. Almost no wetland vegetation occurs in vicinity of Dworshak. Along Brownlee Reservoir, riparian vegetation includes communities dominated by willow, creeping wild rye on islands at the upper end, limited distribution of cattail and cottonwood around shallow bays. Wetland habitat is limited to shallow bay areas at the upper end and is characterized by sparse amounts of cattails.

Along the lower Snake River, the Army Corps reservoirs are characterized by scrub-shrub, forest scrub, and forest-shrub riparian communities. Factors contributing to lack of extensive riparian vegetation along areas of lower Snake River include steep shorelines, inundation of former river bottom riparian areas, and the presence of railroad embankments, which occupy areas that might otherwise support riparian vegetation. Emergent wetlands are also associated with the reservoirs along the lower Snake.

Storage Projects:
Dworshak Reservoir, 2,015,800 acre-feet reservoir capacity
Run of the River Projects:
Lower Granite
49,000 acre-feet
738 ft normal full pool
733 ft minimum operating pool
Little Goose
49,000 acre-feet
633 ft minimum operating pool
638 ft normal operating pool
Lower Monumental
20,000 acre-feet
537 ft minimum operating pool
540 ft normal operating pool
Ice Harbor
25,000 acre-feet
437 ft minimum operating pool
440 ft normal operating pool

Appendix A: River Operation Simulation (ROSE): Reviews the models and its components and outcomes in estimating reservoir flows.

Appendix E: Flood Control: The Pacific Northwest has two principal flood seasons. November through March is a rain produced flood period and is often augmented by snowmelt from rain on snow events. May through July is the snowmelt flood period. Factors determining the magnitude of the flood are amount of snow in the basin, whether or not a critical sequence of hot weather occurs during the spring, and whether spring rainfall adds to the runoff. Dworshak dam on the North Fork of Clearwater is operated for flood control.

Appendix L: Soils, Geology and Groundwater: The Snake River originates in Yellowstone National Park in the Rocky Mountains Province. The Rocky Mountains consist of high, linear mountain ranges separated by deep and often broad valleys. Extensive upland forests are present in this area. In eastern Idaho, the river flows into the Snake River Basalt Plain, a generally flat, arid area. It then flows through Hell's Canyon, a 7,000 foot deep gorge on the eastern edge of the Blue Mountains. The Blue Mountains are a broad, semi-arid to subhumid range. The Snake River then flows west through small canyons of the Snake River Basalt Plain to meet the Columbia River in eastern Washington.

<u>The Snake River Plain</u>: The Snake River Plain consists primarily of a thick succession of gently dipping basaltic lavas and has a volcanic history that extends to the present. Thick sequences of basalt are found frequently interbedded with river gravels and other sediments. The young volcanic surface has not developed strong drainage patterns. Many of the streams from the mountains in the north seep underground through the porous surface material into the Snake River Aquifer. The Snake River cuts this aquifer and consequently thousands of high-volume springs flow into the river in the area between Milner Dam and Hell's Canyon.

Surficial geology of the basin has been heavily influenced by continental glaciation.
The Blue Mountains have a core of volcanic and sedimentary rocks that are covered by the Columbia River Basalt Group to the north. Much of the province is formed of schists, slates, and greenstones. Within these metamorphic rocks are major intrusions of gabbros, peridotites, and granodiorie. Younger sequences of volcanics, including ashes, tuffs, flow breccias, and lavas, also appear in the southern and western areas of the province.

<u>Clearwater River</u>: The Clearwater River flows west out of the northern Rocky Mountains in central Idaho. Dworshak Reservoir on the North Fork of the Clearwater is flanked by several unstable areas. These areas consist of semi-consolidated shales and deep clay deposits and some of these areas are active and continue to move. One currently active area is located at RM 32 near Falls Creek with slide areas are up to 2 acres in size. In addition, much of the lake shore is in granitic soils, which are highly erodible, especially at steep angles on long slopes.

<u>Snake River</u>: Brownlee Reservoir has significant potential for slope failure under existing operating patterns. The main impact is due to rapid drawdown decreasing the stability of existing landslide

areas due to removal of the buoyant force of water. Numerous slides are present along the perimeter of the reservoir. One large slide exists at the mouth of Powder River and is capable of damming that drainage.

Lower Granite Dam: Founded on the lower flows of the Grande Ronde Basalt and partially on Missoula flood gravels and recent alluvium.

Appendix D

Annotated Studies on Geomorphology of Rivers and Dam Effects

Allen, P. M., R. Hobbs, and N. D. Maier, 1989, Downstream impacts of a dam on a bedrock fluvial system, Brazos River, Central Texas, Bulletin of the Association of Engineering Geologists 26(2):165-189.

Localized aggradation at tributary deltas for over 22 miles downstream of a dam was found on a bedrock controlled, mixed-load stream system in central Texas. Surveyed tributary delta systems have shown a steady growth since the dam was constructed in 1951 to a maximum of 4-5 ft. Subsequent thresholds of bank erosion are related to delta planform size, where initiation of erosion begins when deltas occupy about 68% of the mainstem channel with. Bank loss in these areas ranges from 5-14 ft per year.

Andrews, E. D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado, Geological Society of America Bulletin 95:371-371.

Twenty-four gravel-bed rivers in the Rocky Mountain region of Colorado were selected for a detailed investigation of bed-material mobility and hydraulic geometry.

Andrews, E. D., 1986, Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah, Geological Society of America Bulletin 97:1012-1023.

Flows on the Green River, a principal tributary of the Colorado River, have been regulated by Flaming Gorge Dam since 1962, with mean annual sediment discharge at downstream gages decreasing substantially. The mean annual sediment discharge has decreased by 54 percent (from 6.29 million to 2.92 million tons) at the Jensen gage, by 48 percent (from 11.6 million to 6.02 million tons) at the Ouray gage, and by 48 percent (from 15.5 million to 8.03 million tons) at the Green River, Utah, gage. The decrease in mean annual sediment discharge at the Ouray and Green River, Utah gages exceeds the quantity of sediment trapped in the reservoir, and is attributed to a decrease in the magnitude of river flows that are equaled or exceeded 30 percent of the time. Channel response to flow and sediment alterations varies with distance downstream, revealing a longitudinal trend from degradation (from river mile 0, at the dam, to mile 68), quasi-equilibrium (from river mile 68 to 166), to aggradation (from river mile 166 to mouth with Colorado).

Andrews, E. D., 1994, Sediment transport in the Colorado River Basin.

Water and sediment are not contributed to the channel network uniformly across the Colorado River basin. The location of a reservoir affects the resulting downstream hydraulic impacts. In this paper, several sediment-transport data records from throughout the basin are analyzed for pre- and post-reservoir periods. Results show that the downstream effects of the reservoir depend on not only the size and operating schedule of the reservoir but also the location of the reservoir within the basin relative to the major runoff and sediment-contributing areas. Changes in both water and sediment discharge can be attribute to flow regulation and climate changes throughout the century.

Brussock, P. P., A. V. Brown, and J. C. Dixon, 1985, Channel form and stream ecosystem models, Water Resources Bulletin 21(5):859-866.

A system is proposed to classify running water habitats based on their channel form, which can be considered in three different sedimentological settings: a cobble and boulder bed channel, a gravel bed channel, or a sand bed channel.

Carling, P. A., 1988, Channel change and sediment transport in regulated U.K. rivers, Regulated Rivers: Research and Management: 2:369-387.

Reviews investigations on regulated rivers in the U.K. from the late 1960s. Literature review falls into three categories: analysis of changes in hydraulic geometry of channels, reach-scale adjustments of sediment transport and channel change, and utilizing holistic concepts of channel change over longer time periods. The paper emphasizes the lack of a credible theoretical model of channel adjustment, which makes it difficult to predict regulation effects on channel form downstream of impoundments.

The author comes to the conclusion that each river system is unique, and that climate, geology, and operational regime combine to produce singular responses that cannot be integrated into a single predictive model. A combination of geomorphological and sedimentological approaches may provide the best interactive mode of investigation required to make full sense of downstream impacts and predictions.

Church M., 1995, Geomorphic response to river flow regulation: case studies and time-scales, Regulated Rivers: Research and Management: 11:3-22.

Alterations in flow regimes were studied on two gravel-bedded rivers in British Columbia. A reduction in flow on the Peace River resulted in channel bed stabilization and channel narrowing, as flows are no longer competent to move gravel and cobble sized material. Flow augmentation on the Keman River caused channel bed degradation, but only after a very high threshold flow initiated movement of the armored channel bed.

Galay, V. J., R. S. Pentland, and R. A. Halliday, 1985, Degradation of the South Saskatchewan River below Gardiner Dam, Canadian Journal of Civil Engineering 12:849-862.

Degradation of a reach downstream from a dam on the South Saskatchewan River, which originates in the Rock Mountains and flows across the southern prairies of western Canada, is quantified through repeated cross-section measurements for 15 years of data. Degradation is evident for about 8 km downstream from the dam, with a maximum degradation of 2 m immediately downstream of the dam. The development of an armoring layer has slowed degradation, although through HEC-6 modeling of flows, degradation immediately downstream of the dam is expected to continue and reach 5.3 m in 2001.

Graf, W. L., 1980, The effect of dam closure on downstream rapids, Water Resources Research 16(1):129-136.

This study looks at the stability of rapids in the canyons of the Green River in Dinosaur National Monument, 68 km downstream from Flaming Gorge Dam. Peak flows have been reduced from maximum flood record of 510 m3/s before dam closure to a maximum of 170 m3/s since dam closure. This article estimates the amount of shear stress on boulders to determine if current flows have enough force to entrain the largest particles. Although smaller boulders will move at lower shear stresses, the author argues that the presence of the largest particles will ensure the long-term stability of the rapid in the channel. Due to the reduction of peak flows, an increase in stable rapids has occurred from 62 percent pre-dam, to 93 percent post-dam.

Gregory, K. J., and C. Park, 1974, Adjustment of river channel capacity downstream from a reservoir, Water Resources Research 10(4): 870-873.

The reduction of channel capacity downstream from a reservoir on the River Tone, Somerset is quantified by comparing channel cross-section capacity above and below the Clatworthy reservoir. Peak flows with discharges of the 1.5- and 2.33-yr recurrence intervals are determined to be reduced by about 40% from pre-regulation flows. Eight of the 14 channel cross-sections below the dam revealed evidence of "multiple cross sections," where the inner cross section appears to be the contemporary bankfull level, according to present limits of vegetation. Channel capacity is estimated to be 54 percent of the original capacity immediately below the dam and persists for at least 11 km downstream until the catchment area contributing to the Tone is at least 4 times that of the area draining the reservoir.

Hammad, H. Y., 1972, River bed degradation after closure of dams, Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers 98:591-607.

This paper describes the armoring process downstream of dams through the application of empirical equations for two different armoring processes, using suspended sediment data from the Nile River downstream from Aswan High Dam. Two types of armoring conditions are possible from the degradation process: a plane bed of coarser sand particles may remain, or a rippled bed of coarser sand particles may result depending on the variation of flow conditions. Based on these calculations and

available data, the author argues that an armoring condition for the Nile River bed may be attained before an appreciable change of bed slope takes place, which will halt the degradation process.

Jiongxin, X., 1990, An experimental study of complex response in river channel adjustment downstream from a reservoir, Earth Surface Processes and Landforms 15:43-53.

This study describes the complex response of river channel to changes in flow and sediment regimes downstream of a reservoir using a flume experiment. A descriptive model describing three stages of adjustment was developed to explain this response. Two experiments were conducted to explain the adjustment process of wandering braided rivers with heavy sediment loads after the construction of dams. In the first part of the experiment a steady discharge and heavy sediment load was introduced to the river. During the second part, water discharge remained unchanged but no sediment was added. From the results of this experiment, it was determined that interactions among variables in a river system, width, depth, sinuosity, gradient are quite complicated. The feedback mechanism of channel adjustment can be described using a three-stage model. Stage I: Altered input conditions, lack of sediment with similar pre-dam discharges, width-depth ratio decreases, slope decreases and sinuosity increases. Stage II: Because of the feedback from changing boundary conditions, a reverse tendency appears, that is width-depth ratio increases and sinuosity decreases. The rate at which gradient decreases becomes very slow. Stage III: Equilibrium is achieved again and width-depth ratio, gradient, and sinuosity become constant as the system enters a new stable state. Because of the differences in the physical environmental backgrounds and in river channel boundary conditions, the duration of the three stages are different between different rivers.

Kearsley, L. H., J. C. Schmidt, and K. D. Warren, 1994, Effects of Glen Canyon Dam on Colorado River sand deposits used as campsites in Grand Canyon National Park, USA, Regulated Rivers: Research and Management: 9:137-149.

This paper discusses the downstream effect of Glen Canyon Dam on alluvial sand deposits used as campsites by recreational boaters. Inventories of campsites from 1965 to 1991 show a system-wide decrease in the number and size of campsites, despite a temporary increase as a result of the 1983 flood event. Aerial photography and beach inventories were used, and reaches were designated as critical and non-critical. Critical meaning that campsites were limited in number within a particular reach. Sandbars do not respond in the same manner to high flows, fluctuating flows, or vegetation encroachment, and response is different between narrow and wide reaches.

Komura, S., and D. B. Simons, 1967, River-bed degradation below dams, Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers 93(4):1-14.

The purpose of this paper was to derive an empirical equation to explain the effects of river bed degradation below dams. The premise was the assumption that after dam closure, sediment transport will stop downstream from the dam, as the finer fractions of bed material are carried away and only the larger, more resistant particles are left in place. When the coarser particles have developed into an armor layer, sediment transport is arrested and the channel is in a state of static equilibrium. This paper derives a differential equation for degradation below dams, based on this model of channel response. Five assumptions are built into this equations: sediment transport is completely arrested by the dam, the river banks are not erodible, seasonal variations in discharge and temperature of water do not occur, sediment injections by tributaries do not occur, and meandering and the growth of vegetation do not occur.

Pemberton, E. L., 1976, Channel changes in the Colorado River below Glen Canyon Dam, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado 5:61-73.

This study describes the results of a long-term study quantifying channel degradation of the Colorado River downstream of Glen Canyon Dam from 1956 to 1975. Results of repeated cross-section surveys and bed material samples show that 7.57 million cubic meters of sands were scoured from 1959 to 1965 above Lees Ferry (located 16 miles downstream from Glen Canyon Dam). The channel became stable with little change from 1965 to 1975 and showed no significant degradation with only 120,000 cubic

meters of material scoured from the river bottom. The Paria Riffle, located approximately 15 mi. downstream from the dam shows little to no signs of degradation.

Petts, G. E., 1977, Channel response to flow regulation: the case of the River Derwent, Derbyshire, River Channel Changes**:** 145-164.

This paper quantifies the response of a river channel to an upstream dam. Pre-dam data for the channel is limited, for the first dams on the river were in place by 1912. Using channel cross-sectional data, determination of bankfull stage, regional analysis of discharge and drainage area, historic maps and aerial photos, and dendrochronology, the author quantifies the amount of channel change downstream from the reservoir. The author determines that even the most conservative estimate of pre-dam channel form indicates that the deposition of a bench has reduced channel capacity by nearly 40 percent. The bench is not evident until a tributary has joined the mainstem, and may imply that the introduction of sediment into the regulated mainstem may be a significant factor in controlling bench formation and channel narrowing. Changes in the mainstem indicate that morphometry changes must be interpreted not only in relation to changes in flow regime and competence, but also a reduction in sediment load and input of water and sediment from tributaries. Response of a fluvial system is complex, and variations between river channels not only need to be explained, but also the spatial patterns in the magnitude, rate and direction of response along a single river need to be evaluated.

Petts, G. E., 1980, Long-term consequences of upstream impoundment, Environmental Conservation 7(4):325-332.

This paper is presented as short summaries of impacts of dams on downstream reaches with the focus on long-term management of ecological systems. The effect of upstream impoundments can be viewed in terms of three orders of impact. The first-order impact is the effect of an activity upon environmental processes that occur simultaneously with the activity, such as a reduction in flow and entrapment of sediment. Second-order impacts are changes of form, both geomorphological and ecological, that result from process alteration and are modified by system constraints. These changes can occur from 1 to 100+ years after alteration. Third-order impacts reflect the feedback effects of the channel morphological changes on the ecology and the ecological change on the physical components. There may be a lag time of ecological change from the initial alteration. The response of a river system will be complex and the channel will attempt to adjust to an equilibrium or new steady-state condition. Response will be episodic and controlled by thresholds, so that considerable time may elapse before any semblance of equilibrium is achieved.

Petts, G. E., 1988, Accumulations of fine sediment within substrate gravels along two regulated rivers, UK, Regulated Rivers: Research and Management: 2:141-153.

Two rivers in upland, glaciated basins with large tracts of peat in Britain were studied to investigate the effect of flow regulation on the distribution of fines within channel substrate gravels. Both regulated rivers receive uncontrolled runoff from a major tributary within a short distance of the dam. Samples of bed sediments were taken using bulk and freeze-sampling techniques and analyzed by weight for different size classes. Along both rivers, the proportion finer than mm exceeds 20 percent immediately below confluences, concentrations of coarse sand (1-2 mm) exceed 10 percent of the substrate, by weight, and on the River Derwent this level is maintained for about 2 km. Determination of the extent of downstream channel siltation is difficult because of a reduction in channel width and accumulation of mounds of fine gravel and sand along the bed.

Schmidt, J. C., and J. B. Graf, 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona, US Geological Survey Professional Paper 1493, 74 p.

Changes in alluvial sand deposits as a result of flow regulation are quantified in the Colorado River of the Grand Canyon. High flow releases in 1983 and 1984 resulted in aggradation of alluvial deposits in wide canyon reaches and degradation in narrow canyon reaches. Subsequent flow fluctuations initiated degradation of all deposits along the canyon.

Schumm, S. A., 1969, River metamorphosis, Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 95:255-273.

Explanation of river adjustment to changes in hydrologic regime, deriving empirical equations to explain adjustment using data from alluvial rivers from the semiarid, subhumid region of the United States. Channels will adjust to changes in discharge of water sediment, no only by a change in gradient but also by adjustments of channel width and depth. The dimensions, shape, gradient, and pattern of stable alluvial rivers should be controlled by the quantity of water and quantity and type of sediment moved through their channels. As channels change as a result of changes in water and/or sediment, the change from one stable morphology to another may involve changes in all aspects of a channel, and the initial response of a river to altered hydrologic regimen may not necessarily indicate the type of final adjustment that will occur.

Sear, D. A., 1992, Impact of hydroelectric power releases on sediment transport in pool-riffle sequences, *in* P. Billi, R. D. Hey, C. R. Thorne, and P. Tacconi, eds., Dynamics of gravel-bed rivers, John Wiley & Sons Ltd**:** 629-650.

This study studied sediment transport in pool-riffle sequences on the River North Tyne, a regulated river in northwest Northumberland. The River North Tyne is a low-sinuosity, partially geologically confined cobble-bed river. Impoundment of the North Tyne was completed in 1981 with reservoir filling achieved by 1982. Kielder Reservoir impounds 22.5 percent of the total North Tyne catchment and effectively traps all sediment supplied from the largely afforested area. Flows, since 1985, have been dominated by hydropower generation for revenue maximization.

Study looked at effects of regulation on sediment transport examining fine bedload , fine to coarse bedload, and coarse bedload, using magnetic tracer and basket samplers, simultaneous helley Smith sampling, and painted clasts respectively. Results were interpreted as river regulation producing a decoupling of the sediment transport conveyor belt. Riffle surfaces, in the absence of sediment supply from upstream pools, are coarsening and structural bed strength is accentuated. Reach scale differences in sediment transport is affected by unregulated tributary events with bankfull floods destroying compacted riffle surfaces and replenishing fine sediment. The longer the period between bed-disrupting floods, the larger the flood required to disrupt the bed. The effectiveness of the flood is controlled by local morphology, sediment size and steepness of the wave front. Sedimentation of riffle sediments of <2 mm material is site-specific and affect by the permeability below the armor layer. Permeability rates are low, and currently below critical levels for salmonids, except during and after foods when levels increase by 100 percent. Flushing of fines is maintained by hydropower generation. Localized spawning bed armoring below dams is clearly documented, but channel scale strengthening of riffle sediments after only 10 years of regulated flows may accelerate ecological impact.

Van Steeter, M. M., and J. Pitlick, 1998, Geomorphology and endangered fish habitats of the upper Colorado River, Water Resources Research 34(2):287-302.

Three study reaches on the Colorado River, up and downstream of the junction with the Gunnison River, were examined to determine the extent regulation of streamflow and sediment flow on alluvial reaches near Grand Junction. Annual peak flows on the Colorado River near Cameo and on the Gunnison River near Grand Junction have decreased by 29-38 percent, although the total volume of runoff has not changed significantly. Average annual suspended sediment loads of both the Colorado and Gunnison have decreased. Reductions of 40-65% from the long-term average occurred for the period from 1964 to 1978. Localized scour or fill of 0.5-1.0 m of the channel bed is possible at USGS gaging station, however, widespread degradation or aggradation is not evident. The Colorado River has narrowed by an average of 20 m and about ? of the area formed by side channels and backwaters have been lost.

Williams, G. P., and M. G. Wolman, 1984, Downstream effects of dams on alluvial rivers, US Geological Survey Professional Paper 1286, 83 p.

This study describes the effects of upstream impoundment on streamflow, channel width, bed material size and sediment loads in 21 alluvial rivers, primarily from the semi-arid western United States. Average daily discharge in a reach may increase, remain the same, or decrease after a dam has been built.

Low flows also were diminished in some instances and increased in others. Peaks discharges were reduced from 3 to 91 percent. Reservoirs are efficient sediment traps, effectively trapping 99 percent of all sediment. Response of channel width varied from no appreciable change, to increases of 100% to decreases of 90%. Degradation occurred immediately downstream for all channels, the rate degradation and distance downstream varied with time. Vegetation generally increased in the reaches downstream from the dams, covering as much as 90% of the channel bars and banks along some rivers.

Appendix E
Studies on Geomorphology of Rivers

Ackers, P., and F. G. Charlton, 1975, Theories and relationships of river channel patterns -- a discussion, Journal of Hydrology 26: 359-362.

Anderson, H., 1976, Reservoir sedimentation associated with catchment attributes: landslide potential, geologic faults, and soil characteristics, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:35-46.

Andrews, E. D., and J. D. Smith, 1992, A theoretical model for calculating marginal bedload transport rates of gravel, *in* P. Billi, R. D. Hey, C. R. Thorne, and P. Tacconi, eds., Dynamics of gravel-bed rivers, John Wiley & Sons Ltd**:** 41-52.

Benoit, T., and J. Wilcox, 1997, Applying a fluvial geomorphic classification system to watershed restoration, US Forest Service. 1999.

Bonacci, O., Z. Tadic, and D. Trninic, 1992, Effects of dams and reservoirs on the hydrological characteristics of the Lower Drava River, Regulated Rivers: Research and Management: 7:349-357.

Burgi, P. H., 1976, Model study of riverbed material in Canyon Ferry Dam spillway stilling basin, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 5:86-99.

Chien, N., 1985, Changes in river regime after the construction of upstream reservoirs, Earth Surface Processes and Landforms 10:143-159.

Church, M., and D. Jones, 1982, Channel bars in gravel-bed rivers, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 291-338.

Dawdy, D. R., 1994, Hydrology of Glen Canyon and the Grand Canyon, Colorado River Ecology and Dam Management, Santa Fe, New Mexico, NH Academy Press: 40-53.

DeCoursey, D. G., and C. G. Hunt, 1976, Characteristics of stable natural channels and their relation to channel design, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 5:13-21.

Dissmeyer, G. E., 1976, Erosion and sediment from forest land uses, management practices and disturbances in the southeastern United States, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:140-148.

Dolan, R., A. Howard, and A. Gallenson, 1974, Man's impact on the Colorado River in the Grand Canyon, American Scientist 62:392-401.

Edwards, R. W., and D. T. Crisp, 1982, Ecological implications of river regulation in the United Kingdom, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 843-865.

Fan, S.-S., 1976, The role of sediment problems in hydroelectric development, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 4:149-161.

Fan, S.-S., and G. Morris, eds., 1993, Notes on sediment management in reservoirs: national and international perspectives, Water Resources Publications, LLC, 248 p.

Frissel, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley, 1986, A hierarchical framework for stream habitat classification: viewing streams in a watershed context, Environmental Management 10:199-214.

Gillilan, S., 1996, Use and misuse of channel classification systems, US Forest Service., 1999.

Gore, J. A., and G. E. Petts, eds., 1989, Alternatives in regulated river management, Boca Raton, Florida, CRC Press, Inc., 344 p.

Grimshaw, D. L., and J. Lewin, 1980, Reservoir effects on sediment yield, Journal of Hydrology 47:163-171.

Guillen, J., and A. Palanques, 1992, Sediment dynamics and hydrodynamics in the lower course of a river highly regulated by dams: the Ebro River, Sedimentology 39:567-579.

Hansen, E. A., and G. R. Alexander, 1976, Effect of an artificially increased sand bed material on stream morphology and its implications on fish habitat, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 3:65-76.

Harpman, D. A., 1999, The economic cost of the 1996 controlled flood.

Hey, R. D., J. C. Bathurst, and C. R. Thorne, eds., 1982, Gravel-bed rivers: fluvial processes, engineering, and management, New York, John Wiley & Sons, Ltd., 875 p.

Higgs, G., and G. Petts, 1988, Hydrologic changes and river regulation in the UK, Regulated Rivers: Research and Management: 2:349-368.

Howard, A., and R. Dolan, 1981, Geomorphology of the Colorado River in the Grand Canyon, Journal of Geology 89:269-298.

Inbar, M., 1990, Effect of dams on mountainous bedrock rivers, Physical Geography 11(4):305-319.

James, L. A., 1997, Channel incision on the lower American River, California, from streamflow gage records, Water Resources Research 33(3):485-490.

Johnson, C. W., and C. L. Hanson, 1976, Sediment sources and yields from sagebrush rangeland watersheds, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:71-80.

Kellerhals, R., 1982, Effect of river regulation on channel stability, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 685-715.

Klingeman, P. C., and W. W. Emmett, 1982, Gravel bedload transport processes, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 141-179.

Klock, G. O., and J. D. Helvey, 1976, Debris flows following wildfire in north central Washington, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:91-98.

Komar, S., and D. B. Simons, 1967, River-bed degradation below dams, Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers 93:1-14.

Kondolf, G. M., 1995, Managing bedload sediment in regulated rivers: examples from California, USA, Natural and anthropogenic influences in fluvial geomorphology, American Geophysical Union, Geophysical Monograph 89.

Kondolf, G. M., and M. Larson, 1995, Historical channel analysis and its application to riparian and aquatic habitat restoration, Aquatic Conservation: Marine and Freshwater Ecosystems 5:109-126.

Kondolf, G. M., and W. V. G. Matthews, 1991, Unmeasured residuals in sediment budgets: a cautionary note, Water Resources Research 27(9):2483-2486.

Kondolf, G. M., and P. R. Wilcock, 1996, The flushing flow problem: defining and evaluating objectives, Water Resources Research 32(8):2589-2599.

Lai, J.-S., and H. W. Shen, 1995, Flushing sediment through reservoirs, Journal of Hydraulic Research 34(2):237-255.

Laursen, E. M., S. Ince, and J. Pollack, 1976, On sediment transport through the Grand Canyon, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 4:76-87.

Leopold, L. B., and J. Maddock, Thomas, 1953, The hydraulic geometry of stream channels and some physiographic implications, US Geological Survey Professional Paper 252, 56 p.

Li, R.-M., M. A. Stevens, and D. B. Simons, 1976, Water and sediment routing from small watersheds, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:193-204.

Marcus, W. A., S. C. Ladd, J. A. Stoughton, and J. W. Stock, 1995, Pebble counts and the role of user-dependent bias in documenting sediment size distributions, Water Resources Research 31(10):2625-2631.

McCool, D. K., and F. L. Brooks, 1976, The Universal Soil Loss Equation as adapted to the Pacific Northwest, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 2:135-147.

McCully, P., 1996, Silenced rivers: the ecology and politics of large dams, London and New Jersey, Zed Books, 350 p.

Milhous, R. T., 1982, Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 819-842.

Miller, A. J., 1995, Valley morphology and boundary conditions influencing spatial patterns of flood flow, Natural and Anthropogenic Influences in Fluvial Geomorphology, American Geophysical Union, Geophysical Monograph 89**:**57-81.

Montgomery, D. R., and J. M. Buffington, 1997, Channel-reach morphology in mountain drainage basins, Geological Society of America Bulletin 109(5):596-611.

Mostafa, M. G., 1957, River-bed degradation below large-capacity reservoirs, American Society of Civil Engineers Transactions 122:688-704.

Mutchler, C. K., 1976, Effect of land use on sediment delivery ratios, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:11-21.

Osterkamp, W. R., 1976, Variation and causative factors of sediment yields in the Arkansas River Basin, Kansas, Third Federal Inter-Agency Sedimentation Conference, Denver, Colorado: 1:59-70.

Petts, G. E., 1979, Complex response of river channel morphology subsequent to reservoir construction, Progress in Physical Geography 3(3):329-362.

Petts, G. E., 1980, Morphological changes of river channels consequent upon headwater impoundment, Journal of the Institution of Water Engineers and Scientists 34(4):374-382.

Pitlick, J., and M. M. V. Steeter, 1998, Geomorphology and endangered fish habitats of the upper Colorado River: 2. Linking sediment transport to habitat maintenance, Water Resources Research 34(2):303-316.

Price, R. K., 1982, Flow routing for river regulation, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 603-632.

Rosgen, D. L., 1994, A classification of natural rivers, Catena 22:169-199.

Rubin, D. M., R. A. Anima, and R. Sanders, 1994a, Measurements of sand thicknesses in Grand Canyon, Arizona, and a conceptual model for characterizing changes in sand-bar volume through time and space, US Geological Survey Open-File Report 94-597.

Rubin, D. M., and R. R. McDonald, 1995, Nonperiodic eddy pulsations, Water Resources Research 31(6):1595-1605.

Rubin, D. M., J. M. Nelson, and others, 1998, Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon, Geology 26(2):99-102.

Rubin, D. M., J. C. Schmidt, R. A. Anima, K. M. Brown, R. E. Hunter, H. Ikeda, B. E. Jaffe, R. R. McDonald, J. M. Nelson, T. E. Reiss, R. Sanders, and R. G. Stanley, 1994b, Internal structure of bars in Grand Canyon, Arizona, and evaluation of proposed flow alternatives for Glen Canyon Dam, US Geological Survey Open-File Report OF94-594.

Rubin, D. M., J. C. Schmidt, and J. N. Moore, 1990, Origin, structure, and evolution of a reattachment bar, Colorado River, Grand Canyon, Arizona, Journal of Sedimentary Petrology 60(6):982-991.

Schmidt, J. C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona, Journal of Geology 98:709-724.

Schmidt, J. C., P. E. Grams, and R. H. Webb, 1995, Comparison of the magnitude of erosion along two large regulated rivers, Water Resources Bulletin 31(4):617-631.

Schmidt, J. C., and D. M. Rubin, 1995, Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, Natural and anthropogenic influences in fluvial geomorphology, American Geophysical Union, Geophysical Monograph 89.

Schmidt, J. C., D. M. Rubin, and H. Ikeda, 1993, Flume simulation of recirculating flow sedimentation, Water Resources Research 29(8):2925-2939.

Simons, D. B., and R.-M. Li, 1982a, Application of flow routing techniques to river regulation, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 583-602.

Simons, D. B., and R.-M. Li, 1982b, Bank erosion on regulated rivers, *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Gravel-bed rivers, John Wiley & Sons Ltd**:** 717-754.

Sparks, R. E., J. C. Nelson, and Y. Yin, 1998, Naturalization of the flood regime in regulated rivers, BioScience 48(9):706-720.

Stevens, L. E., J. C. Schmidt, T. J. Ayers, and B. T. Brown, 1995, Flow regulation, geomorphology, and Colorado River marsh development in the Grand Canyon, Arizona, Ecological Applications 5(4):1025-1039.

New, productive fluvial marshes may develop along regulated canyon rivers through reduction in flood frequency, thereby increasing diversity, production, and wildlife habitat availability.

Trush, W., R. Franklin, and S. McBain, 1995, Assessing downstream variation of fluvial processes for recommending maintenance flows in regulated rivers, 10 p.

Wilcock, P. R., A. F. Barta, C. C. Shea, G. M. Kondolf, W. V. G. Matthews, and J. Pitlick, 1996a, Observations of flow and sediment entrainment on a large gravel-bed river, Water Resources Research 32(9):2897-2909.

Wilcock, P. R., G. M. Kondolf, W. V. G. Matthews, and A. F. Barta, 1996b, Specification of sediment maintenance flows for a large gravel-bed river, Water Resources Research 32(9):2911-2921.

Williams, G. P., 1978, Bank-full discharge of rivers, Water Resources Research 14(6):1141-1154.