



# **Sediment Transport, Supply, and Stability in the Hells Canyon Reach of the Snake River**

Shaun Parkinson, IPC  
Engineering Leader

Kelvin Anderson, IPC  
Engineer II

Jeff Conner, IPC  
Engineer II

James Milligan  
U of I Civil Engineer (ret.)

**Technical Report  
Appendix E.1-1**

Hells Canyon Complex  
FERC No. 1971

March 2002  
*Revised July 2003*

Copyright © 2003 by Idaho Power Company



## TABLE OF CONTENTS

Table of Contents .....	i
List of Tables .....	viii
List of Figures .....	ix
List of Appendices .....	xiii
Executive Summary .....	1
1. Introduction.....	3
2. Study Area and HCC Development.....	7
2.1. General Location.....	7
2.2. River Morphology.....	7
2.3. Geologic Setting.....	8
2.4. Upstream Basin Development History .....	9
2.5. Hells Canyon Complex Development .....	12
2.5.1. Brownlee Dam and Reservoir.....	13
2.5.2. Oxbow Dam and Reservoir.....	13
2.5.3. Hells Canyon Dam and Reservoir.....	13
2.6. Operational Scenarios .....	14
3. Issues Addressed.....	14
3.1. Sandbar Erosion and Development.....	14
3.1.1. Definition .....	14
3.1.2. Concern.....	15
3.1.3. Approaches to Addressing Concern about Sandbars .....	15
3.2. Riparian Areas .....	15
3.2.1. Definition .....	15

---

3.2.2. Concern.....	15
3.2.3. Approaches to Addressing Concern about Riparian Areas.....	16
3.3. Maintenance of Areas Important to Aquatic Resources .....	16
3.3.1. Fall Chinook Spawning Beds.....	16
3.3.2. Fall Chinook Rearing Areas.....	16
3.4. Bank Stability.....	16
3.4.1. Definition .....	16
3.4.2. Concern.....	17
3.4.2.1. Archaeological Sites .....	17
3.4.2.2. Recreation Sites .....	17
Aesthetics—Information Needed.....	17
Sediment Routing and Regime—Recreation-Related Questions .....	18
Recreational Use (Project Operations)—Issue Statement .....	18
4. Identification and Description of Significant Sites.....	18
4.1. Sandbar Erosion and Deposition.....	18
4.2. Aquatic Habitat Areas.....	19
4.2.1. Spawning Beds for Fall Chinook.....	19
4.2.2. Rearing Areas for Fall Chinook.....	19
4.3. Erosion at Historically Significant Sites.....	19
5. Sources of Data and Information.....	20
5.1. Existing Maps and Photographs.....	20
5.1.1. Aerial Photographs of Sandbars.....	20
5.1.2. General Aerial Photographs.....	21
5.2. Data from Computer Models .....	21
5.2.1. Reservoir Operations Model.....	22

---

5.2.2. 1-D Hydraulic Computer Model.....	22
5.3. Miscellaneous Data.....	22
5.3.1. Sampling Data for Suspended Sediments.....	22
5.3.2. Data on Reservoir Bathymetry.....	23
5.3.3. Data on River Bathymetry.....	23
5.3.4. Basin Characteristics for Estimation of Flow-Duration Curves.....	23
5.3.5. General Reservoir Data.....	23
5.4. Field Data Collection by IPC.....	24
5.4.1. Surveying Data.....	24
5.4.1.1. Hydraulic Characteristics of Tributaries.....	24
5.4.1.2. Hydraulic Characteristics of the Mainstem Snake River.....	24
5.4.2. Bulk Samples of Bed Material.....	25
5.4.3. Analysis of the Size Distribution of Surface Particles.....	25
5.4.4. Samples of Suspended Sediments.....	25
5.4.5. Sandbar Surveys.....	26
5.4.6. Piezometer Data.....	26
5.5. Field Sampling by Others.....	26
5.5.1. Sediments in Brownlee Reservoir.....	26
5.5.2. Freeze-Core Sampling.....	27
5.6. Other Studies by IPC.....	27
6. Methodology for Acquiring Field Data.....	27
6.1. Bed Material.....	28
6.1.1. Sampling of Surface (Armor) Materials.....	28
6.1.1.1. Wolman Pebble Count (Tributaries).....	29
6.1.1.2. Photographic Sampling (Mainstem Snake River).....	29

---

Still Photographic Sampling .....	29
Underwater Photographic Sampling .....	30
6.1.2. Sampling of Subsurface Bed Materials.....	31
6.2. Bedload .....	31
6.2.1. Tributaries .....	31
6.2.2. Mainstem.....	32
6.3. Suspended Sediment .....	32
6.3.1. Tributaries .....	32
6.3.2. Mainstem.....	33
6.4. Bars .....	34
6.4.1. Sandbars .....	34
6.4.2. Gravel Bars .....	35
6.5. Bathymetry, Cross Sections, and Hydraulic Geometry .....	35
6.6. Tributary Hydraulic Geometry .....	35
6.6.1. Hydraulic Geometry for Sediment Transport Calculations .....	36
6.6.2. Hydraulic Geometry for Estimating Tributary Flows.....	36
7. Sample Analysis and Laboratory Results .....	36
7.1. Analysis of Suspended Sediment Samples .....	37
7.2. Sieve Analysis for Particle-Size Distribution .....	37
7.2.1. Analysis of Bed-Material Samples .....	37
7.2.2. Analysis of Bedload Samples .....	38
7.3. GoldSize Photographic Analysis of PSD.....	38
7.3.1. Image Enhancement.....	38
7.3.2. Photograph Sizing.....	39
7.3.3. Sizing Analyses.....	39

---

7.3.4. PSD Data Conversion .....	39
8. Geographic Information Systems Methodology and Applications.....	40
8.1. Delineation of Tributary Basins.....	40
8.2. Tracked Locations.....	41
8.3. Rectification of Aerial Photographs.....	41
9. Calculation and Analysis Methodology.....	41
9.1. Surface and Subsurface Materials.....	42
9.2. Characterization of Surface Layer .....	42
9.3. Calculations of Flow Resistance.....	43
9.3.1. General Background .....	43
9.3.2. Flow Resistance for Channels with Coarse Bed Materials.....	45
9.4. Calculations of Armor Formation.....	50
9.4.1. Background.....	50
9.4.2. Armoring in the Mainstem Snake River .....	52
9.5. Calculations of Incipient Motion .....	53
9.5.1. General Background .....	53
9.5.2. Incipient Motion for Uniform Sediments .....	54
9.5.3. Use of Shields Diagram for Nonuniform Sediments .....	57
9.5.4. Procedure .....	61
9.5.5. Incipient Motion Analysis of Fall Chinook Spawning Sites .....	62
9.6. Transport Modeling for Tributaries .....	63
9.6.1. Equations for Transport of Gravel Beds.....	64
9.6.2. Special Considerations.....	68
9.7. Estimation of Sediment Supply to the Snake River.....	69
9.7.1. Development of Flow-Duration Curves for Tributaries .....	69

---

9.7.2. Transport Calculations for Tributaries and Application of Flow-Duration Curves to Estimate Annual Sediment Yield to Snake River .....	70
9.7.3. Reference Values for Sediment Yield.....	71
9.7.4. Measured Quantities of Sediment Yield from Tributaries.....	71
9.8. Sediment Source Analysis of Bed Materials in the Snake River.....	71
9.9. Changes in Sandbars Based on Analysis of Aerial Photographs.....	72
9.9.1. Area Method .....	72
9.9.2. Sandbar Count.....	74
9.10. Reservoir Trapping Efficiency.....	76
10. Results and Conclusions .....	76
10.1. Sandbars and Terraces .....	76
10.1.1. Sandbar Material.....	77
10.1.1.1. Sandbar Material Particle Size.....	77
10.1.1.2. Sandbar Material Provenance .....	78
10.1.2. Sandbar Monitoring .....	80
10.1.2.1. Background.....	80
10.1.2.2. Hydrology .....	80
10.1.2.3. General.....	81
Pine Bar.....	81
Salt Creek Bar.....	82
Fish Trap.....	82
China Bar .....	83
General Discussion .....	83
10.1.3. Bar Counts .....	84
10.1.4. Area and Distance Measurements.....	86
10.1.5. Sandbar Summary.....	87

10.2. Bed Stability.....	88
10.2.1. USGS Gauge—Snake River Downstream of Hells Canyon Dam.....	88
10.2.2. USGS Gauge—Snake River Near Joseph, Oregon .....	89
10.2.3. Incipient Motion Calculations.....	89
10.2.4. Bed Stability Summary .....	91
10.3. Bank Stability.....	92
10.3.1. General Bank Stability.....	92
10.3.2. Sandbar Stability.....	93
10.3.3. Terrace Stability.....	93
10.4. Sediment Supply to the Mainstem .....	94
10.4.1. Sediment Supply Upstream of Hells Canyon Complex.....	95
10.4.1.1. Snake River above Brownlee Reservoir .....	95
10.4.1.2. Transport Capability of the Snake River above Brownlee Reservoir .....	98
10.4.1.3. Sediments Trapped in Brownlee Reservoir .....	98
10.4.1.4. River Cross Section Stability .....	98
10.4.2. Sediment Supply from Wildhorse River and Pine Creek .....	99
10.4.3. Sediment Supply from Tributaries.....	101
10.4.3.1. Sediment Supply From Tributaries Below HCD .....	101
10.4.3.2. Sediment Supply From Tributaries Within the HCC.....	102
10.4.3.3. Confirmation of Sediment Supply Estimates.....	102
10.4.3.4. Indicators of Sediment Availability .....	103
Visual Field Investigation.....	103
Hillside Slopes in Hells Canyon .....	103
10.4.4. Bed-Material Mineralogy.....	103
10.4.5. Bed-Material Size Distribution.....	105

10.4.6. Sediment Supply Summary .....	105
10.5. Description of Operating Scenarios .....	106
10.6. Impacts from Changes in Operation .....	107
10.7. Sediment Budget by Size Class .....	108
11. Acknowledgments.....	110
12. Literature Cited .....	111
13. Additional Resources.....	121

## LIST OF TABLES

Table 1.	Upstream reservoirs and sediment trapping efficiency.....	125
Table 2.	Sources, years, scale, and approximate coverage of aerial photographs used in the study (RM 247.6 downstream to RM 188.28).....	126
Table 3.	Sandbars surveyed by location, date, and daily average flow (cfs) at time of survey.....	127
Table 4.	Coefficients and exponents for power form flow resistance equations. ....	128
Table 5.	Bed shear stress values ( $\tau_b$ ) from MIKE 11 model in N/m <sup>2</sup> . ....	128
Table 6.	Calculated dimensionless shear stress values ( $\theta^*$ ) using equation 31. ....	128
Table 7.	Sediment yield values from published sources. ....	129
Table 8.	PSD of Sand Data Collected During Provenance Sampling at Fish Trap Bar.....	130
Table 9.	PSD of Sand Data Collected During Provenance Sampling at Pine Bar.....	131
Table 10.	Total sediment yields based on various methods/data.....	132
Table 11.	Selected flows and return periods for the current/proposed and full pool run-of-river operating scenarios.....	133
Table 12.	Percent of mainstem river bed that mobilizes—Snake River, Hells Canyon. ....	134
Table 13.	Evaluation of fall chinook spawning sites for 25-mm (1-inch) gravels—Snake River, Hells Canyon. ....	135

Table 14.	Evaluation of fall chinook spawning sites for 50-mm (2-inch) gravels— Snake River, Hells Canyon. ....	136
Table 15.	Particle size distribution of sediment loads and resources.....	137
Table 16.	Summary of sediment loads from tributaries in Hells Canyon.....	138
Table 17.	Summary sediment loads from tributaries within Hells Canyon Complex. ....	139

## LIST OF FIGURES

Figure 1.	Area and vicinity map.....	141
Figure 2.	Geology of the study area. ....	143
Figure 3.	Upstream basin development.....	145
Figure 4.	Hells Canyon Complex development. ....	147
Figure 5.	Significant sites in Hells Canyon.....	149
Figure 6.	Aerial photography coverage in the Hells Canyon reach of the Snake River.....	151
Figure 7.	Bed-material structure in a typical gravel-bed river or stream. ....	153
Figure 8.	Photograph of a dry gravel bar with the PVC frame and two golf balls for scaling. ....	153
Figure 9.	Underwater photograph of surface particles. ....	153
Figure 10 (panel 1 of 3).	Tributaries selected for sediment supply calculations. ....	155
Figure 10 (panel 2 of 3).	Tributaries selected for sediment supply calculations. ....	157
Figure 10 (panel 3 of 3).	Tributaries selected for sediment supply calculations. ....	159
Figure 11.	Screen capture of a photograph of gravel bar during the GoldSize process. ....	161
Figure 12.	Calculated dimensionless critical shear stress as a function of critical roughness Reynolds number for values of particle diameter to bed roughness on a scale from 0.2 to 5.0 (from Wiberg and Smith 1987).....	162
Figure 13.	Sandbar areas delineated at Johnson Bar. ....	163
Figure 14.	Sandbar counts raw (unadjusted for flow) and adjusted to 12,000 cfs. ....	165

Figure 15.	Particle-size distribution data for Pine Bar and cutbank.....	166
Figure 16.	Particle-size distribution data for Salt Creek Bar and cutbank.....	167
Figure 17.	Particle-size distribution data for Fish Trap Bar and cutbank.....	168
Figure 18.	Particle-size distribution data for China Bar and cutbank.....	169
Figure 19.	Particle-size distribution of material trapped in Brownlee Reservoir and in sandbars in Hells Canyon.....	170
Figure 20.	Particle-size distribution of material trapped in Brownlee Reservoir and in sandbars in Hells Canyon normalized with sand at 100%.....	171
Figure 21.	PSD comparing Brownlee Reservoir samples (both along the thalweg between RM 325-285 and from all three deep cores) with downstream sandbar samples (P2 and P3 are from Pine Bar, TS5 is from Tin Shed Bar, and F1, F3, and F4 are from Fish Trap Bar).....	172
Figure 22.	Particle size distribution of sediment in taken from core F1 in Fish Trap Bar.....	173
Figure 23.	Particle size distribution of sediment in taken from core F2 in Fish Trap Bar.....	173
Figure 24.	Particle size distribution of sediment in taken from core F3 in Fish Trap Bar.....	174
Figure 25.	Particle size distribution of sediment in taken from core F4 in Fish Trap Bar.....	174
Figure 26.	Particle size distribution of sediment in taken from core P1 in Pine Bar.....	175
Figure 27.	Particle size distribution of sediment in taken from core P2 in Pine Bar.....	175
Figure 28.	Particle size distribution of sediment in taken from core P3 in Pine Bar.....	176
Figure 29.	Core locations at Fish Trap Bar.....	177
Figure 30.	Core locations at Pine Bar.....	178
Figure 31.	Pine Bar plan view (a) 1997–1998, (b) 1998–2000.....	179
Figure 32.	Pine Bar Transect A.....	180
Figure 33.	Pine Bar Transect B.....	180
Figure 34.	Pine Bar Transect C.....	181

Figure 35.	Pine Bar Transect D.....	182
Figure 36.	Salt Creek Bar plan view.....	183
Figure 37.	Photograph of Salt Creek Bar.....	184
Figure 38.	Salt Creek Bar Transect A.....	185
Figure 39.	Salt Creek Bar Transect B.....	186
Figure 40.	Salt Creek Bar Transect C.....	186
Figure 41.	Fish Trap Bar plan view (a) 1997–1998, (b) 1998–1999, (c) 1999–2000.....	187
Figure 42.	Fish Trap Bar Transect A.....	188
Figure 43.	Fish Trap Bar Transect B.....	189
Figure 44.	Fish Trap Bar Transect C.....	190
Figure 45.	Fish Trap Bar Transect D.....	190
Figure 46.	China Bar plan view (a) 1997–1998, (b) 1998–2000.....	191
Figure 47.	China Bar Transect A.....	192
Figure 48.	China Bar Transect B.....	192
Figure 49.	China Bar Transect C.....	193
Figure 50.	USFS photograph of Pine Bar in 1994.....	193
Figure 51.	IPC photograph of Pine Bar in 1999.....	194
Figure 52.	IPC photograph of Fish Trap Bar in 1999.....	194
Figure 53.	Photograph series of Pine Bar and associated flow: 1946 (top), 1949 (middle), and 1964 (bottom).....	195
Figure 54.	Sandbar counts (adjusted to 12,000 cfs) for three reaches in Hells Canyon.....	196
Figure 55.	Comparison of Bar #11-Oregon (downstream of Dug Bar) showing no sand in 1946, and sand/gravel in 1955. The occurrence of sand/gravel in 1955 is due to the disturbance of the soil and vegetation caused by the newly formed access into the area.....	197
Figure 56.	Pine Bar aerial photographs 1955 and 1964.....	199

Figure 57. USGS gauge (13290450) measurements for the Snake River below Hells Canyon Dam.....	201
Figure 58 (panel 1 of 9). Bed stability at 30,000 cfs.....	203
Figure 58 (panel 2 of 9). Bed stability at 30,000 cfs.....	205
Figure 58 (panel 3 of 9). Bed stability at 30,000 cfs.....	207
Figure 58 (panel 4 of 9). Bed stability at 30,000 cfs.....	209
Figure 58 (panel 5 of 9). Bed stability at 30,000 cfs.....	211
Figure 58 (panel 6 of 9). Bed stability at 30,000 cfs.....	213
Figure 58 (panel 7 of 9). Bed stability at 30,000 cfs.....	215
Figure 58 (panel 8 of 9). Bed stability at 30,000 cfs.....	217
Figure 58 (panel 9 of 9). Bed stability at 30,000 cfs.....	219
Figure 59 (panel 1 of 9). Bed stability at 39,670 cfs.....	221
Figure 59 (panel 2 of 9). Bed stability at 39,670 cfs.....	223
Figure 59 (panel 3 of 9). Bed stability at 39,670 cfs.....	225
Figure 59 (panel 4 of 9). Bed stability at 39,670 cfs.....	227
Figure 59 (panel 5 of 9). Bed stability at 39,670 cfs.....	229
Figure 59 (panel 6 of 9). Bed stability at 39,670 cfs.....	231
Figure 59 (panel 7 of 9). Bed stability at 39,670 cfs.....	233
Figure 59 (panel 8 of 9). Bed stability at 39,670 cfs.....	235
Figure 59 (panel 9 of 9). Bed stability at 39,670 cfs.....	237
Figure 60 (panel 1 of 9). Bed stability at 100,000 cfs.....	239
Figure 60 (panel 2 of 9). Bed stability at 100,000 cfs.....	241
Figure 60 (panel 3 of 9). Bed stability at 100,000 cfs.....	243
Figure 60 (panel 4 of 9). Bed stability at 100,000 cfs.....	245
Figure 60 (panel 5 of 9). Bed stability at 100,000 cfs.....	247
Figure 60 (panel 6 of 9). Bed stability at 100,000 cfs.....	249

Figure 60 (panel 7 of 9). Bed stability at 100,000 cfs.....	251
Figure 60 (panel 8 of 9). Bed stability at 100,000 cfs.....	253
Figure 60 (panel 9 of 9). Bed stability at 100,000 cfs.....	255
Figure 61. USGS gauge measurements for the Snake River at Weiser, Idaho. ....	257
Figure 62. Rating curves for the USGS gauge located on the Snake River at Weiser (13269000).....	257
Figure 63. Rating curves for the USGS gauge located on the Snake River below Hells Canyon Dam (13290450). ....	258
Figure 64. Particle-size distribution data from above and below the HCC (light blue lines are from above the HCC and thin red lines with an x are from below the HCC). ....	259
Figure 65. Particle-size distribution data from above and below the HCC, as well as from tributaries below the HCC (blue lines are from above the HCC, thin red lines are from below the HCC, and thick green lines are from tributaries below the HCC). ....	260
Figure 66. Average $d_{16}$ , $d_{50}$ , and $d_{84}$ with plus and minus one standard deviation.....	261
Figure 67. Flow-duration curves for proposed and full pool run-of-river operational scenarios.....	262

## LIST OF APPENDICES

Appendix A. Glossary
Appendix B. Brownlee Reservoir aquatic sediment study (prepared by CH2M HILL)
Appendix C. Surface particle-size distribution analysis (GoldSize)
Appendix D. Laboratory analysis results and plots of particle-size distributions for bed material sediment samples
Appendix E. Calculated transport rates for tributaries to the Snake River in Hells Canyon
Appendix F. Flow-duration curves
Appendix G. Sample transport computation sheets
Appendix H. Stability analysis of sandbars (prepared by CH2M HILL)

This page left blank intentionally

## EXECUTIVE SUMMARY

This report on sediment transport, supply, and stability addresses two central questions. First, how has the construction and operation of the Hells Canyon Complex (HCC) affected the supply and movement of sediment in the Snake River downstream of the complex? Second, what are the resulting effects to sediment-related features in the downstream reach?

It is widely accepted that damming a river causes several effects to the downstream reach. Dams typically decrease peak flows, can increase or decrease minimum flows, trap sediment (thereby causing erosion of the riverbed below the dam), and in the case of dams operated primarily for hydropower production, increase daily flow fluctuations. The combination of these changes can dramatically alter the river's character downstream of the dam. Inherent in these widely accepted impacts are several assumptions, such as the following, that are not always noted, clearly understood, or (in some cases) accurate:

- The reservoir is large enough and operated in such a way that it substantially modifies flow patterns downstream.
- The river was in dynamic equilibrium before the reservoir was constructed, and any changes in river dynamics following construction were caused by the reservoir rather than as part of a continuing trend or by projects upstream.
- The river was in an alluvial environment condition (and could therefore adjust its shape) before the dam was constructed, and the river had sufficient sediment load to maintain that condition.
- The riverbed and bank materials are such that the river can respond to changes in the hydrograph and sediment supply.
- Supplies of sediment from other sources, such as local tributaries, are insufficient to achieve a new dynamic equilibrium that does not significantly differ from the one that existed before the dam was constructed.

The most effective description of a natural system generally depends on empirical data collected from that specific system. The more complex and variable a system is, the more important measured data and clearly understood assumptions are. Sediment transport, supply, and stability are complex issues that are not fully understood. Nor can they be fully described, even using state-of-the-art models and tools.

Sediment transport and mobility are highly irregular and depend on many variables. Among these variables, fixed characteristics can be measured at essentially any time while other characteristics, such as hydrology, can be measured only during specific periods. For example, a system's response to high flows can only be measured during high-flow events.

Because information on sediment-related processes in the Hells Canyon reach of the Snake River was limited, Idaho Power Company (IPC) used a combination of measured data and modeling to describe sediment transport, supply, and stability through the HCC. Because of this combined approach, some results and conclusions are derived from studies conducted by either IPC or others. Other results and conclusions are based on modeled data, with the models themselves based on methods described in the literature and adapted to conditions found in the study area. Still other results and conclusions are based on a combination of modeled results supported by measured data where they were available.

This report includes results of the data analyses and modeling. It also includes conclusions about the validity of the assumption statements listed above, based on study results. The data, analyses, and conclusions indicate the following:

- The storage capacity of the HCC is only about 11% of the average annual volume of the Snake River as given by calculated inflow to Brownlee Reservoir. Therefore, the HCC has a relatively small effect on the hydrograph downstream of the complex.
- Changes in the river observed since the construction of the HCC (such as shrinking sand beaches) may be caused by human activity higher in the Snake River Basin since the mid-1800s and not by construction and operation of the HCC.
- The transport competency of the Snake River upstream of the HCC is insufficient to mobilize and transport materials such as those found in the riverbed of the Hells Canyon reach. Therefore, no supply of bed materials would be available from sources upstream of the HCC under historical hydrologic conditions.
- Less than 4% of the sediment trapped in Brownlee Reservoir (the uppermost dam in the HCC and the first of the three constructed by IPC) is larger than fine sand (14% is larger than silt/clay). All of the features of interest downstream are largely made up of sediments larger than fine sand (and were before the construction of the HCC).
- Because the basic form and character of the river were established under vastly higher flow conditions, the bed and bank materials provide extremely limited opportunity for river movement.
- Continuing supplies of sands, gravels, and cobbles from local sources below Hells Canyon Dam (HCD) have not been affected by the construction and operation of the HCC.
- Human activities in and above the Hells Canyon area, such as mining and grazing, modified hillslope processes from the mid-1800s to the mid-1900s. These activities may have introduced an unusually large sediment supply to the river that decreased as the activities that introduced them also decreased. This “slug” of sediment may be working its way out of the Hells Canyon system.

These findings are consistent with information and conclusions presented in Miller et al. (2003), who stated:

Due to the strong valley-wall confinement found in the Hells Canyon reach, the river lacks the floodplain morphology and alluvial character typical of other lowland rivers of comparable gradient and drainage area. Much of the river morphology is forced by large scale geologic and geomorphic controls that significantly reduce the range of fluvial processes and types of channel adjustment found in other lowland alluvial rivers.

Given the results of data and analysis, we conclude that, while the HCC has some impact on the Snake River system, the effects that can be directly attributed to the HCC are much smaller than originally thought. Other factors occurring over the last 150 years or so have also affected the system. Therefore, examining only those changes that have occurred in the last 20 to 30 years is insufficient for determining what effects (or what portion of those effects) have been caused by construction and continued operation of the HCC.

## 1. INTRODUCTION

This report presents the results of a study on the supply and movement of sediments above, through, and below the Hells Canyon reach of the Snake River. The study area extends from river mile (RM) 145.6 to 351.3, with the primary focus on the Hells Canyon reach. The study addressed how the supply of sediment to this reach from the mainstem Snake River upstream of and within the Hells Canyon Complex (HCC) has changed, what happens to sediment that is supplied to this reach from tributaries in the reach, and how this supply might change under different operating scenarios of the HCC. A common understanding of the terms used is important in a study such as this one. Therefore, we have prepared a glossary of key terms, which is presented as Appendix A to this report.

The supply and movement of sediment are important to many of the resources in the Hells Canyon reach of the Snake River. For example, fall chinook salmon (a species under the protection of the Endangered Species Act) prefer to spawn at sites with particular sizes and qualities of gravels (Groves and Chandler 1999, 2001). The supply and movement of these gravels are important to the quality and quantity of present and future spawning habitat. Recreational users—hikers, rafters, boaters, and others—prefer beaches composed of sand-size particles rather than cobble- and boulder-size particles and sand beaches are an important amenity to many campsites. All of these issues are discussed in more detail in this report.

Early in the relicensing process, IPC was encouraged by various agencies and entities to not narrowly focus on particular issues but evaluate the system in a more holistic manner. Thus, this sediment report (E.1-1) and the related geomorphology report (Miller et al. [2003]) are intended to serve as a comprehensive description and information set. This is particularly relevant for readers unfamiliar with Hells Canyon or the Snake River. The reports are set up so that readers only interested in one aspect such as sandbars or spawning gravels can go to those sections directly and disregard the rest of the reports. However, it is important for readers unfamiliar with

the area or those interested in sediment and geomorphological processes as a whole to have the full range of information available.

Geomorphic and sediment processes and features in an environment as complex as the Hells Canyon cannot be narrowly focused and limited to local features and select particle sizes and still be accurately understood. It is important that a full range of factors be taken into account to achieve as complete an understanding of the sediment processes as possible. In order to present as thorough and complete a picture as possible, IPC chose to research and provide information on as many aspects of geomorphology and sediment processes related to the Snake River Basin as were available, and not limit the studies to the area just below the HCC. Early in the study process the agencies strongly promoted this holistic approach that IPC has followed. The agencies' support of this process is clear in the following quotes:

In a letter from Dave Wegner to Bob Simons dated May 19, 1999, Mr. Wegner states *“As we have discussed, it is my contention, which is shared by the Forest Service and other Federal and State representatives, that an understanding of the geomorphology of the Snake River system and watershed is essential to interpreting the effects of HCC. The geomorphic information will aid in placing in context the results that are being generated from the individual studies.”*

In A Geomorphic Basis for Interpreting the Hydrologic Behavior of Large River Basins by Gordon E. Grant (with the USFS), Mr. Grant states that *“Understanding controlling processes at appropriate scales has become a fundamental challenge to hydrologists”* and *“The broad geographic setting, as defined by climate, geology, soils, topography, and vegetation therefore strongly influences riverine systems over ecologically relevant time scales”* and *“One reason for the sometimes contradictory results of research into effects of forest management on streamflow (e.g., Ziemer, 1981; Wright et al., 1990) is differences in the larger geomorphic context in which these studies occur.”* and *“Recognizing the importance of geomorphic controls on streamflow is the first step toward placing human alterations to hydrology in their proper context.”*

In the study of any natural system, it is generally preferable to make actual measurements of the subject of the study rather than to rely exclusively on computer models or mathematical formulas to develop conclusions about the subject. However, an empirical approach depends on the availability of baseline sediment data collected over both a significant period of time and range of flow conditions. In many, if not most, cases (including the Snake River), such baseline data are unavailable. Other researchers have also noted the lack of sediment data in the Hells Canyon reach of the Snake River, notably Grams and Schmidt, who were commissioned by the USFS to study sand beaches and terraces in Hells Canyon (1999a and 1999b). This lack of baseline data requires that measurements be supplemented and/or extended with mathematical descriptions of the study subject. A benefit of this requirement is that changes based on alternative scenarios can be estimated. This situation is particularly true in the case of sediment mobility in gravel-bed streams because of the episodic nature of sediment supply and mobility. That is, most sediment is mobilized and transported during higher flow periods. Typically during the summer, fall, and winter of the year, little sediment is transported in streams, so sampling would not provide significant information. Even during the spring runoff season, there may be just a few hours or days of the peak flow during which sediment could be mobilized. In some dry years (e.g., 2001),

runoff may be insufficient to initiate sediment movement even for a short period. Also, given that much sediment is transported during high-flow periods, collecting samples representative of the complete width of the stream can be unsafe. In some places, structures may be required for accurate and safe sampling at high flows. This study, like many other sediment transport studies, relied on a combination of [1] empirical (or measured) data, 2) mathematical modeling based on research in other streams and areas, and 3) other reference information with which to develop estimates of sediment supply and transport into and through the system.] We were careful to ensure that the mathematical models used in the sediment evaluations were appropriate for the specific situations and conditions to which we applied them.

Throughout the process of setting up this study and performing the fieldwork, various experts participated in tours of the study area and offered their guidance. For example, Hsieh Wen Shen and Thomas Dunne participated in a river trip in January 1998. Their initial approaches to analyzing sediment processes in the reach are summarized in informal memoranda and are very similar to the approaches we adopted in this study. Mr. Shen listed a series of analyses we could undertake to understand the system more completely. His recommendations included a flow analysis to compare flow-duration curves from before and after the HCC was constructed, a hydraulic analysis to evaluate sediment stability, a bed-material analysis to get size distributions of sediments, use of Shields criteria to evaluate bed stability, and collection of suspended sediment samples from locations in different river reaches. Also, Mr. Shen recommended sampling in Brownlee Reservoir to investigate the size distribution of sediment trapped in the reservoir.

Mr. Dunne's notes focused mostly on the issue of sandbars. Mr. Dunne comments that the "sand beaches within the canyon must have been delicate features...rather small for a river of this size, but not for one with this gradient." Much of the study presented in this report focuses on addressing the key questions that Mr. Dunne raised in his memorandum, including potential sediment supply and sediment trapped in the reservoirs.

The methods of addressing the issues discussed in this report are included in two broad categories applied in two different areas. The categories are [1] sediment supply and 2) sediment mobility.] Sediment supply addresses the question of how much sediment is introduced to the system over some time period from all sources. Sediment supply also considers the sizes of individual particles within the total sediment supply (i.e., sand sizes, gravel sizes, and so on). Sediment mobility deals with how or whether the riverbed or streambed sediment moves. It is important not to confuse the issue of bed stability/mobility and sediment transport. Even when a riverbed is immobile, sediment can still be transported through that reach. However, this does not mean that bed material is available as a supply of sediment under those conditions. In this report, we consider the issue of sediment supplied by tributaries to the Snake River below the HCC, directly to the HCC, and the Snake River above the HCC. In our assessment of sediment mobility, we focus primarily on the mainstem of the Snake River.

We focused our study on the reach between Hells Canyon Dam (HCD) and the Salmon River for several reasons. First, the upper part of this reach includes the majority of the Hells Canyon National Recreation Area (HCNRA) and sections of the Snake River designated as wild and scenic. The first 52.3 kilometers (km) (32.5-mile [mi]) reach below the HCC is designated as wild, and the next 55 km (34.4-mi) reach is designated as scenic (NPS 2001). Second, the bulk of

historical interest is in this reach. Third, this reach contains much of the spawning habitat for anadromous fish (Groves 2001a). Finally, in this reach, the operational effects of the HCC are not masked by the effects of inflows from the major tributaries such as the Salmon River and the Grande Ronde River. IPC operations almost completely control the discharge in the 96-km (60-mi) reach of the Snake River between HCD and the confluence of the Salmon River (except for flows above plant capacity of about 30,000 cubic feet per second [cfs]). Because the Salmon River contributes relatively large quantities of sediment to the Snake River below the confluence, there is less concern with changes imposed by the HCC on the Snake River downstream of the Salmon River. In any event, the large quantities of sediment supplied by the Salmon River tend to mask any influences of the HCC to the point that identifying any distinct sediment-related effects in this downstream reach is difficult.

The Snake River within the Hells Canyon reach differs from most streams of comparable size in several important aspects. The average slope of the river within this reach varies systematically from 0.002 to 0.0007 (10.5 and 3.7 feet [ft] per mi) in the downstream direction. These slopes are quite steep for a river of this size and order. In addition, the gradient is governed primarily by natural structural controls within the canyon, with local variations in slopes controlled by relict landslide and bar features from an earlier hydrologic regime. Narrow valley walls composed of erosion-resistant bedrock and coarse colluvium and alluvium also confine the river so that this reach has little opportunity for alluvial expression or typical bankfull morphology such as floodplain development. This channel confinement affects the relationships among discharge, channel hydraulics, and sediment transport. At the reach scale, under flow conditions within the operating range of the HCC, the river exhibits a regular pool-riffle morphology between HCD and the Salmon River confluence.

We hypothesized that there would be little, if any, bed-material transport within the mainstem Snake River in the Hells Canyon reach, with or without the influence of the HCC. We based our hypothesis on three primary factors: [1) the considerable development of storage on the upstream reaches of the river and its major tributaries, 2) the confined geomorphic character of this reach of the river, and 3) observations of the armored character of bed materials in the river.] In addition, our hypothesis was supported by the stable character of the gauging station on the Snake River near Weiser, the relatively low concentrations of suspended sediment (mostly silt/clay sizes) reported at this same gauging station, the very large size of armor materials in the streambed throughout the Hells Canyon reach, and the discharge records. Those records suggest that, under current hydrologic conditions, flows are seldom sufficient to mobilize the armor materials within the reach. These conditions seemed to preclude the more typical approach of a sediment budget type of study. Based on these conditions, we decided to focus on determining sediment supplies from sources other than the bed materials within the mainstem and understanding the stability of the sediments in the riverbed. In other words, we focused on sediment supplies to determine the probable magnitude and character of sediment supplies contributed by the numerous small tributaries. In addition, we conducted studies to determine the character of sediments transported to and trapped within Brownlee Reservoir to determine whether the HCC was trapping significant sand and gravel sediments above the Hells Canyon reach.

## 2. STUDY AREA AND HCC DEVELOPMENT

This section presents information about the geographical area covered in this study and briefly describes some of the important features of the area that are important to the study of sediment supply and transport. Also, we briefly discuss the development of the HCC. More detailed information is available in other technical reports and, where appropriate, we refer to those reports.

### 2.1. General Location

The study area for this investigation includes the Snake River from about Weiser, Idaho, downstream through the HCC to near Lewiston, Idaho. The length of the study reach is approximately 331 km (206 mi) from RM<sup>1</sup> 145.6 upstream of Lewiston to RM 351.3 at the U.S. Geological Survey (USGS) gauge near Weiser. The area of primary focus and detailed analysis is the Snake River from the HCD at RM 247.6 downstream to the confluence with the Salmon River at RM 188.2. Some general information and data from the watershed above RM 351.3 is also discussed in the analyses.

This reach of the Snake River forms a portion of the border between Idaho and Oregon and between Idaho and Washington. The HCD is the last dam (farthest downstream) of the three-dam HCC, which is owned and operated by IPC. For the purposes of this report, we define the HCC as the reach from the upper end of Brownlee Reservoir downstream to HCD. Figure 1 shows the location of the study area and the HCC. The study area does not include the drainage basins of either the Imnaha or Salmon rivers. The primary area of concern is upstream of both of these rivers and is therefore not affected by sediment supply from those rivers. Cherry Creek and Cook Creek (included in the study) are also downstream of the area of primary concern. However, these tributaries are similar in size and character to many of the tributaries upstream. Therefore, including these streams in the study allowed us to collect additional data to characterize the tributaries that supply sediment to the Snake River downstream of the HCC.

The next two subsections provide general descriptions of the study area's morphology and geology. For more information on these subjects, see Miller et al. (2003).

### 2.2. River Morphology

Downstream of HCD, Hells Canyon is the deepest and one of the most rugged river gorges in the continental United States. The average slope of the river downstream of HCD to the confluence

---

<sup>1</sup> River miles are typically established starting at 0.0 at the river mouth and increasing upstream, nominally along the river thalweg. Occasionally, due to changes in the river channel, errors in cartography, or other reasons, river miles from two or more sources will not agree. The river mile designations used in this report are generally in agreement with those shown in the informational booklet "The Wild and Scenic Snake River Hells Canyon National Recreation Area" produced by the U.S. Department of Agriculture's Forest Service (USFS 1985).

with the Salmon River is approximately 10 ft per mi (Miller et al. 2003). Below the dam, the river enters a narrow, steep-sided chasm averaging 1,676 meters (m) (5,500 ft) deep.

Hells Canyon is characterized by a very deep and narrow v-shaped valley canyon entrenched in erosion-resistant basalt and metamorphic bedrock. A recent geomorphic classification indicated that this reach of the river could be classified as an F1-type stream within the Rosgen and Silvey (1996) framework (Miller et al. 2003). Rosgen and Silvey (1996) characterized this stream type as “an entrenched, meandering, high width/depth ratio channel that is deeply incised in valleys that are structurally controlled with bedrock ... [where] the ‘top of banks’ cannot be reached by floods that may be developed with the modern-day climate.”

The average valley and river channel widths in Hells Canyon are only about 129 m and 76 m (425 and 250 ft), respectively. Given the relatively confined nature of this reach, a substantial supply of debris from hillslope processes can be provided if valley sides are formed in materials such as loose rock (talus) or soil (Thorne 1997). The floodplain is extremely limited in occurrence and extent because of the combined effects of progressive downward scour and gradual geologic uplifting of the mountainous region. Therefore, interaction between the river and its bed and banks is limited to near-river areas that can be mobilized by the flow. These areas include bars, islands, terraces, and fans. Elevated terraces from the Bonneville Flood are typically located up to tens of meters above the river channel where the river valley broadens or tributaries join the Snake River (Vallier 1998). However, these terraces are functionally disconnected from contemporary Snake River flows because the Bonneville Flood flows (calculated by O’Connor [1993]) dwarfed those of any contemporary floods.

When viewed in planform, this reach of the Snake River appears to meander occasionally. However, geomorphically, it is a straight or slightly sinuous river because the ratio of channel length to distance down the valley is less than 1.2 between HCD and the confluence with the Salmon River (Miller et al. 2003). The apparent meanders are typically forced channel features around geologic structures such as tributary fans, paleo debris flows, or landslides. For a more detailed analysis of the channel, see Miller et al. (2003).

## 2.3. Geologic Setting

It is believed that many of the rocks in the study area formed in the ancestral Pacific Ocean millions of years ago (Vallier 1998). These rocks are composed primarily of volcanoclastic and sedimentary rocks that were transported across the Pacific Ocean by plate tectonics and conjoined to the North American continent (Figure 2). During this process, these rocks metamorphosed under extreme temperatures and pressures. Thick sequences of basaltic and andesitic volcanic flows metamorphosed to a rock commonly known as “greenstone.” The greenstones are hard, brittle, dense formations that tend to resist weathering, as evidenced by the steep canyon walls within the Seven Devils formation. The Seven Devils rocks tend to form massive, rugged cliffs (914 -1,524 m [3,000–5,000 ft] thick) with red to maroon and dark-green to black outcrops. Basalt dikes that cut through these rocks are more easily eroded and commonly form narrow, talus-filled side canyons or talus chutes (CH2M HILL 1990).

Recent studies suggest that the Snake River began significantly cutting Hells Canyon around 2.0 to 2.5 million years ago (Miller et al. 2003). This downcutting continued not only by the

drainage of large volumes of water during glacial periods, but also by tectonic uplift along the many faults in the canyon. Normal faults appear to have uplifted large blocks of the Seven Devils Mountains hundreds to thousands of feet high (Alpha and Vallier 1994). During this time, the river appears to have preferentially eroded its course along north- to northeast-trending faults. During siting studies conducted for HCD, bedrock in the channel was found to be overlain by up to 37 m (120 ft) of silt, sand, gravel, and boulders (CH2M HILL 1987). The presence of these materials indicates that the river extensively eroded adjacent bedrock as it cut downward through the canyon.

Following this rapid downcutting, the Quaternary period (within the last 1.8 million years) is generally marked by a long period of glacial activity throughout the region. Textures and bedding of regional gravels suggest deposition by glaciated and unglaciaded streams with “sustained seasonal flows probably at least 10 times larger than discharges of present streams” (Pierce and Scott 1982). Active glacial processes throughout the region during this period contributed large amounts of sediments in the tributaries and mainstem of the Snake River. During these conditions, the Snake River is believed to have had increased scour and downcutting, particularly in Hells Canyon (Othberg 1994).

Approximately 14,500 years ago, a catastrophic flood of water from Lake Bonneville escaped into the Snake River Plain via the Portneuf River drainage. The Bonneville Flood left large-scale geomorphic features throughout the flood route between Red Rocks Pass and Lewiston, including the study area. O’Connor (1993) conducted a study on the hydraulics of the flood and concluded that peak flows within the study area were 20 million cfs. To put these calculations in perspective, the estimated peak discharge at 20 million cfs is 80 times greater than the current 500-year flood flow of approximately 250,000 cfs measured at the Anatone gauge at RM 167.2 (USGS 2001). This latter flow includes flows from the Imnaha, Salmon, Grande Ronde, and Snake rivers. In Hells Canyon, depositional features from this flood are somewhat limited because of the narrow valleys. Large gravel terraces formed by the Bonneville Flood are present periodically along the channel (some as high as 183 m [600 ft] above the river level) and into side tributaries (Vallier 1998).

Following this enormous event, the floodwaters receded and the Snake River adjusted to post-flood conditions. Over the last 10,000 years, climate conditions fluctuated between periods with higher average temperatures than now and neoglacial periods (Othberg 1994). Within Hells Canyon, higher terraces (over 30 m [100 ft] above the current channel) have been strongly affected by the Bonneville Flood and subsequent Holocene flooding (Vallier 1998). Lower terraces and river bars (3–5 m [10–15 ft] above the current channel) that parallel the river banks may have been formed by natural flows prior to basin regulation (more than 100 years ago). Gravels from the river bars appear to consist primarily of sediments carried from local landslides, talus, and tributary deposits (Miller et al. 2003). A more detailed geologic history is presented in Miller et al. (2003).

## **2.4. Upstream Basin Development History**

Beginning in the early 1800s, anthropogenic activities such as trapping, mining, forest management, fires, and agricultural development produced elevated sediment loads throughout

the watershed that drains into Hells Canyon. During the 1900s, further growth (particularly agriculture) continued to add to some of this sediment load. As early as 1905, a significant portion of this sediment load was prevented from moving through the Snake River watershed because of numerous water regulation projects that cut off the majority of drainage area in upstream tributaries and along the upper mainstem of the Snake River upstream from the HCC. These alterations in sediment yields and transport mechanisms likely affected the pre-settlement sediment baseline condition in Hells Canyon and progressively altered any equilibrium condition that may have existed prior to the 1800s and prior to 1958. Particularly in a system of this size, the time required for a stream to readjust to a new equilibrium can be several years, depending on the hydrologic regime and the sediment supply. Thus, the evaluation of sediment features in Hells Canyon, including sandbars, needs to consider this larger temporal and spatial context.

IPC is not maintaining that such a slug is the sole cause of changes in the sediment features in Hells Canyon, or that the HCC does not have any effect on these sediment features. IPC is maintaining that in addition to the construction and operation of the HCC (Grams and Schmidt 1991, 1999a, and 1999b), other larger temporal and spatial factors have played, and will continue to play, a role in the dynamics of features within Hells Canyon. IPC maintains that these other factors likely had an influence on sediment features (including size, shape, and quantity) in Hells Canyon that were observed by early visitors as well as recorded by aerial photography.

The anthropogenic, or human caused, disturbances that have most affected Hells Canyon include trapping, mining, forest management, agricultural development, water regulation and storage, fire suppression, and urbanization. A summary of these activities is provided below; a detailed discussion is presented in Miller et al. (2003) and Blair et al. (2001).

- Since the early 1900s, numerous reservoirs have been constructed on the mainstem Snake River and along its tributaries (Figure 3). On the mainstem between Jackson Dam in Wyoming and the HCC, there are 13 major facilities used to store water for irrigation, flood control, hydropower, or some combination of the three. An additional 35 facilities (each with at least 5,000 acre-feet of storage capacity) are located along the Snake River tributaries upstream of Brownlee Reservoir (Miller et al. 2003). A database search using a variety of sources, including Idaho Department of Water Resources (IDWR) and Idaho Department of Fish and Game (IDFG), located 468 diversion structures upstream of HCD to Shoshone Falls. Thirty-nine of these are either less than 10 feet high or had no height information available. The total reservoir storage capacity in the Snake River Basin upstream of Brownlee Reservoir exceeds 10.3 million acre-feet (MAF). By the time Brownlee Dam was constructed in 1958, more than 9.75 MAF of storage (95% of the current storage capacity upstream of the HCC) had already been built. In other words, sediment from much of the drainage area of the Snake River was already trapped upstream of dams that were constructed before 1958. Many of these dams are highly effective at trapping sediment with trap efficiencies ranging from 58 to 100% with an average of about 95%. Table 1 shows some of the different dams and how effective they are at trapping sediment.
- As a result of widespread fur trapping in the 1800s and early 1900s, beaver numbers dwindled to between 3 to 10% of their historical abundance (Naiman et al. 1988, cited in Spence et al. 1996). Beaver dams were historically very extensive in nearly all alluvial

and low-gradient tributaries to the Snake River (NPPC 2000). Quantitative estimates of the sediment yield from beaver trapping activities have not been determined (R.J. Naiman, Aquatic and Fisheries Sciences, University of Washington, pers. comm.). However, given the widespread removal of the beaver population, the downstream sediment pulses from failing beaver dams were likely to have been significant over the 30-year trapping period.

- Gold mining began in Idaho in the 1860s with large dredge and hydraulic mining activities throughout major tributaries to the Snake River upstream of the study area (e.g., the Wood, Boise, Payette, and Owyhee rivers). These hydraulic mining processes resulted in significant volumes of sediment being washed into stream channels and rivers. One study estimates the volume of dredged material produced by hydraulic mining between 1860 and 1960 at 560 cubic yards (yd<sup>3</sup>) per acre per year in the area mined (USDA 1997). This sediment yield is more than 1,500 times higher than a natural erosion estimate of 0.33 yd<sup>3</sup> per acre per year from debris slides in the region (USDA 1995).
- By the late 1800s, logging in the study area was well established (Spence et al. 1996). To provide wood for miners and railroads, streamsides were heavily logged (Clark and Sampson 1995). Sediment yields in timber production areas along major and minor tributaries are estimated to have increased the magnitude of erosion (Dickerson 1975, cited in NCASI 1999). This increase was due primarily to skid piles and log dams that caused water, soils, and rocks to cut through the riparian areas along the creeks (Clark and Sampson 1995). To support the expansion of the timber industry, road construction opened the forests within the study area. In the early 1900s, many roads were constructed through river valleys, riparian areas, floodplains, and adjacent hillsides (USDA 1996). Mass wasting associated with roads can produce between 26 and 346 times the volume of sediment in the areas with roads compared with sediment from undisturbed forests (Spence et al. 1996).
- Livestock grazing in the West during the late 1800s and early 1900s was essentially unrestricted. According to Tisdale (1986), with the settlement of Hells Canyon, large numbers of cattle were introduced into the area's rangelands and grazed well into the 1940s. In riparian zones and upland areas, livestock increase sediment transport rates by increasing surface erosion and mass wasting (Marcus et al. 1990, Platts 1991, Heady and Child 1994, cited in Spence et al. 1996).
- The Snake River corridor represents the focus of agricultural development and human settlement in Idaho. According to the U.S. Bureau of Reclamation (USBR 1998), irrigation from the Snake River and its tributaries in the eastern Snake River Plain began in the late 1800s. Between 1890 and 1992, irrigated acreage within Idaho increased from 0.2 million acres to more than 3.0 million acres. Older irrigation methods (e.g., surface-applied systems) used in the early 1900s resulted in severe erosion and sedimentation. More recent improvements (e.g., sprinkler irrigation systems) decreased sediment yields. On agricultural lands within the Snake River Plain, estimated seasonal sediment yields between 1976 and 1981 ranged from 0.67 to 51 yd<sup>3</sup> per acre per year, depending on the field slope and crop cultivated (IDEQ 1993).

- Before pioneers settled the area, Native Americans supplemented wildfires by starting their own fires. If fire-damaged soil is covered with heavy rain or snowmelt before protective vegetation recovers, the soil easily erodes into adjacent creeks and rivers (Clark and Sampson 1995). In the early 1900s, concurrent with the rise of the timber industry, fire began to be systematically suppressed (USDA 1996). However, between 1970 and 1995, the average cost of wildfire suppression, fatalities of firefighters, and the amount of high-intensity fire in the region were double the corresponding amounts occurring between 1910 and 1970 (Clark and Sampson 1995, USDA 1996). Current fires tend to be infrequent, high-intensity events that are more damaging to topsoil and produce higher erosion rates than the more frequent, low-intensity historical wildfires (Clark and Sampson 1995).
- Although urbanization does not have a large direct influence on Hells Canyon, within the last 40 years, urbanization has become a more predominant land use within the Snake River Basin. Initial settlement and expansion often involved clearing of riparian areas, as well as the construction of levees or other physical structures that affected fluvial processes. Within the Snake River Basin, the net change in sediment loading caused by replacing agricultural land with urban land uses has not been well quantified. The net effects of changes in land use are unclear because agricultural activities can produce high suspended sediment loads associated with livestock, range, and cropland management. However, construction and road-building activities associated with development of urban land use can also elevate sediment loads.

To summarize, many of these activities very likely significantly increased sediments (especially fine sediments) contributed to the Snake River before dams were constructed on the major tributaries and mainstem. Some passage of time would have been required for some of these sediments to work their way from their source locations to the Hells Canyon reach of the Snake River. Following these major sediment contributions, construction of several major dams on larger tributaries to the Snake River would have cut off the supply of sediments coming from the dammed tributaries.

Because there is very limited quantitative data regarding the “slug” of sediment that may be working its way out of Hells Canyon, IPC is unable at this time to determine the timing and processes of potential sediment slug delivery to Hells Canyon, and to define the relatively short-term geomorphic consequences of the altered sediment supply on features such as the sandbars in Hells Canyon. Despite these data limitations, IPC continues to believe this conceptual model is supported by available data and investigations based on both professional judgment and local knowledge of the system. This conceptual model is discussed further in Miller et al. (2003).

## **2.5. Hells Canyon Complex Development**

IPC owns and operates three dams on the Snake River between Oregon and Idaho. Collectively, these facilities are known as the HCC. IPC constructed these dams between 1955 and 1968 under one Federal Energy Regulatory Commission (FERC) license (No. 1971). Under normal conditions, the HCC provides approximately two-thirds of IPC’s total hydroelectric generating

capacity. Sections 2.5.1 through 2.5.3. describe each dam, and Figure 4 shows the development of the HCC.

### **2.5.1. Brownlee Dam and Reservoir**

Brownlee Dam (RM 284.6) was the first dam completed by IPC in the HCC. Construction began in 1955 and closure occurred in 1958. Brownlee Dam is located just downstream of Brownlee Creek, which flows into the east side of the reservoir a few miles upstream of the dam. Brownlee Dam is the largest of the three dams, with an embankment that is 120 m (395 ft) high and 424 m (1,380 ft) long at the crest. Brownlee Dam also creates the largest reservoir at 93 km (58 mi) long (to the project boundary) with 1,420,062 acre-feet of total storage capacity. The original power plant was completed in 1959 and had 360.4 megawatts (MW) of capacity. In 1980, an additional unit was installed that is capable of generating 225 MW, increasing the total capacity of the Brownlee Reservoir project to 585.4 MW.

### **2.5.2. Oxbow Dam and Reservoir**

Oxbow Dam and reservoir are located approximately 21 km (13 mi) downstream of Brownlee Dam at RM 272.5. In 1906, a dam and tunnels to a powerhouse were constructed near present-day Oxbow Dam (Collier et al. 1996). Reconstruction of Oxbow Dam was completed in 1961. Oxbow Dam gets its name from a 4.8-km (3-mi) oxbow-shaped bend in the Snake River, making it one of the world's most unusual dam sites. The penstocks and turbines are not located at the dam site. The penstocks pass through the narrow portion of the oxbow bend, and the turbines and power plant are located on the downstream side of the oxbow. The dam, consisting of earth and rock construction, is 62 m (205 ft) high and 350 m (1,150 ft) long at the crest. The two penstocks are 12.8 m (42 ft) in diameter and 274 m (900 ft) in length. The power plant capacity is 190 MW. Oxbow Reservoir is 19 km (12 mi) long and has a total storage capacity of 58,385 acre-feet. The headwaters extend to the tailwater of Brownlee Dam.

### **2.5.3. Hells Canyon Dam and Reservoir**

HCD is located at RM 247.6 and was the last of the HCC dams to be constructed by IPC. Power generation began in 1967 with two of its three generating units. The third unit was put into full power production in 1968, giving the plant a total nameplate capacity of 391.5 MW. The dam is of concrete construction, measures 100 m (330 ft) high and 304 m (1,000 ft) long at the crest, and creates a reservoir 40 km (25 mi) long. Hells Canyon Reservoir has a total storage capacity of 167,720 acre-feet, and the headwaters extend to the tailwater of Oxbow Dam. The Snake River downstream of HCD flows for approximately 193 km (120 mi) before it enters the backwaters created by Lower Granite Dam, which is the next dam on the Snake River. It is in this reach of the Snake River downstream of HCD that we focused much of our study.

## 2.6. Operational Scenarios

For the purpose of this analysis, the operation designated as the *proposed* scenario will be used as the base case, which defines the operational parameters under which the HCC typically operates. Because the operation of hydropower projects depends on a number of factors, and to capture the operational variability caused by hydrologic conditions, operational definitions of the HCC are separated into low-, medium-, and high-water years. The scenario designated as *full pool run-of-river* is the scenario that IPC will compare with the base case (or proposed operation) to understand project effects. The full pool run-of-river operation establishes a scenario where inflow to the HCC plus inflows from the tributaries equal outflow from the HCC. This scenario does not reflect optimization of environmental or other conditions. Rather, it allows us to analyze conditions with the project in place but not affecting the outflow hydrograph.

IPC has applied the CHEOPS™ model to simulate system operations. CHEOPS is a simulation package developed by Duke Engineering & Services (DE&S) to evaluate physical and operational changes at multiple-development hydroelectric projects. CHEOPS has been configured to the HCC to ensure that critical aspects of the project are simulated accurately. CHEOPS was designed to emphasize long-term simulations of project operations as a means of comparing results under various project constraints and hydrology. For further explanation of the HCC operations, see Parkinson (2002).

## 3. ISSUES ADDRESSED

This section identifies and discusses issues related to sediment supply and transport that have been raised by various interested parties involved in relicensing efforts for the HCC. The discussion includes the basis for raising the issues and for either including the issues in the analysis or choosing not to analyze them further. Some issues mentioned in this report are discussed in greater detail in other IPC reports.

### 3.1. Sandbar Erosion and Development

#### 3.1.1. Definition

Sandbars are areas in the mainstem Snake River that are generally connected to or part of the shoreline. Sandbars are formed primarily by sand-size particles (between 0.062 and 2 mm [0.002 and 0.07 inch]). Sandbars that are connected to the shoreline are more commonly called sand beaches. They are important amenities for recreationists, who use them as stopping places along the river.

### **3.1.2. Concern**

The general perception of sandbar areas in Hells Canyon is that they are declining in both number and size. A related perception assumes that the existence and operation of the HCC caused the decline. According to this theory, the sand- and gravel-size materials that previously formed and maintained the sandbars and beaches are trapped in the three HCC reservoirs, and replenishing materials coming from tributaries downstream of HCD are insufficient to mitigate the loss.

### **3.1.3. Approaches to Addressing Concern about Sandbars**

We addressed the issue of changes in sandbars by regularly surveying selected sandbar areas to measure changes in their size and shape. We also collected and reviewed historical aerial photographs to estimate changes in sandbar areas and numbers over time. In addition, we addressed the perception of material trapped in the HCC by analyzing sediments trapped in Brownlee Reservoir (both volume and size distribution).

We addressed potential reasons for the changes (if any) in the sandbars by estimating supplies of sand-size sediments available from tributaries below the HCC and evaluating potential sources of sand-size sediments that may have been eliminated by the HCC. We also investigated other causes of changes to sandbars, including fluctuating water surface elevations from changes in flow. Although boat-induced wave erosion has been mentioned as a potential cause of sandbar change, this report does not include it because of a lack of quantitative information and research in literature applying to conditions in Hells Canyon.

## **3.2. Riparian Areas**

### **3.2.1. Definition**

Riparian areas are those areas along the shoreline that support the growth of various plant species associated with water. Suitable substrate sediments are necessary to support riparian vegetation.

### **3.2.2. Concern**

The extent and character of riparian vegetation in Hells Canyon depend on the types of available shoreline substrate. One concern identified early in the consultation process for relicensing the HCC was the effect that current and potential operational scenarios might have on the availability and character of shoreline sediments and the type, abundance, and distribution of riparian vegetation. This concern is addressed in two studies: Miller et al. (2003) and Rocklage and Edelman (2001).

For Blair et al. 2001, Simons and Associates (1989) conducted a near-bank geomorphic classification of Hells Canyon in the reach below HCD that followed protocols developed in consultation with the Geomorphology Subgroup of the Aquatic Resources Work Group. This classification describes the type, abundance, and distribution of shoreline substrates throughout

the study area. Braatne et al. 2002 used the results of this classification, as well as original data collected for their study, to discuss the type, abundance, and distribution of riparian vegetation under the two operational scenarios: proposed operations and full pool run-of-river operations.

### **3.2.3. Approaches to Addressing Concern about Riparian Areas**

The assumption in the work discussed above is that the existing shoreline substrate will not change because of any modified operations at the HCC. The general stability of the river reach tends to support this assumption. However, except for some selected localized areas (see Section 4.3.), this report does not address the assumption.

## **3.3. Maintenance of Areas Important to Aquatic Resources**

### **3.3.1. Fall Chinook Spawning Beds**

In addition to other criteria, fall chinook salmon spawning beds are composed of gravels 25 to 150 mm (1 to 6 inches) in size (Groves and Chandler 1999, 2001a, 2001b). To maintain salmon spawning beds, these sizes of gravels must be in dynamic equilibrium. That is, areas where these gravels may be mobilized and transported downstream must have a continuing supply of new material to prevent a net loss of spawning bed area. Alternatively, the spawning beds may be stable if no gravel at the sites is mobilized.

### **3.3.2. Fall Chinook Rearing Areas**

The question of sediment supply for fall chinook rearing has focused generally on the stability of sandbars. Though fall chinook use sandbars for rearing purposes, rearing areas are associated with a relatively broad range of substrate sizes from sand to large cobble and sand is not a prerequisite for describing rearing areas for juvenile chinook. Fall chinook have been observed avoiding large riprap-type shorelines for Columbia River reservoirs (Garland et al. 2001). Fall chinook salmon rearing areas are best characterized by low-velocity, shallow, near-shore habitats with lateral slopes less than 30% and bed material generally composed of cobbles or smaller substrate (Garland et al. 2001, Tiffan et al. 2002 submitted).

## **3.4. Bank Stability**

### **3.4.1. Definition**

The stability of a riverbank determines the conditions under which the bank may move. Primary causes of movement include erosion, deposition, or mechanical failure. Typically, bank loss is more of a concern than changes caused by accumulation because when a portion of a bank is lost, the bank and resources located close to the river may be destroyed.

### 3.4.2. Concern

Concerns related to bank stability identified in the Hells Canyon reach of the Snake River fall into two different areas: archaeology and recreation.

#### 3.4.2.1. Archaeological Sites

Approximately 1,000 mapped archaeological sites are located along the Snake River between Farewell Bend (RM 334) and the confluence with the Salmon River (RM 188) (Gross 2000, Chatters et al. 2001, Mauser et al. 2001). Most of these sites are historically significant. In certain places, shoreline erosion has undermined bank stability and disturbed soils containing archaeological deposits such as artifacts, organic materials, and in one case, Native American remains. These materials are nonrenewable cultural resources that are protected by various state and federal laws and by IPC's current FERC license (FERC No. 1971) for the HCC.

The conventional wisdom espoused by some federal agency staff and supported by a Senior Thesis (Grams 1991) and two additional studies commissioned by the USFS (Grams and Schmidt 1999a and 1999b) is that “sediment starved floods” cause the shoreline erosion that damaged several archaeological sites below HCD. The implication of this position is that IPC is responsible for all or most of the bank stability problems at archaeological sites below HCD. We believe that our study allows for a better determination of what, if any, effect the construction and operation of the HCC has had on erosion at these archaeological sites.

#### 3.4.2.2. Recreation Sites

IPC and the U.S. Forest Service (USFS) identified more than 150 dispersed recreational-use sites along the river corridor from HCD downstream to Cache Creek, the northern entry portal for the HCNRA (Hall and Bird 2002). With few exceptions, these sites are relatively flat areas adjoining the river. They usually consist of sandbars or low-lying terraces that—depending on topography, bank material composition, and channel morphology—are susceptible to erosion.

Recreationists use these sites in a number of ways. The majority of use is for overnight camping during boating, fishing, or hunting trips. Day use for picnicking, fishing, swimming, sightseeing, and hiking is also common at many sites. Aside from preferring relatively flat areas, recreationists appear to select sites based on ease of grounding or mooring boats, accessing camping or day-use areas, and accessing shade.

The USFS, in a draft *Information Needs Assessment* dated November 6, 1998, listed several issues related to recreational use, sandbars, and bank erosion associated with the Snake River within the HCNRA. These issues were identified under several distinct categories:

#### *Aesthetics—Information Needed*

Constituency analysis regarding public attitude toward views of foreground resources and losses of sand beaches and vegetation.

***Sediment Routing and Regime—Recreation-Related Questions***

1. How have changes in sediment regimes and loss of sandbars affected recreational use in the river corridor?
2. Is sandbar loss shifting recreational use to adjacent terraces?
3. If there is a shift in recreational use, how is this affecting heritage resources along the river?
4. What have been the visual effects of sandbar erosion?

***Recreational Use (Project Operations)—Issue Statement***

Beach erosion is reducing carrying capacity (e.g., campsite availability for dispersed camping), which may affect the type of use (fishing, hunting, and sightseeing) and cause a need to limit use numbers in the future.

The quality of the recreational experience is being reduced by beach/bench erosion (e.g., crowding at fewer campsites and increased social encounters). Reduced availability and quality of campsites may create conflicts between float boaters and jet boaters.

The lack of beaches caused by erosion is diminishing visual quality within the corridor.

Other agencies and entities have expressed the same or similar concerns related to loss of beaches and bench erosion within the HCNRA.

## **4. IDENTIFICATION AND DESCRIPTION OF SIGNIFICANT SITES**

In the last section, we described the various issues that this study addresses. These issues can be addressed, to some extent, by general sampling and modeling throughout the Snake River. However, in addition to this more general approach, we selected specific areas in Hells Canyon to study in more detail. We selected these sites for various reasons, including the particular importance of the area, information available from previous studies, and applicability of the results to the general Hells Canyon area. This section describes both the sites that were selected for detailed study of each issue and the basis for selecting those sites. Figure 5 shows the locations of the significant sites discussed in this section.

### **4.1. Sandbar Erosion and Deposition**

We selected four sandbars for detailed study (additional sandbar areas are studied using aerial photographs). We based our selections primarily on the size and distribution of sandbars throughout the study area. The sandbars selected were Pine Bar (RM 227.5), Salt Creek Bar (RM 222.4), Fish Trap Bar (RM 216.4), and China Bar (RM 192.3). Another potential criterion for sandbar selection could have been “use by the recreation community.” However, this

criterion was not useful in narrowing the field of potential sites because, although few sandbars in Hells Canyon are suitable for recreational use, recreationists do use almost all of the sandbars in the canyon. The four sandbars we selected to study are the same ones selected for detailed surveys and discussion by Grams (1991) and Grams and Schmidt (1999a).

## **4.2. Aquatic Habitat Areas**

### **4.2.1. Spawning Beds for Fall Chinook**

Groves (2001a) summarized the distribution of spawning areas for fall chinook downstream of HCD. Since intensive surveys of spawning grounds began in 1991, aerial surveys have identified 85 distinct shallow-water spawning areas. The majority of redds (salmon spawning sites) identified from 1991 to 1993 were located downstream of the Snake River's confluence with the Grande Ronde River. However, since 1994, most observed redds have been located upstream of the confluence with the Salmon River. In addition to the shallow spawning sites, 29 deep-water spawning sites have been documented through underwater video surveys within the Snake River since 1993.

In a cooperative study with the U.S. Fish and Wildlife Service (USFWS) (Groves 2001b), several known spawning areas were chosen for purposes of habitat modeling using the physical habitat simulation (PHABSIM) approach described by Milhous et al. (1989). These sites were the basis for assessing the stability of spawning areas. In addition to the modeled sites in Groves (2001b), seven sites were chosen for 2-D habitat modeling (Chandler et al. 2001). Of these seven sites, five are known spawning locations for fall chinook. These five sites are Hastings Bar, Fish Trap Bar, the Tin Shed site, Camp Creek, and Robinson Gulch. Only Robinson Gulch has been used consistently each year since 1991.

### **4.2.2. Rearing Areas for Fall Chinook**

Rearing areas for juvenile fall chinook salmon are patchily distributed throughout the entire length of the Snake River below HCD. The distribution of potential rearing areas was described using a 1-D model integrated with descriptions of shoreline substrate and a digital elevation model for the river channel (Chandler et al. 2001). In addition to the 1-D model, 2-D habitat modeling to describe fall chinook rearing areas was done using the seven 2-D sites described in Section 4.2.1. Of these sites, Pine Bar and Fish Trap Bar are documented rearing areas for fall chinook salmon (Chandler et al. 2001).

## **4.3. Erosion at Historically Significant Sites**

We used two criteria to select sites for detailed study of erosion affecting historically significant sites. First, each site had to have some historical significance. Second, the riverbank next to each site had to be eroding and potentially affecting the area of interest. Archaeological reports prepared for IPC provided the number of sites subject to erosion and indicated the extent of the

impact (Gross 2000, Chatters et al. 2001, Mauser et al. 2001). Also, IPC conducted an erosion reconnaissance survey below HCD (Holmstead 2001).

## 5. SOURCES OF DATA AND INFORMATION

This section describes the information and data that we obtained and reviewed specifically for this study and the specific relevance of that information. The effort to gather the information required both extensive research for existing data among agencies and archives and the collection of additional field samples. We also reference the large amounts of data and information used in the development of other studies and their resulting reports. While some of these data were used in developing the background for this study and the study plan, they are only referenced indirectly in this report.

### 5.1. Existing Maps and Photographs

#### 5.1.1. *Aerial Photographs of Sandbars*

IPC conducted an extensive search for aerial photographs covering the HCNRA. The intent in collecting historical aerial photographs was to establish the status of or trends in sandbars before and after the HCC was constructed. Not all aerial photographs we located were used in this study because many contained various deficiencies such as inappropriate scale, insufficient coverage, poor image quality and imprecise camera orientation.

The area of interest for this component of the study was the Snake River from HCD (RM 247.6) downstream to the confluence of the Salmon River (RM 188.2). We began our search for aerial photographs at the headquarters of each of the three national forests that border the HCNRA. We contacted representatives of the Payette National Forest (McCall, Idaho), Wallowa–Whitman National Forest (Enterprise, Oregon), and Nez Perce National Forest (Grangeville, Idaho) to gain their assistance in compiling aerial photographs that covered the study area. The photographs made available from the Payette National Forest were not used because they did not cover the Snake River. However, photographs obtained from the Wallowa–Whitman and the Nez Perce National Forests proved to be very useful, and provided a fair amount of coverage of the Snake River. There were two major sources of aerial photographs that provided full coverage of the study area for numerous years: [1) USDA Aerial Photographic Field Office (APFO) in Salt Lake City, Utah, and 2) the U.S. Army Corp of Engineers (USACE) (Walla Walla District).] These two sources provided the majority of aerial photography for the sandbar study. Two other minor sources of aerial photographs were IPC and the USFS office in Boise, Idaho.

Table 2 includes the sources, year, scale, and approximate coverage of the aerial photographs used in the study. The years for which we had enough aerial photographs for complete coverage of the study area were 1955, 1964, 1973 (three sets of photographs at three different flows), 1977, 1982, and 1997. The remaining years of aerial photographs were used as supplemental photographs. Figure 6 shows the sections of river covered by each series of aerial photographs.

Many of the early aerial photographs (1940s) were originally taken for fire and transportation planning. Fire protection was the main concern for the federal resource agencies (such as the USFS and Bureau of Land Management [BLM]) at that time. In the 1950s, the motivation for taking aerial photographs shifted to identifying and delineating timber types within each national forest. For these reasons, most of the earlier aerial photography did not focus on the Snake River specifically. Therefore, these photographs contain more shadows and distorted images along the river's edge. Many portions of the river were not covered at all by these earlier photographs. Numerous aerial photographs taken in later years did focus on the river as the primary target. Flights in 1973, for example, were part of a comprehensive study that included four separate flights, during four consecutive days and at four distinct flows (5,000 cfs, 7,700 cfs, 12,000 cfs, and 18,000 cfs) (Pacific Northwest River Basins Commissions 1973). Even though the river was the primary focal point for the flights, there are still portions of the photographs that contain shadows or distortions along the riverbank from glare.

Whenever possible, IPC used the best available resources to minimize any error that might be associated with this project. When obtaining aerial photographs, IPC first requested a scanned image from the film negative to help maximize the image quality used in the analysis. The scanned images allowed zooming in to specific areas, which led to more accurate depictions of river reaches that were covered with shadows or had an increased amount of glare. The scanned images also eliminated the grainy texture seen on the paper prints, in turn, improving the overall quality of the image. If scanned images were not available, then IPC requested positives to allow for future scanning of the images. If neither scanned images from negatives nor positives were available, IPC requested a paper print of the desired image. Years for which scanned images were available include 1964, 1973, 1977, 1982, and 1997. Positives were obtained for 1955, and scans were made from the positives to conduct the surveys on this photograph set. Paper prints were used as the media for the remainder of the images.

### **5.1.2. General Aerial Photographs**

In addition to the aerial photographs used specifically in analyzing sandbars, we also used aerial photographs to identify and analyze geologic and geomorphic features. We were careful to choose photographs that accurately portrayed the geomorphology at each sampling site within the study area. Photographs with too many shadows, distorted images, or poor resolution were not used. The IPC photographs from 1955, 1961, and 1968 were taken with the primary goal of photographing the Snake River Basin. Therefore, these photographs allowed for a more detailed study of the geomorphology of the Snake River.

## **5.2. Data from Computer Models**

All analyses that depend on river discharge information below HCD use discharges measured at the USGS Snake River gauge at Hells Canyon Dam (ID-OR 13290450), as well as flow data from the downstream gauges on the Imnaha (Imnaha, Oregon, 13292000), Salmon (White Bird, Idaho, 13317000), and Grande Ronde (Troy, Oregon, 13333000) rivers. All water surface elevation and location-specific discharge information in the reach below the HCC are simulated using the MIKE 11 model (Parkinson 2002).

### **5.2.1. Reservoir Operations Model**

Flow data from HCD used for comparison between proposed operations and the full pool run-of-river scenario are from the CHEOPS model. This model is a reservoir operations model that routes flow through the HCC based on operational criteria. The flow data at HCD used in this report are daily average flow values. Information about inflows that were used in the CHEOPS model include 72 years of data prepared to model the current level of development in the basin above the HCC. These data and the CHEOPS model are described in more detail in Parkinson (2002).

### **5.2.2. 1-D Hydraulic Computer Model**

Data about water surface elevation throughout the Hells Canyon reach are based on a 1-D computer model of the Snake River from HCD to near Lewiston, Idaho. This model, the MIKE 11 model, was developed by DHI Water and Environment. This model and its calibration are discussed in more detail in Parkinson (2002). For the purposes of this study, inputs to the model are generally fixed flows (30,000 cfs, 100,000 cfs, and so forth) meant to match a particular condition such as HCD plant capacity, normal operating range, or flow at a particular return interval. Flows from the primary tributaries (Imnaha, Salmon, and Grande Ronde rivers) were selected to provide a consistent return interval for the flow throughout the system.

Stage-discharge curves from the MIKE 11 model were used to evaluate the effects of flow fluctuation on sandbars and terraces.

## **5.3. Miscellaneous Data**

This section includes sources of various data that have been published by agencies or collected from other sources, including IPC, although the data were not collected specifically for our study.

### **5.3.1. Sampling Data for Suspended Sediments**

In 1977, the USGS began collecting data about suspended sediments at the gauge site on the Snake River at Weiser, Idaho (13269000). Data were collected every year through 1986. After 1986, the station was put on a rotation, and suspended sediment data were collected only every 2 or 3 years. The last data were collected in 1999, and the next scheduled collection date is in 2002. The USGS analyzed some of the suspended sediment samples to determine the sand fraction. Suspended sediment data were collected at flows ranging from below 10,000 cfs to about 69,000 cfs. A substantial number of samples were collected at flows ranging from 30,000 to 50,000 cfs. However, the majority were collected with flows in the 10,000- to 20,000-cfs range.

### **5.3.2. Data on Reservoir Bathymetry**

Contour maps of all three reservoir areas were prepared in the mid-1950s before each reservoir was filled. Aerial Mapping Company of Idaho prepared the maps for IPC using the multiplex topography method. These maps have 6-m (20-ft) contours and extend only to the water surface of the original river channel.

In 1996 through 1998 bathymetry data were collected in Brownlee Reservoir. See Butler (2002) for details of this data collection effort.

In 1999, the Oxbow Reservoir near the Wildhorse River was surveyed from Brownlee Dam downstream for about 8 km (5 mi) to RM 279.4. Depths were measured using a single-beam transponder mounted on a boat. Transects across the reservoir were spaced at approximately 30 m (98.4 ft), with depths measured at approximately 2-m (6.5-ft) intervals along each transect. Data about depths were converted to bottom elevation based on water surface elevations collected during the bathymetric survey. A licensed surveyor measured water surface elevations based on established horizontal and vertical control points.

During this same period, the upper end of Hells Canyon Reservoir—from just above Pine Creek downstream for about 6 km (3.7 mi) to RM 266.1—was surveyed using the same technique. Transects were spaced at 20-m (65.6-ft) intervals. Horizontal controls were referenced to the State Plane Coordinate System (the 1927 North American Datum [NAD27]), while vertical controls were referenced to USGS benchmarks (National Geodetic Datum of 1929). Additional information on the bathymetry data and mapping are included in Butler (2002).

### **5.3.3. Data on River Bathymetry**

For the area below HCD, including the Snake River and adjacent areas, topographic information above the water surface was collected using LIDAR (laser light detection and ranging). Multi-beam sonar equipment was used to collect information about river bathymetry. The collection and generation of usable maps and data files are described in more detail in Butler (2002).

### **5.3.4. Basin Characteristics for Estimation of Flow-Duration Curves**

Estimates for flow-duration curves were based on regression equations developed by the USGS (Hortness and Berenbrock 2001). Basin characteristics used in generating the flow-duration curves were taken from the same sources as those used by USGS in developing these regression equations. These sources are geographic information system (GIS) coverages generally available on the Internet for basin areas, slopes, forest cover, and other characteristics.

### **5.3.5. General Reservoir Data**

Reservoir data such as capacity, length, inflow, and discharge works capacity were used in estimating the efficiency of reservoir traps. These data were collected from a variety of sources

including internal IPC documents, web sites (maintained by the USACE and USBR), and USGS data.

## **5.4. Field Data Collection by IPC**

Data collected by IPC included topographic surveys of the river corridor, bulk samples of bed material, photographs of bed-surface material, samples of suspended sediments, and samples of bedloads. We also used information collected during field sampling for other studies. This section provides a description of the data collected in the field.

### **5.4.1. Surveying Data**

#### **5.4.1.1. Hydraulic Characteristics of Tributaries**

We selected 17 tributaries to the mainstem Snake River for detailed study. These tributaries were selected based on location and watershed characteristics (discussed in more detail in Section 6.3.1.). Survey data were collected on all of these tributaries.

We surveyed tributaries for two purposes. First, we wanted to collect general information on the overall shape and slope to calculate the amount of sediment transported in the tributaries. Second, we wanted to collect specific information during each sediment-sampling event to estimate the flow for that specific event.

Cross sections, longitudinal bed profiles, and water surface elevations were surveyed for the 17 tributaries. We selected a representative section of the tributary and surveyed a cross section across the streambed far enough up on each side to get well above the high-water mark. We also surveyed a profile along the streambed to measure a representative slope. Sites were selected that provided the best uniform flow characteristics to achieve the most accurate data possible for the hydraulic computations.

The cross sections surveyed for flow calculation during the sampling of suspended sediments were not always surveyed in the same location. Some of the tributaries, such as Divide Creek, shifted during the spring of 2001. In other tributaries, the locations of flow controls—such as drops, bars, or constrictions—changed with varying flow conditions. In all cases, we chose the location of the cross section to accurately represent uniform flow conditions for the flow measured. This decision sometimes required us to survey a cross section some distance upstream or downstream of the previously measured cross section.

#### **5.4.1.2. Hydraulic Characteristics of the Mainstem Snake River**

A hydraulic model of the Snake River from HCD downstream to the end of the study area was prepared (Parkinson 2002). Cross sections in the mainstem Snake River were taken from the bathymetry and cross section information developed for the MIKE 11 hydraulic model. Vertical controls were established with USGS benchmarks, which are based on the 1929 National Geodetic Datum. Flow velocities, shear stress, energy slope, water surface elevations, and other hydraulic data used in the evaluation of bed stability were also taken from the hydraulic model

and its results. A more complete description of the surveying procedures and topographic data collected on the mainstem is provided in Butler (2002).

IPC fisheries biologists surveyed a few additional cross sections not included in the MIKE 11 model upstream, downstream, and at the location of particular redds. Fishery biologists surveyed these cross sections using local elevation references.

#### **5.4.2. Bulk Samples of Bed Material**

To complete a sediment study to any degree of accuracy, we must understand the range of particle sizes in the bed materials that comprise the river and tributary channels. Bed material is the mixture of sediments that form the bed of a stream or river. Particle-size distribution curves (PSD) and specific gravities of the sediment particles are necessary for understanding the mobility of the riverbed. To acquire this understanding in this study area, we collected at least one or two 75- to 200-lb bulk samples of bed material in each of the 17 tributaries and at numerous locations along the mainstem Snake River. Larger sample sizes were collected when larger individual particles were included in the sample. Bed-material samples excluded material in the armor layer. To collect a sample, we removed all particles in the top layer (approximately one particle-diameter thick) in the area where the sample was to be collected. We collected the bulk samples manually with a shovel, transported them in double bags to prevent the loss of fines, and sent them to a laboratory where they were sieved using standard sieve analysis methods to generate a PSD. Specific gravities were also obtained using several of the bulk samples. For the tributaries and the mainstem river, we sorted samples down to a #200 sieve size (0.075 mm [0.003 inch]). A detailed description of the methods for collecting these bed-material samples is provided in Section 6, and Section 7 outlines the analysis procedures and results of each sample.

#### **5.4.3. Analysis of the Size Distribution of Surface Particles**

In addition to the bulk samples, we collected extensive data on the surface layer of the mainstem riverbed between HCD and the Salmon River and of the 17 tributaries. We used two different methods to collect these data: the Wolman pebble count method and photographic sampling. These methods are discussed in detail in Section 6. The analysis procedures are outlined in Section 7.

#### **5.4.4. Samples of Suspended Sediments**

We collected samples of suspended sediments at four locations on the mainstem Snake River, one location on the Salmon River, and one location on the Weiser River. One of the locations on the mainstem Snake River was upstream of the HCC at the USGS gauge located at Weiser, Idaho (13269000). We also collected samples on the 17 tributaries. Suspended sediment sampling took place between 1998 and the spring of 2001. All samples were analyzed for total solids using procedures documented at the University of Idaho analytical laboratory. A more detailed description of the methods used to collect these suspended material samples is included in Section 6 of this report. Section 7 outlines the analysis procedures and results of each sample.

### **5.4.5. Sandbar Surveys**

We surveyed transects on four sandbars: Pine Bar at RM 227.5, Salt Creek Bar at RM 222.4, Fish Trap Bar at RM 216.4, and China Bar at RM 192.3. Table 3 lists the site location, date of survey, and flow rates during the surveys. These surveys were conducted in the fall when flows from HCD had been maintained at relatively constant levels. A detailed description of the methods used during data collection and analysis is included in Sections 6 and 9, with the results of the surveys presented in Section 10.

### **5.4.6. Piezometer Data**

In April 1999, twelve piezometers in three transect lines were installed on the Oregon-side terrace at the Tin Shed site (at RM 215.7 just upstream of Pittsburg Landing). We selected the installation sites both to provide groundwater information in upland areas of the site relative to the river and to avoid known concentrations of artifacts. The piezometers consist of 2.5-cm (1-inch) iron pipe in 1.2 m (4-ft) sections driven into the ground to various depths. The bottom 0.61 m (2 ft) of each piezometer was perforated with 3-mm (1/8-inch) holes. A plug on the bottom, which was used in the installation, was removed after the piezometer reached full depth.

## **5.5. Field Sampling by Others**

This section describes field sampling, conducted by contractors, during which IPC personnel had direct involvement in setting up the field sampling, collecting data, or analyzing and reviewing the results. In general, IPC has access to the raw data in these cases. However, in the case of published reports, IPC may only have the results as presented by the contractors.

### **5.5.1. Sediments in Brownlee Reservoir**

In December 1999, CH2M HILL collected core and shallow samples of the sediments in Brownlee Reservoir. The primary objective of the Brownlee Reservoir sediment sampling effort was to characterize the physical and mineralogical attributes of the substrate in the reservoir and riverine approach. The cores and most of the shallow samples were analyzed for various chemical constituents and also PSD. The complete CH2M HILL report, with PSD data from these sediments, is included in Appendix B. Three cores were collected in the upper area of the reservoir where deposition appeared to be most significant based on the difference between 1997 bathymetry and preimpoundment topography and on a visual survey made during reservoir drawdown in the fall of 1998. Based on a visual analysis of material collected and the depth of penetration, two of the three cores are estimated to have penetrated to preimpoundment levels. Additional shallow samples (up to approximately 1.5 m [5 ft] deep) were collected every 8 km (5 mi) along the thalweg from Brownlee Dam to RM 340, or approximately 8 mi (12.8 km) upstream of the reservoir. In summary, a total of 51 samples in, and just upstream, of Brownlee Reservoir were collected and analyzed for physical and mineralogical properties. From the three deep cores collected from the reservoir delta, 30 subsamples were sieved. There were a total of 21 samples recovered and analyzed as a result of 39 sampler deployments throughout the reservoir thalweg and in the Snake River just upstream of the reservoir.

In addition to the reservoir sampling, 19 fine sediment samples were collected further upstream in the Snake River and the major tributaries between Swan Falls Dam and Brownlee Reservoir for mineralogical analysis. Additional substrate samples were collected and analyzed through the upstream Snake River reach and used for PSD analyses and mineralogical and sediment provenance analyses.

IPC used the PSD data from this sampling effort in conjunction with the bathymetry data to estimate a volume weighted average PSD for sediment trapped in Brownlee Reservoir. Bathymetry was used to estimate the volume of sediment trapped in each 5-mi segment of the reservoir corresponding to the shallow samples taken. The PSD from that sample was applied to that volume. Volumes of each size class were then summed to create an overall PSD for the sediments trapped in Brownlee Reservoir. Data from the deep cores were used to show that PSD in the vertical profile are consistent enough (between samples) to allow using surface samples to represent the entire depth of trapped sediment.

While the sampling in Brownlee Reservoir focused on areas determined to be the most likely to contain coarse sediment, the samples show a relatively high degree of consistency in particle size between samples. This supports the validity of the sampling effort (i.e., enough samples were collected to reasonably represent the sediment deposition in the reservoir). This issue is discussed in greater detail in Appendix B.

### **5.5.2. Freeze-Core Sampling**

IPC contracted with Batelle Laboratories to collect freeze-core samples from four spawning sites in Hells Canyon. Three of the sites were upstream of the Salmon River confluence, while one was downstream of the confluence. Batelle also collected several freeze-core samples at two sites above the HCC.

## **5.6. Other Studies by IPC**

IPC also studied erosion along the Snake River and reservoirs of the HCC. The study covered the area from Weiser to the Snake River's confluence with the Salmon River. The study focused on erosion along and above the shoreline banks but not along the riverbed. Areas of erosion were located and identified on a map. The reach below the HCC had relatively little erosion: about 2% of the shoreline showed signs of erosion (Holmstead 2001). A complete copy of this report is included in the appendices to Miller et al. (2003).

Data from many other studies performed by IPC are used in this report. These reports are included in the Literature Cited section and referenced in the report where appropriate.

## **6. METHODOLOGY FOR ACQUIRING FIELD DATA**

This section describes the methods we used to collect the necessary field data to better understand the supply, movement, and stability of sediment in the Snake River below HCD. This

section only describes the methods used in collecting field data, except where an example is useful for illustration. It does not present any of the data, analysis methods, or results. These topics are discussed in their own separate sections.

Describing in quantitative terms the supply and movement of sediment in a large river with a gravel bed is a difficult task that involves a series of largely subjective decisions about sampling locations, times, and procedures. Because information directly quantifying the amount of sand and gravel supplied to the Snake River below HCD is limited, we conducted extensive investigations of bed materials to extend our knowledge of the armoring process; grain-size distribution; and sediment stability, supply, mobility, and transport under different flow regimes. Our specific objectives included generating PSD values of the bed material for the entire study area (including tributaries to the mainstem river), collecting sufficient survey data to characterize flow channels for various purposes, and collecting as much data as possible on sediment movement. To best use available time and resources, we prioritized our data needs and designed our sampling efforts to obtain the most basic and important information first.

We used several methods to determine the PSD of the riverbed materials in both the mainstem river and its tributaries. These methods included two methods for sampling the subsurface materials and two methods for sampling the surface materials. In addition, we used the methods described in Sections 6.2. and 6.3. to sample bedload materials and suspended sediments, respectively.

We made several attempts to sample bedload in the mainstem of the Snake River. However, no movement of materials was detected, so no bedload samples are available for the mainstem. Our analyses show that most of the bed is not in motion except possibly under extremely high-flow conditions. Therefore, it is not surprising that sampling efforts in the mainstem produced no measurable material. We also collected suspended and bedload samples in the 17 tributaries.

Other more specific areas in the canyon, such as sandbars and some riverbank areas, are of particular concern. We also studied these areas using field data, including surveys and additional physical sampling.

## **6.1. Bed Material**

Bed material is the mixture of sediments that forms the channel of the stream or river. The bed materials may be segregated to form an armoring surface layer of coarser material with a mixture of fine and coarse material below it, as shown in Figure 7. This underlying material is referred to as subsurface material. It includes the full size range of material from the larger particles found in the armor layer to very fine particles. The term *bed material* refers to the full range of materials in the stream or riverbed column, not just the surface layer.

### **6.1.1. Sampling of Surface (Armor) Materials**

The armor layers of the riverbed and tributaries were sampled using two different methodologies. The first method was the classic Wolman pebble count method (Wolman 1954), and the second was to take a photograph of the surface and analyze it using GoldSize™ 2.0 software, a

Windows<sup>®</sup>-based photographic sizing program. The Wolman pebble count has been used extensively and is widely accepted as a defensible method of determining the PSD of the surface layer. However, this method is labor intensive and time consuming. It is also impractical in situations where the surface is not readily accessible, such as in the deep, fast-moving flow found in both the mainstem Snake River and some of the tributaries during much of the year. Safety and logistical considerations generally limit the use of this method to areas where the surface layer is exposed or under shallow water. Therefore, we used the photographic method combined with the GoldSize software to obtain data about surface armor in the Snake River, and we used the Wolman pebble count method in the tributaries as flow conditions allowed. The following sections explain the procedures used for both methods.

#### **6.1.1.1. Wolman Pebble Count (Tributaries)**

We used the Wolman pebble count method (Wolman 1954) to determine characteristics of the armor layer of the tributaries. The sample area of a tributary was established by using the same area for collecting flow data (cross section and slope). One hundred rocks were randomly collected from this sample area and measured. A sample size of 100 particles is the most commonly used sample size (Wohl 2000). To ensure random selection of the rocks, the sampler would take a step or two within the sample area and then reach down and collect the first rock touched without looking. The rocks were measured with a pocket rod scaled in hundredths of a foot and the measurement recorded.

#### **6.1.1.2. Photographic Sampling (Mainstem Snake River)**

We used photographic sampling in the mainstem Snake River, both for underwater sampling of the bed surface and for exposed gravel bars that were accessible above the water surface. The majority of the samples analyzed using this procedure were underwater photographs.

#### ***Still Photographic Sampling***

Because photographs can provide a quick surface assessment of sizes and an accurate representative measure, we used photographic sampling as one of the methods to determine the PSD of the armor layer in the mainstem. Photographic sampling consisted of photographing surface bed materials (gravel bars) using a Sony still digital camera during low-flow conditions that exposed as much of the bed as possible.

For accurate analysis of the PSD and to reduce sampling errors, we took all photographs as close as possible to perpendicular to the plane of the bed material. A sampling frame or scaling objects of known dimension covering the entire plane of the image were also employed to quantify particle sizes. The sampling frame, made from PVC pipe measuring 1 m by 1 m (3.28 ft by 3.28 ft) (1-m<sup>2</sup> inside dimension), could only be used where the bed was exposed, not under flowing water. Using a frame around the sample gave the photographer a target and ensured that the photograph fully included the desired area. We found that the sample area of 10.8 ft<sup>2</sup> was adequate for manageable handling and sufficiently large for accuracy with grains at 10 mm (0.39 inch). A tape measure or golf balls ( $\varnothing = 4.3$  cm [0.14 ft]) were used to show scale because using two easily identifiable, equal-size discs or balls in each photograph is suggested (Golder Associates 1996). This method is recommended because the maximum apparent chord of these objects in the image will always correspond to their diameter regardless of the viewing angle.

When the sample area was defined and the scaling established, an image of a representative portion of the gravel bar was collected. The image was then downloaded as a Windows bitmapped file (.BMP) from which the PSD could be determined using the GoldSize software. Figure 8 shows a typical image of a dry gravel bar with the PVC frame and two golf balls for scaling.

### ***Underwater Photographic Sampling***

A distinguishing feature of the Snake River is that it consists of deep pools and swift water that makes representative bed-material sampling challenging. To overcome this challenge, we used an underwater video camera to collect information about underwater surface armor at various locations throughout the study area. A fixed apparatus—consisting of an underwater camera, light, lead weight, and scaling objects—was lowered from a boat into the water using a boom and pulley setup. The lead weight held the camera apparatus in a fixed location relative to the bed in the swift currents. Golf balls ( $\varnothing = 4.3$  cm [0.14 ft]), located within the plane of the sampling area, were used as reference objects. The apparatus was constructed so that when the lead weight was sitting on the riverbed and the cable was held taut, the camera and light were a constant distance above the bed and focused ahead of the lead weight. A rod projecting from the front of the lead weight held two golf balls in the camera's field of view, one near the top of the frame and another near the bottom. The actual sample area was approximately 1.64 ft<sup>2</sup> (0.15 m<sup>2</sup>). When the camera was positioned correctly above the riverbed, a digital video clip (approximately 15–20 seconds long) was taken to verify the existing material at each specific point. The digital video clips were viewed using VideoWave 3 video-editing software, which allowed us to view the clips frame by frame. We then selected a frame to represent each point and converted it to a Windows bitmapped file (.BMP). Figure 9 shows a typical photograph selected from one of the underwater video clips of surface material in the mainstem Snake River.

We conducted underwater photographic sampling above the confluence of the Salmon and Snake Rivers between 1999 and 2001 and recorded approximately 600 video clips. We sampled below the Salmon River in December 2001 and recorded about 400 video clips. Sampling sites were randomly generated to reduce regional bias, and sampling was repeated throughout the study area during varying flow regimes. To establish repeatability and reduce bias, we used a Trimble Pro-XR global positioning system (GPS) unit and GIS to navigate to each of the previously generated random sample points. This GPS/GIS approach was also used to locate points where site-specific data were collected. Some of the randomly generated points fell in rapids, shallow rocky areas, or other locations where it was not possible to deploy the camera. In these cases, the point was noted and skipped. About 32 of the 600 points above the Salmon River and 38 of the 400 points below the Salmon River were not sampled because of inaccessibility. In addition to data from the random points, additional site-specific data were collected at Pine Bar, Fish Trap Bar, and the Tin Shed site to gain a more detailed understanding of the substrate and the geomorphic features of these sites.

Photographic sampling allowed us to collect data on the underwater bed material safely and efficiently without disrupting the river channel. When the photographs were converted to the bitmapped file format, we used the GoldSize software to develop the surface grain-size distributions. Section 7.3. describes the process we used to obtain data on surface grain-size

distributions. Appendix C includes summary statistics from the PSD curves generated using the GoldSize analysis.

### **6.1.2. Sampling of Subsurface Bed Materials**

We used two extraction methods to collect bed material for sieve analysis. Under one method, bed materials normally covered with water, but accessible at some locations during low flows, were collected with a shovel and placed into a sample bag. Sample locations were selected by visual observation to ensure that the sample represented the whole bed. Samples were removed either from a flat location on the bed or from cutbank areas. Then they were carefully excavated to ensure that neither fines nor larger gravels and cobbles were excluded from the sample so the sieving analysis would represent the soil column. Samples were double-bagged to minimize the loss of fine material. A typical sample filled one sample bag (approximately 60–90 lb), but occasionally two bags were required to contain a single sample. This method was used to collect samples in the Snake River and tributaries.

The other extraction method used to collect bed material for sieving analysis was freeze-core collection. This method of collection requires that the sample location be submerged in shallow water. With this method, a pipe is (or multiple pipes are) inserted into the bed at the sample location, and liquid nitrogen is poured into the pipe(s) to freeze the surrounding material (water and bed material). This frozen lump of sample material is then extracted with a tripod and winch or other lifting device before being deposited in a sample container. Freeze-core samples were taken only in the mainstem Snake River. Considerations in using this method include [1) the amount of equipment and supplies required (such as liquid nitrogen), 2) saturated sample location required, 3) a water temperature cool enough to allow freezing of a cubic foot or more of substrate, and 4) water velocities slow enough that the sample can be frozen and maintained while it is being extracted and placed in the sample container.]

During both extraction methods, we noted sample location, description of the area, and other pertinent information. A copy of the notes was enclosed in the sample bag to ensure correct sample identification. Samples were then transported to a soils laboratory for analysis. Section 7 of this report describes this analysis procedure.

## **6.2. Bedload**

### **6.2.1. Tributaries**

We used a Helley-Smith Model 8035 bedload sampler (7.62-cm [3-inch] throat width) to collect bedload samples in the tributaries. Any time sediment samples were being collected and flow depths appeared to be sufficient to move bed material, this sampler was manually lowered into the water and left for 15 minutes. Most of the time, we collected only organic material (such as twigs and leaves), indicating no movement of the bed. Bedload samples that were collected were sent to the laboratory to determine total sediment weight and PSD.

### **6.2.2. Mainstem**

We used the same equipment in the mainstem Snake River that we used for the tributaries. The difference was that, in the mainstem, the sample was deployed using a winch and hoist mounted on a jet boat. The jet boat was held in a fixed location, and the bedload sampler was lowered for a measured amount of time. No bedload movement was apparent at the locations sampled.

## **6.3. Suspended Sediment**

### **6.3.1. Tributaries**

The spring of 2001 was the first time that sediments were regularly and systematically sampled in a fixed set of tributaries. Before this, sediments in the tributaries were sampled on a case-by-case basis when flows were high and the tributaries appeared to be transporting sediment.

In January 2001, sediment-sampling sites were established on 17 tributaries. Seven of these sites were on the Oregon side, and the remaining 10 sites were on the Idaho side. All but two sites were above the confluence of the Snake and Imnaha rivers (and therefore above the Salmon River as well). Figure 10 (3 panels) shows the tributaries in which these sample sites were located. In selecting tributaries to sample, we considered several criteria: large flows, a range of catchment sizes, representation from both sides of the Snake River and the full river reach, indications of significant sediment load in the recent past, accessibility, potential for flow estimation, and efficiency in covering the area of interest. Tributaries sampled represent about 70% of the area drained by identified tributaries to the Snake River between HCD and Cook Creek (below the Salmon River and the lowest tributary sampled), excluding the drainages of the Imnaha and Salmon rivers.

Once we had chosen the tributaries, we used the following criteria to select the actual sampling sites:

- The site did not have potentially high loss of water into the loose fan adjacent to the river (i.e., the site was back from the immediate riverbank area).
- The site represented the general channel characteristics as far as channel cross section and slope in the lower reaches of the channel.
- The site was reasonably accessible from the river.
- The site was long enough to obtain a representative measure of water surface slope (no large drops, waterfalls, or changes in cross section).

Sites were visited and selected, and an initial sample was collected in January 2001 before spring runoff. Samples were collected approximately every 2 weeks starting before runoff increased in the spring and continuing until flows in all tributaries had clearly peaked and started to recede. We adjusted the timing of the sample trips to capture peak flow, but logistics allowed only limited shifts in timing. One of the sites (Salt Creek) was not selected in time to get a sample

during the January site visit. Another site (Corral Creek) had no flow at the sampling site until the April 3–4 sampling trip.

We collected two samples of suspended sediment at each tributary during each sampling visit. One of the pair of suspended samples was sent to the lab for analysis, and the other was stored at the IPC facilities until results were received from the lab in case a sample was missing or damaged.

The reaches of the tributaries near the Snake River do not lend themselves to easy flow measurements. Given the sensitive location of most of the tributary mouths, an extensive permitting process would probably be required before any physical structure could be constructed. Sediments in the bed are large, and flow depths are relatively small for most of the time. Therefore, discharge was estimated using channel geometry and flow resistance equations rather than measured using velocity-area measurements or weir structures. Because of this restriction and the size of the tributaries under most flow conditions, it was not practical to use the standard equal-flow or equal-width method of collecting suspended sediment samples. A depth-integrated sample was collected using a DH-48 sampling container. In some cases, the flows were low enough and the substrate large enough that the sampler could only collect flow in one or two locations in the stream. Appendix D includes results of the suspended sediment samples collected.

### **6.3.2. Mainstem**

During each sediment sampling trip, we collected two samples of suspended sediment in the mainstem Snake River at three locations. We also collected one pair of samples in the Salmon River.

The following locations were used in sampling the mainstem Snake River and the Salmon River:

- Above Temperance Creek at about RM 224.4
- Near Dug Bar at about RM 196.6
- Upstream of the Salmon River at about RM 189.2
- In the Salmon River about 0.8 km (0.5 mi) upstream of the confluence with the Snake River

A US D-77 sampling container and B-56 reel were mounted on a jet boat and used to collect 3-liter samples. While the jet boat held position near the thalweg of the river, the sampler was lowered and raised at a uniform rate to collect a depth-integrated sample. The rate of lowering and raising the sampler was adjusted to allow the sample container to be filled between 70 and 80% full. The sample was collected at a single station in the river cross section.

We analyzed the consistency of sediment concentration in the water column to verify that a single point in the cross section would provide a representative sample of suspended sediment. This analysis used the ratio of the fall velocity of the particles to the shear velocity of the flow to

determine how nonuniform the sediment concentration would be in the water column (Yang 1996). This analysis showed that, at all sample locations, the suspended sediment would be distributed consistently in the water column. Appendix D shows results of the analysis of the suspended sediment samples collected.

Given that earlier bedload sampling at approximately bankfull flow conditions in the mainstem Snake River showed no sign of bedload and that flows during the spring of 2001 were relatively low, we made no further attempt to collect a bedload sample in the mainstem during 2001.

## 6.4. Bars

We sampled two main types of bars. One type of bar is attached to the riverbank and composed primarily of sand-size materials. The other type of bar sampled can be located either on one bank of the river or in midchannel. The surface of these bars is armored, while immediately below the surface layer the full range of bed-material sizes are found. The two types of bars are referred to as sandbars and gravel bars, respectively.

### 6.4.1. Sandbars

The sandbar monitoring component of the study was designed to monitor the general bar development over time with designated transects. There are local areas of change in the banks and sandbars that are not included in the transect data. Those areas of local change have been documented by photographs, maps, and field notes. Hall and Bird (2002) cover the bars' usages and site conditions in detail.

IPC conducted transect surveys on Pine Bar (RM 227.5), Salt Creek Bar (RM 222.4), Fish Trap Bar (RM 216.4), and China Bar (RM 192.3) in 1997, 1998, and 2000. In 1999, IPC conducted additional surveys on Pine Bar and Fish Trap Bar to enhance the 2-D model's collection of topographical data. Data collection for the sandbars consisted of surveying the major features of the bars and banks along transect lines using a Sokkia Set 4A standard electronic total station. The tolerance of the elevation data are considered plus or minus 0.03 m (0.1 ft). This tolerance allows for variations in the local sand and water surfaces and for the sand displacement by the survey rod. Surveys were performed during the fall when flows from HCD were low and stable for fall chinook salmon spawning. Each survey used control points for matching the established transects. Transects were laid out by repeating the angle and distance from the previous year's surveys and photomaps. In 2000, areas with different sizes of material were also surveyed and noted for future reference.

Once collected, the field data were imported into ArcInfo for analysis. In ArcInfo, survey data were transformed from generic coordinates to Universal Transverse Mercator (UTM) (Zone 11, NAD27), using the georeferenced control point/temporary benchmark (TBM) contained in each survey. Data points that were outside a 2-m (6.56-ft) range of a common transect line were not used in the cross section profile. In sections of high variability (such as the cutbank), the allowable range was reduced to 1 m (3.28 ft). IPC analyzed the bank accretion or regression with georeferenced aerial photographs from sources discussed in Section 5.1. The survey data were plotted over the aerial photograph in ArcView by using the survey data  $x, y$  position for the 1998,

1999, and 2000 surveys. Not all sites contained usable georeferenced aerial photographs. The 1997 data for all bars contained an elevation control but not a horizontal control. Therefore, 1997 data were not used in the analysis of georeferenced aerial photographs.

In 2002, we also collected bulk sediment samples at four of the main sandbar locations (Pine Bar, Salt Creek Bar, Fish Trap, and China Bar). These bulk sediment samples were analyzed for mineralogical signatures and PSD. Both the cutbank areas adjacent to the bars and depositional areas forming the bars were sampled. This sampling effort is described in more detail in Appendix F of Miller et al. (2003).

#### **6.4.2. Gravel Bars**

Sampling of gravel bars was limited to collecting bed material and surface-layer samples. Most of the bed material samples on bars were collected during a low-flow period (September 2000) so that the maximum amount of streambed area could be sampled. Bars that were submerged even at this low flow were sampled as part of the random collection of underwater video points. We made no distinction between bars and the rest of the riverbed during the underwater video sampling. Sample locations on bars were selected to represent the riverbed (Gee and Thomas 1991). On smaller bars, we selected the location to avoid unrepresentative areas of finer or coarser material. On some of the larger bars, we collected multiple samples. Although not all bars were sampled, the bars selected for sampling were chosen to represent the full reach of river from downstream of the HCD through Hells Canyon. In addition to the bulk samples taken, we photographed the surface material, generally with a scale in the picture or a frame to allow an analysis of the PSD.

Miller et al. (2003) delineated gravel bars based on photography and topography.

### **6.5. Bathymetry, Cross Sections, and Hydraulic Geometry**

Cross sections for the mainstem Snake River were taken from the bathymetry data collected as described in Section 5.4. The bathymetry, cross section selection, and hydraulic geometry are described in more detail in Parkinson (2002) and Butler (2002).

Some additional cross sections (not included in the hydraulic model) were surveyed by biologists at redd locations. These cross sections were not tied into any reference datum and were used only to compare the shape of cross sections at redds with shapes of cross sections available upstream or downstream in the hydraulic model. Judgment was used in balancing cross section shape and proximity when selecting a model cross section to use in evaluating flow conditions at redd sites.

### **6.6. Tributary Hydraulic Geometry**

We collected data on tributary hydraulic geometry for two purposes. Data about the general hydraulic geometry were collected for use in the sediment transport equations, while data about the event-specific hydraulic geometry were collected when samples of suspended sediments

were taken to estimate flow. All surveys on tributary cross sections and slopes were based on a local reference elevation and not tied to mean sea level or any established benchmarks.

### **6.6.1. Hydraulic Geometry for Sediment Transport Calculations**

Not all sediment transport equations require the same data. In general, the sediment transport equations used in this study require that a slope, cross sectional area, hydraulic radius, and top width be computed for each flow condition. Data for these calculations were collected on each tributary with either a total station or a “self-leveling” level.

We measured general slopes for stream channel using a total station to measure both distance and relative elevation. The distance over which the general slope was measured was limited to the range that could be measured from a single instrument setup. Typically, this distance was on the order of several hundred feet. We avoided abrupt drops in the stream channel that were large enough that they were not washed out in high flows. Smaller drops that would probably disappear under high-flow conditions were included in the slope distance. Slope was measured using the elevation of the bottom of the stream. None of the slopes were measured during high-flow events, so we did not attempt to measure from the water surface elevation or from marks left by high-water. We were careful to ensure that the resulting slope represented the water surface slope during high flows (i.e., the end points of the slope were not located in pools or other areas where nonuniform flow would likely occur).

### **6.6.2. Hydraulic Geometry for Estimating Tributary Flows**

Flows associated with the sediment samples taken on the tributaries were estimated using the slope-area method. The water surface elevation, cross sectional area, and water surface slope were measured when the sample was collected. The locations of the cross section and slope were nominally the same between events, but each was adjusted based on flow conditions. We adjusted the slope distance to maximize the horizontal distance while avoiding nonuniform flow areas such as drops and major changes in cross section. This adjustment generally meant that water surface slopes were measured from the base of a drop upstream of the cross section to the upper end of the next drop below the cross section. During periods of fairly low flows, the slope distance was necessarily quite short, generally ranging from 4.6 to 9 m (15 to 30 ft). The cross section was moved upstream or downstream to represent the flow channel within the limits of the measured slope.

## **7. SAMPLE ANALYSIS AND LABORATORY RESULTS**

This section contains a discussion of the analyses of field samples. This discussion is not intended to present the results of those analyses except where necessary to clarify the description of the individual analysis. Section 10 of this report includes analysis results. Also, this section does not describe how the information will be used to obtain results. That description is included in Section 9. All of the analyses discussed in this section are on physical samples of sediment particles. These samples were either brought into the laboratory—such as bulk samples and

suspended sediment samples—or measured in the field so that raw data could be brought into the office for analysis. Examples of these data are pebble counts and photographs.

This section does not discuss the laboratory analysis of data not collected directly by IPC, but by CH2M HILL, Battelle, or other contractors. Reports from those contractors include descriptions of their analyses.

## **7.1. Analysis of Suspended Sediment Samples**

Samples of suspended sediments collected in the tributaries were transported to the laboratory in 0.5- or 3.0-liter plastic containers. Electrical tape was wrapped around the lids to prevent them from loosening and samples from spilling. Samples were transported to the laboratory at the University of Idaho. Procedures followed standard methods for total suspended solids with a detection limit of 4 mg/liter. Appendix D shows the results of these analyses.

## **7.2. Sieve Analysis for Particle-Size Distribution**

Bulk samples were analyzed by either the soils laboratory in the Department of Civil Engineering at the University of Idaho in Moscow or by Terracon's materials laboratory in Boise, Idaho.

These samples were sieved in standard 20-cm- (8-inch-) diameter sieves using a set of sieves that entirely encompassed the range of sizes included in the samples. Sieve sizes were selected to provide four sieves in the sand-size range and eight sieves in the gravel-size range. Sieve intervals were selected to provide approximate doubling of the sieve opening between each successive sieve. Particles finer than a #200 sieve (0.074 mm [0.003 inch]) were not subdivided or analyzed further. Samples were dry sieved, after which the material retained on each sieve size was weighed and reported to the nearest gram. Standard procedures were followed for weighing the sieves for tare weights and loaded weights. Results were reported as the percentage passing for each sieve size in the set.

Appendix D includes the results of the PSD analysis of all of the samples collected, as well as plots of the PSD analysis. The cumulative percentage passing is plotted on the vertical ( $y$ ) axis with a normal scale, and the size plotted on the horizontal ( $x$ ) axis using a logarithmic scale.

Because the range of particle sizes for the bedload samples was less than that for the bed-material samples and the sample sizes were significantly smaller than those for the bed-material samples, we used a slightly different procedure for each type of sample as described in the next sections.

### **7.2.1. Analysis of Bed-Material Samples**

Because the bed-material samples often included particles in the large cobble-size range and the sample sizes were very large, these samples were analyzed by using two sieve sets. First, the entire dry sample was sieved through a set of large 2-ft<sup>2</sup> sieves with sieve sizes from 76.2 mm

(3 inches) down to a #4 sieve (4.75 mm [0.18 inch]). The entire sample smaller than the #4 sieve was retained on a pan for this set of sieves. Next, the sample portion from the large pan was weighed and then split to a subsample size that would not overload the smaller 20-cm (8-inch) sieves. This sample split was weighed and subjected to standard sieving procedures in the 20-cm (8-inch) set of sieves.

Some samples contained particles larger than the 7.62-cm (3-inch) sieve size of the large sieve set. Each of these particles was measured individually on the three orthogonal axes, and the size was reported as the length of the intermediate axis. Each of these particles was individually weighed and reported in size classes in the same doubling intervals used for selecting sieves in the sieve set. Results were reported as the “percent finer” for each size class based on the entire sample weight.

### **7.2.2. Analysis of Bedload Samples**

In some cases, gravels up to 50.8 mm (2 inches) in diameter were found in the bedload samples. However, most of the particles in these samples were much smaller, consisting of sands and small to medium gravels. Sieve intervals were selected to provide approximate doubling of the sieve opening between each successive sieve, and sieve sizes were selected to provide four sieves in the sand-size range and eight sieves in the gravel-size range.

Bedload samples were sieved in standard 20-cm- (8-inch-) diameter sieves using a set of sieves that entirely encompassed the range of sizes included in the samples. Sample sizes were small enough that no splitting was required. Standard procedures were followed for weighing the sieves for tare weights and loaded weights. Results were reported as the percentage passing for each sieve size in the sieve set.

## **7.3. GoldSize Photographic Analysis of PSD**

Section 6 of this report describes the methods used to collect and process photographs and video images of the surface material. This section describes the methods and computer programs used to enhance the images, size the particles, and create PSD curves from the images.

### **7.3.1. Image Enhancement**

When all images were collected and converted to a Windows bitmapped file format, some of the poor-quality images were enhanced for analysis using Adobe® Photoshop® 5.5 image processing software. This process was necessary to enhance the overall image quality (to add distinction between individual particles) by adjusting the brightness and contrast, sharpening the resolution, and correcting any distortions caused by low light, shadows, turbidity, or other adverse conditions. The enhanced images have improved contrast and clarity that offer workable images from which the particles can be digitized accurately. This process was repeated for the images that needed enhancement until an adequate level of sharpness and clarity was achieved. For accurate results, distortion caused by the camera angle must be corrected. Placing a reference

object of known size near the top and bottom of the photographed area allows the software to correct for this distortion.

### **7.3.2. Photograph Sizing**

After the photographs were enhanced to a sharper image, the next step involved using GoldSize software, to develop the PSD of the surface bed material. GoldSize, a software tool developed by Golder Associates (1996), processes earth images into PSD.

After an image was opened, the scaling objects (golf balls or PVC pipe) were traced and the dimension of that object entered. The scaling links the top and bottom of the image to the back and front of the collection of objects in the picture, assuming that all objects are lying on one flat surface. The next step of the analysis was to digitize the boundary of all particles in each image. The images were manually digitized by tracing the edge of each particle in the image. Only those particles lying within the 10.8-ft<sup>2</sup> grid were digitized.

There are advantages and disadvantages to digitizing the particles in the photographs manually. The primary disadvantage is the time and effort required to perform the work. The primary advantage is that, by manually tracing each particle, the orientation of the particle can be judged. Particles that are not completely visible in plan view can be completed with a reasonable degree of accuracy and repeatability.

Figure 11 shows an example of a photograph that has been digitized (i.e., all of the particles within the frame are outlined).

### **7.3.3. Sizing Analyses**

GoldSize offers two ways to estimate the size distribution of the particles in an image. One is called the “simple estimate,” and the other is called the “best estimate.” The “simple estimate” counts each particle and puts it into a size class or bin that corresponds to the measured size of that particle. The sizes are calculated based on object width (shortest visible axis) because width most closely corresponds to the sieving behavior of rocks. Sediments deposited in an alluvial environment normally have the shortest axis oriented in the vertical direction. Therefore, by selecting the shortest visible axis in plan view, the intermediate axis is actually measured (note that this method corresponds to measurements taken for the Wolman pebble count method). The “best estimate” method uses a model-fitting approach to find the Rosin Rammler distribution that most closely produces the sizes of the particles that appear in each sample (Golder Associates 1996). We used the “simple estimate” method because it was best suited to the sampled particles and allowed an accurate comparison with data from the more customary bulk sieve analysis.

### **7.3.4. PSD Data Conversion**

Kellerhals and Bray (1971) discuss some of the different methods of gathering data about PSD (such as count by area and weight by volume) and the conversion of data necessary to be equivalent to a customary bulk sieve analysis. The photographic analysis of surface materials that we employed uses areal sampling (as opposed to volumetric, or excavating a hole and

extracting bulk samples) and counting by size (as opposed to sieve analysis and weighing). The GoldSize software allows the results to be raw data, such as reported counts of sizes of rocks, or conversions to allow comparison with standard bulk sieve analysis. The settings in the GoldSize software (e.g., bin size, number of bins, and others) were set to correspond to a standard sieve analysis of area-by-weight distribution as proposed by Proffitt (1980).

The simple estimate that is proposed by Proffitt (1980) and calculated by GoldSize is based on the following formula:

$$p_i = \frac{q_i d_{gi}^3}{\sum_{i=1}^n q_i d_{gi}^3}$$

In this formula,  $p_i$  is the percentage by weight,  $q_i$  the percentage by number,  $n$  the number of fractions, and  $d_{gi}$  the geometric mean diameter of the  $i$ th class.

## 8. GEOGRAPHIC INFORMATION SYSTEMS METHODOLOGY AND APPLICATIONS

This section describes how IPC used GIS and GPS technology to develop, store, and analyze thematic layers of sediment characteristics. IPC also used GIS and GPS technology to locate, record, and map sample locations.

### 8.1. Delineation of Tributary Basins

IPC used GIS to build a spatial database for the study area. The beginning point selected for this analysis began with the establishment of a surface model. Existing 1:24,000 scale digital elevation models (DEM) and related contour maps were acquired in electronic format from the USGS. The DEMs were combined into one seamless topological surface in ArcInfo. ArcInfo and ArcView are recognized as among the world's leading GIS software applications.

We defined the majority of tributary basins (those with sufficient relief) by using GRID modeling tools for delineating basins and watersheds. GRID is a raster- or cell-based geoprocessing module that is integrated with ArcInfo. Some basins (such as Pine Creek) were more difficult to define because of flatter topography where standard automated procedures yielded misleading boundaries for basins. Our GIS analysts used existing contour data to adjust those boundaries to correspond to known ridge and valley topography. Spatial statistics for mean elevation and slope were calculated from the topographic models. Additional physical characteristics for each basin—such as the percentage of area forested and total annual precipitation—were also needed.

The amount of forested area was determined by overlaying basin polygons with the National Land Cover Data (NLCD). The land cover data set was produced as part of a cooperative effort between the USGS and the U.S. Environmental Protection Agency (USEPA). The data are based on 30-m Landsat thematic mapper data.

Precipitation data were available in a GIS format from the Interior Columbia Basin Ecosystem Management Project (ICBEMP 2001). Much of the data about elevation and preliminary basin boundaries are also available from the ICBEMP; however, basin boundaries available from ICBEMP are based on smaller-scale data, which served only as a guideline for our study.

## **8.2. Tracked Locations**

When appropriate, location data for sampling sites and other locations of interest were collected with a GPS. For most applications, IPC used a GPS Pathfinder<sup>®</sup> Pro XRS receiver and TSC1<sup>™</sup> data collector, which provided submeter GPS positions. The GPS was critical in establishing and relocating temporary benchmarks, bed-material sample locations, and survey cross section locations. With GPS, coordinate data are generally collected in latitude and longitude coordinates for a geographic reference system. GPS point, line, and polygon data were projected to UTM coordinates (Zone 11, NAD27). When feature locations were established, we projected them to the appropriate coordinate system.

## **8.3. Rectification of Aerial Photographs**

High resolution digital scans were obtained for selected years of aerial photography to georeference for further sandbar analysis. Section 9.9.1. describes the methods used to rectify aerial photograph imagery to Universal Transverse Mercator (UTM) coordinates. Section 5.5.1. of this report contains the sources and scales of photography for this component of the study.

# **9. CALCULATION AND ANALYSIS METHODOLOGY**

This section describes the methods and assumptions we used to analyze the different sediment parameters. In several cases, we provide the theory behind different methods of calculating a parameter, even though we used only one, to summarize the many factors to consider and demonstrate the basis we used to select one method over the others. Only those results used to demonstrate or clarify a point or procedure are discussed in this section. Section 10 includes the results and conclusions of our analyses.

As much as possible, the first few paragraphs in each section provide general information about the subject of the section and a simple description of what was done. The rest of the section gives a more detailed analysis of the alternatives and theory behind the calculations.

## 9.1. Surface and Subsurface Materials

As we noted in Sections 6 and 7, we collected and analyzed samples of both bulk (subsurface) bed material and surface layer bed material from the tributaries and mainstem Snake River. The analysis provided PSD data on the surface and subsurface materials. These PSD data are used to obtain particle sizes that are often used to complete incipient motion and transport calculations for gravel-bed rivers. One parameter often calculated to determine particle-size characteristics of a gravel-bed river is the geometric standard deviation ( $\sigma_g$ ), which is a measure of the uniformity of particle sizes in a sample. Samples that are more uniform, or close to the same size, have smaller values, and completely uniform sediment would have  $\sigma_g = 1.0$ . Geometric standard deviation of sediments is commonly computed as

$$\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} \quad (1)$$

where  $d_{84}$  and  $d_{16}$  are the sizes for which 84% and 16%, respectively, of the particles by weight are smaller than the given value.

Therefore, the larger the number ( $\sigma_g$ ), the wider the range of particle sizes in the sample. Normal bed material in a gravel-bed river may have a standard deviation in the range of 4 to 10 or higher (Raudkivi 1998). As armor begins to form, smaller sizes are removed from the surface of the stream or riverbed, and the geometric standard deviation of the particles on the bed surface decreases. At maximum armor formation (i.e., when any increase in flow would break up and mobilize the armor layer), the geometric standard deviation tends to be in the range of 1.8 to 2.0, or nearly uniform (Raudkivi 1998).

## 9.2. Characterization of Surface Layer

We estimated PSD in the surface (or armor) layer using two different methods. In the tributaries, we used the Wolman pebble count method (Wolman 1954) to characterize PSD data for the surface layer. In the mainstem, we used digital photographs and the GoldSize software to characterize PSD data for the surface layer. For a detailed discussion of these methods, see Sections 7.2. and 7.3. of this report.

It is important to present the PSD data results of the two surface methods in a format compatible with the subsurface method. The Wolman pebble count method is essentially a grid-by-number procedure. In other words, the raw results are the number of particles in each size class selected randomly. In our case, the random selections were by step rather than by grid. The photographic method (using the GoldSize software) is essentially an area-by-number procedure. In other words, the raw results are the number of particles in each size class that fall within a selected area (the 10.8-ft<sup>2</sup> PVC frame or the frame of the photograph). Finally, for the bulk samples, sieve analysis is a sieve-by-weight procedure.

Kellerhals and Bray (1971) present conversion factors to allow PSD data from various sampling procedures to be compared. We used the results from the sieve-by-weight procedure as the

baseline or common standard. The table of conversion factors in Kellerhals and Bray (1971) shows that the conversion factor from grid-by-number to sieve-by-weight data is one. In other words, no conversion is necessary. We used the Proffit (1980) method (a selectable option in the GoldSize software) to convert PSD data from photographs to the equivalent sieve-by-weight data format. Therefore, all PSD data that we present are internally consistent.

### **9.3. Calculations of Flow Resistance**

Flow resistance relationships are used to estimate flow depths and velocities at discharges that are not directly measured in the field. We also used flow resistance relationships to estimate discharge during sampling for suspended sediments in the tributaries. We used flow depths and velocities to determine the incipient motion and transport of sediment. Many different forms of flow resistance relationships have been developed for gravel-bed rivers. Generally, values from Limerinos (1970), Bray (1982), and Mussetter (1989) were checked, and we used Mussetter's equation in the final analysis because it appeared to give the most reasonable values in the majority of flow conditions in the tributaries.

#### **9.3.1. General Background**

The issue of flow resistance involves the prediction of velocity of flow in terms of channel properties that contribute to flow resistance. Several quantifications of this relationship (such as Chezy, Manning, and Darcy-Weisbach equations) have been used for many years. All such equations account for the resistance processes with a single coefficient of resistance. Applications using these equations revolve around the central problem of evaluating this single coefficient.

Traditionally, this approach to assessing flow resistance has been a simple empirical procedure that involves providing a coefficient based on experience and past observations. However, this approach tends to result in the coefficient being related mainly to the bed-material size while other important factors—such as nonuniform bed profile, range of particle sizes in the bed material, and dependence of flow resistance on depth—are generally ignored. In particular, the coefficient is assumed to be constant at a given site as discharge varies, despite much evidence that in a uniform channel, flow resistance is greater at low flows than at high flows (Sargent 1979). Uncertainties are therefore associated with the traditional method that, as a consequence, has to be conservative in its estimates. To produce a more satisfactory prediction of flow resistance, we could use a more theoretical approach based on principles of fluid mechanics, such as boundary layer theory, and on processes of flow resistance. Progress has been made in this direction in modeling straight uniform flows (Hey 1979). However, no generally applicable equation has been derived. Such an equation, with its inherent complexity and requirements for field data, has been considered impractical. Also, there are misunderstandings over the application of boundary layer theory to rivers, especially in those cases where resistance factors other than bed-material size are encountered.

Nevertheless, the most successful flow resistance equations for gravel-bed rivers are of the general form derived from boundary layer theory, and they account for variables affecting flow

resistance other than particle size alone. These equations, while still employing empirical data for determining appropriate coefficients and exponents, are built on a strong theoretical foundation. Therefore, they ensure a wider range of applicability than those single-parameter empirical equations that are traditionally used.

The theoretical approach was prompted by the derivation of flow resistance laws for boundary layers and their successful application to flow in pipes. In the case of channel flows, friction at the boundary establishes a shear layer that has many similarities with a boundary layer. Therefore, theoretically based channel resistance equations tend to be based on boundary layer theory (ASCE 1963). In fact, the theory cannot be applied without modifications, but it does provide a useful base on which to build a theory of open-channel flow resistance.

The chief concept of the theory is that the mean flow velocity can be calculated from the shape of the velocity profile. The velocity profile can be quantified as a function of the various resistance factors. The resistance relationship is then a convenient expression of this function. Therefore, the mean depth-integrated velocity in a channel,  $U$ , at a vertical section in an infinitely wide flow or shear layer is given by deduction from pipe flow or by definition as

$$U^2 = \frac{8\tau_0}{\rho f} = \frac{8U_*^2}{f} \quad (2)$$

where  $\tau_0$  is the boundary shear stress,  $\rho$  is the fluid density,  $U_*$  is the shear velocity defined as  $(\tau_0/\rho)^{1/2}$ , and  $f$  is the Darcy-Weisbach coefficient, selected because it is dimensionless.

Under the same conditions, the relationship with other common resistance coefficients is

$$\frac{U}{U_*} = \sqrt{\frac{8}{f}} = \frac{D^{1/6}}{n\sqrt{g}} = \frac{C}{\sqrt{g}} \quad (3)$$

where  $g$  is acceleration due to gravity,  $D$  is the mean flow depth,  $n$  is Manning's coefficient, and  $C$  is the Chezy coefficient.

The ratio  $U/U_*$  is determined by quantifying the resistance coefficient with equations describing the velocity profile. This quantification requires an assessment of the boundary effects and varies with distance from the boundary and other parameters as described above. The boundary effects are different in sand-bed streams than in gravel-bed streams.

Flow resistance for sand-bed channels is a function of river form, discharge and its duration, type of bedforms, size and gradation of bed materials, bars and their geometry, and channel planform. For channels in coarser materials, flow resistance is more a function of size and gradation of bed materials, the degree to which spaces between coarser particles may be filled with finer materials, and magnitude and duration of discharge. For a given channel section in a coarse-material channel, Manning's  $n$  may vary with discharge from a high of 0.20 or greater to a low of 0.05 or less. Based on this significant change in resistance to flow with discharge, using a constant value for flow resistance in hydraulic modeling is not realistic if a range of flow is being

considered in the analysis. Note that resistance to flow decreases with decreasing bed-material size. Most often, resistance to flow decreases as discharge is increased (at least the part of resistance attributable to particle roughness, but this tendency may not be the case for the part of resistance attributable to channel form). These observations on a wide range of river types and sizes lead to the conclusion that, to model open-channel hydraulics accurately, we need a more sophisticated approach for determining flow resistance rather than assuming a constant value, as is often done when the Manning equation is used. For gravel-, cobble-, and boulder-bed streams, large amounts of fine sediments are typically brought to the channel from the watershed during major flood events. This movement of fine sediments may be sufficient to mask the roughness of the coarser particles, and for short periods of time, these channels may behave as sand-bed channels with respect to flow resistance.

### **9.3.2. Flow Resistance for Channels with Coarse Bed Materials**

The physical processes that determine flow resistance in natural streams vary widely depending on the character of the stream. For low-gradient streams with relatively small bed materials, the resistance is primarily a function of surface drag on the channel boundary. For mobile-bed channels, resistance is primarily a function of form drag associated with bedforms generated on the channel bed by the interaction between the flow and the alluvial bed. Form drag is generally less well understood than skin friction drag is, but it is generally a function of energy loss associated with turbulence. As the bed-material size increases, the effect of skin friction on the channel boundary becomes decreasingly significant. Regular bedform patterns (ripples, dunes, and others) observed in sand-bed channels become less prominent and may disappear entirely as the bed-material size approaches gravel and cobble size. It should be noted, however, that ripples and dunes have been observed in gravel-bed rivers at very high discharges, but that their occurrence is very unusual.

In general, the hydraulic characteristics of flow in coarse bed-material streams are related to resistance because of the boundary material; energy losses caused by distortions of the free surface; and changes in flow patterns related to cross sectional shape, longitudinal profile, and planform (Bathurst et al. 1979). According to Bathurst et al. (1979), the only bedform pattern associated with steep cobble- and gravel-bed rivers is the characteristic riffle-pool sequence. For cobble- and boulder-bed streams, the resistance is associated primarily with drag around the individual particles.

Several forms of the flow resistance relationship have been proposed for streams with coarse bed materials. These forms are based on a variety of empirical, semi-empirical, and theoretical considerations. Common forms are variations of Manning's equation and Chezy's equation, which are empirical in nature, and the Darcy-Weisbach equation that is based at least partially on theoretical considerations of boundary layer. For small relative roughness (the ratio of flow depth to boundary-roughness element size), it can be shown that the Darcy-Weisbach resistance function is a semilogarithmic relationship depending on the relative roughness. This form is consistent with the theoretical Keulegan flow resistance relationship. Manning's equation, used extensively by practicing engineers, is considered to provide adequate accuracy for relatively low-gradient, rigid boundary flow conditions. For high-gradient streams with coarse bed material

on the boundary, Manning's equation typically underestimates the flow resistance. Therefore, other flow resistance methods should be used for such conditions.

Several researchers (Bray 1979, Hey 1979, Griffiths 1981) have shown good correlations between measured data and the semilogarithmic form of the resistance equation for gravel- and cobble-bed streams. Bathurst (1985) points out that, while there is some theoretical basis for these forms of the resistance equation, they have not been widely tested for slopes steeper than about 1%. In addition, the theoretical basis does not extend strictly to flows at large-scale roughness. Studies have shown that additional physical processes become important with large-scale roughness and high-gradient slopes and that these processes should be reflected in the resistance relationships.

Jarrett (1984) developed a power function relationship for Manning's  $n$  expressed as

$$n = 0.39S_f^{0.38}R^{-0.16} \quad (4)$$

where  $n$  is Manning's roughness coefficient,  $S_f$  is the channel slope, and  $R$  is the hydraulic radius.

Jarrett's data were collected from about 75 high-gradient streams in Colorado. Simons and Senturk (1992) report the results of studies of other Colorado mountain streams in which flow resistance relationships used the form of Jarrett's equation, but with different coefficients and exponents based on site-specific data. Two examples from these studies are shown as

$$n = 0.29S_f^{0.15}R^{-1.55} \quad (5)$$

and

$$n = 0.29S_f^{0.043}R^{-1.40} \quad (6)$$

In these equations, the coefficients and exponents differ substantially from Jarrett's. The new values for coefficients and exponents imply that a general relationship that is applicable for all streams may not be possible in this form. On the other hand, good results can be achieved by using this general form with site-specific data used to determine the appropriate coefficients and exponents (Simons and Senturk 1992).

Several researchers have recognized that flow resistance for streams with coarse bed materials can be described as the sum of grain resistance and form resistance of the large particles. Grain resistance is described by a semilogarithmic function of the ratio of the flow depth to the characteristic grain size on the channel boundary. This relationship is expressed (Simons and Senturk 1992) as

$$\sqrt{\frac{8}{f'}} = a + b \log\left(\frac{D}{d_s}\right) \quad (7)$$

where  $f'$  is the Darcy-Weisbach friction factor due to grain resistance,  $D$  is the flow depth, and  $d_s$  is the characteristic grain size. The  $a$  and  $b$  are constants.

When the relative submergence (the ratio of water depth to particle size) becomes smaller than about 4.0, the physical processes causing flow resistance begin to change. Numerous studies have been conducted to define flow resistance relationships for such conditions. Bray (1982) summarizes several of these relationships. From the results of these studies, it appears that the semilogarithmic form given in the above equation can be applied to some mountain streams with appropriate choice of the constants in the equation. It should be noted, however, that the above form does not show the effects of form drag on the individual particles, nor does it reflect the influence of PSD on flow resistance. Equations of the above form, with appropriate values selected for the constants, may be used for cases where the channel boundary is rigid, as in the case of an armored streambed, and where the relative submergence is greater than 4.0 (Simons and Senturk 1992). However, equations of this form also have been applied successfully in gravel-bed streams with transport (Bray 1982).

In work performed for Simons, Li & Associates (1989), a flow resistance relationship in the form of a power function was developed from field data. An advantage of the power form for the flow resistance relation is that it can be easily fit to field data using regression techniques (Simons and Senturk 1992). This form evolved from an evaluation of the most influential parameters that could be readily measured through standard field techniques, including hydraulic geometry, bed-material gradation, and channel gradient. The recommended power relation form is

$$\sqrt{\frac{8}{f}} = a \left( \frac{D}{d_{84}} \right)^b \sigma^c \quad (8)$$

where  $a$ ,  $b$ , and  $c$  are constants within defined ranges of channel gradient and relative roughness scale,  $f$  is the Darcy-Weisbach friction factor,  $d_{84}$  is the particle size for which 84% of the material is finer,  $D$  is the average flow depth, and  $\sigma$  is a gradation coefficient of the bed material defined as

$$\sigma = \log \left( \frac{d_{84}}{d_{50}} \right) \quad (9)$$

Considering the physical processes occurring in the flow, the parameter  $\sigma$  was determined to be significant because it represents the range of particle sizes present in the coarse portion of the bed material that affects the amount of form drag, the tendency of the flow to produce localized hydraulic jumps, and the energy dissipation from the associated chutes and pools created by flow between the larger particles. Therefore, this parameter represents processes that have been shown to be dominant in steep streams with large bed materials.

The coefficient  $a$  and exponents  $b$  and  $c$  were determined by multiple linear regressions for the field data for ranges of channel gradient and for the intermediate ( $1.2 < D/d_s < 4.0$ ) and large-scale ( $D/d_s < 1.2$ ) roughness categories proposed by Bathurst (1978) and Bathurst et al. (1981). The resulting values are shown in Table 4.

Other flow resistance relationships using the power form reported by Bathurst (1978) and Bathurst et al. (1981) and by Simons, Li & Associates (1989) include the following equations:

$$\sqrt{\frac{8}{f}} = 1.11 \left( \frac{D}{d_{84}} \right)^{0.46} \left( \frac{d_{84}}{d_{50}} \right)^{-0.85} S_f^{-0.39} \quad (10)$$

$$\sqrt{\frac{8}{f}} = 0.89 \left( \frac{D}{d_{84}} \right)^{0.45} \left( \frac{d_{84}}{d_{50}} \right)^{-0.87} S_f^{-0.50} \quad (11)$$

$$\sqrt{\frac{8}{f}} = 0.24 \left( \frac{D}{d_{84}} \right)^{0.48} \sigma^{-0.81} S_f^{-0.81} \quad (12)$$

$$\sqrt{\frac{8}{f}} = 2.56 + 2.60 \log \left( \frac{D}{d_{84}} \right) - 1.631 \log \sigma - 1621 \log S_f \quad (13)$$

Of these equations, equation 10, referred to as Mussetter's equation for gravel-bed flow resistance, has been suggested as generally applying better for several reasons (Simons and Senturk 1992). For a uniform gradation, the value of  $\sigma$  would approach 1.0 because the exponent from the regression is negative. The ratio of  $d_{84}/d_{50}$  approaches 1.0 for a uniform gradation. Therefore, the value of  $(8/f)^{0.5}$  remains defined. Note that the significance of the relative submergence decreases with increasing gradient, while the significance of the gradation coefficient  $d_{84}/d_{50}$  increases with increasing gradient. Additionally, the significance of the channel slope increases with increasing slope up to about 10%. In the intermediate submergence range ( $1.2 < D/d_{84} < 4.0$ ), the relative protrusion of particles into the flow should have an increasingly significant effect on the resistance to flow. For large-scale roughness ( $D/d_{84} < 1.2$ ), the characteristic particle size protrudes through the entire flow depth so that a changing depth of flow relative to the roughness height has little effect in this range. Mussetter's equation has been applied in cases of several high-gradient streams with large cobble- and boulder-size material with reasonable success (Simons and Senturk 1992).

Limerinos (1970) proposed a flow resistance relationship of semilogarithmic form for gravel-bed streams as

$$\sqrt{\frac{1}{f}} = 2.03 \log \left( \frac{R}{d_s} \right) + 0.35 \quad (14)$$

where  $R$  is the hydraulic radius and  $d_s$  is the characteristic bed-material size, generally taken as the  $d_{50}$ .

Bray's (1979) equation for gravel-bed streams was very similar to Limerinos's. Bray's semilogarithmic equation is

$$\sqrt{\frac{1}{f}} = 2.36 \log \left( \frac{D}{d_s} \right) + 0.245 \quad (15)$$

Equations such as those of Limerinos and Bray should be limited in their application to flow conditions representative of the intermediate-scale relative roughness region ( $1.2 < D/d_s < 4.0$ ).

Use of a single percentile of the size distribution, as represented in several of the preceding equations, requires that the ratio of that percentile to any other percentile should be constant from site to site. This condition can be tested using the standard deviation of the size distribution,  $\sigma$ , which—because natural sediments have size distributions that, though not exactly lognormal, are usually approximately lognormal—depends on a ratio of percentiles. The effect of size distribution for many streams may indeed be approximately constant. However, for many gravel-bed streams, the value of the standard deviation of the size distribution is not constant. In such cases, a flow resistance equation including this parameter in some form should be selected.

The flow resistance relationships we have listed can be used with considerable success as long as the relevant assumptions are observed. They apply to river riffle sites but not to pool sites where the bed profile is nonuniform. Likewise, channel bends introduce additional flow resistance processes not accounted for in these equations. At low flows, ponding is particularly important. The flow resistance function should account for the nonuniform flow in the pools, generally by using gradually varied flow computation procedures. However, at high flows, the features of channel geometry tend to be drowned out and their effects diminished. Therefore, the equations for straight, uniform flow can generally be applied. The high-flow limit of application of the discussed equations appears to depend on the development of sediment movement. When large quantities of sediment are in motion and the particles bounce, or saltate, rather than roll, the shape of the velocity profile is affected and bedforms can appear. In addition, if the channel has an armored bed, removal of the armoring layer would probably expose significant quantities of sand, thereby hiding the effects of bed-material composition on flow resistance.

In fact, it is uncertain whether gravel movement significantly affects flow resistance for in-bank flows. Bray's work (1979) suggests that the basic resistance equations are valid at high in-bank flows. However, Charleton et al. (1978) suggest that sediment movement at high flows affects the resistance. Based on these observations, the equations given here should not be applied once  $D/d_{84}$  exceeds about 50 in uniform flow. Higher values are possible in pools, but the residual depth complicates the relative submergence there.

Choosing an appropriate flow resistance equation to use for a particular reach of a tributary channel is based on comparing calculated flow depths and velocities with conditions observed in the field. Based on such comparisons and on engineering judgment of reasonableness of results, we applied the Mussetter equation to the tributary streams to determine flow depth and average velocity conditions at varying flow rates. We also based our selection of this equation on the recommendation of Simons and Senturk (1992), who suggest that this equation may provide an improved method of predicting resistance to flow in high-gradient streams with large cobble- and boulder-size material.

## 9.4. Calculations of Armor Formation

Whenever a flow is incapable of moving all sizes of sediment in a widely graded streambed, the coarser materials of the sediment may form an armor layer at the bed surface as finer surface particles are selectively removed. This process results in a surface layer of coarser particles that reduces further erosion and transport of materials from the bed. In gravel-bed rivers, the geometric standard deviation,  $\sigma_g$ , of the particle sizes of the bed material may be 3.5 or greater, indicating a wide range of particle sizes. Streams with this characteristic are more likely to become armored than those with more uniformly graded bed materials (Raudkivi 1998). In protecting finer subsurface sediment from being eroded, this armor layer inhibits erosion or streambed degradation and enhances the stability of the surface material. If a given armor layer is stable for a certain discharge quantity, then it is reasonable to conclude that no further degradation of the bed will occur for flows less than or equal to that quantity. Therefore, bed materials protected by an armor layer are not available for transport.

We estimated the PSD of the maximum possible armor layer for the tributaries by assuming a normal distribution of the sediment sizes. We estimated the  $d_{95}$  of maximum armor by using the  $d_{50}$  of the bed material and the standard deviation of the bed material. The  $d_{10}$  of the maximum armor was estimated using Raudkivi's (1998) method ( $d_{10a} = 1.8 \times d_{50}$ ). The maximum armor PSD and the PSD data on bed material were plotted on the same graph, and in some cases, the  $d_{95}$  size was modified to give a more reasonable result. For example, on Bernard Creek, the calculated  $d_{95}$  is 1.6 m. This value is far greater than the largest size collected in the sample and also far larger than would be supported by a visual inspection of the sediments in Bernard Creek. Therefore, for Bernard Creek, the  $d_{95}$  size for the armor was graphically chosen to be 400 mm (15.75 inches).

### 9.4.1. Background

Sediment mixtures with a wide range of particle sizes, as indicated by large values of the geometric standard deviation, tend to show unequal mobility at low shear stress excess. With increasing bed shear stress, the median size of the material in transport effectively increases to that of the parent bed material. Decreasing transport that occurs with the development of armor also means that the threshold shear stress of the surface increases. Several studies show that the transport relationship for this partially supply-limited condition should include the area of the armor as a variable (Karim et al. 1982, Karim and Holly 1986, Parker 1990). Worman (1992) reports that, when the bed is almost fully armored, the critical shear stress may be about five times greater than the incipient motion conditions without armor.

The sediment size that will be at the threshold condition for a given discharge can be evaluated on the basis of incipient motion for that sediment size. If significant quantities of sediment larger than the threshold size are not present in an eroding bed subject to this discharge, then armoring will not occur. Also, the bed will erode to provide flow conditions approaching those for which the bed sediment is generally stable (Little and Mayer 1972). A state of armoring may be reached at any shear stress up to a limiting value beyond which all particles are in general motion and no armoring or cluster building takes place. Only at low bed shear stresses is the grading of the armor layer affected by the grading of the initial parent bed material (Raudkivi 1998). The final

grading of the coarsest possible armor is governed by the coarse fractions in the original material and not by the initial grading. Data from several experiments suggest that the median size of the maximum armor condition is related to the  $d_{\max}$  of the original bed material. This  $d_{\max}$  size is not easy to estimate or measure, but an extra large stone that occurs occasionally does not affect the armor layer. One method to estimate  $d_{\max}$  is to extrapolate the grading curve of the underlying parent bed material on the basis of the last two or three data points of the coarse fraction so that all particles just pass the coarser sieve (Raudkivi 1998).

The relationship between the average grain size of the *limiting* armor layer  $d_{50ac}$  and the  $d_{\max}$  of the underlying parent bed material, as suggested by Raudkivi (1998), is given by

$$d_{50ac} = \frac{d_{\max}}{1.8} \quad (16)$$

where  $d_{50ac}$  is the median size of the limiting armor layer.

Alternatively, the  $d_{50ac}$  may be determined, according to Raudkivi (1998), from

$$\frac{d_{84}}{d_{50ac}} = 1.5 \quad (17)$$

where  $d_{84}$  is taken from the subsurface bed material.

In other words, the top half of the grading curve of the limiting armor layer has the maximum slope in the PSD curve of *uniform* sediments. Available field data tend to support this order of maximum armor size  $d_{50ac}$ . The armor size  $d_{\max}/d_{50a}$  at lower than limiting critical shear velocity  $U_{*ac}$  is from available data well described by the following relationship (Raudkivi 1998):

$$\frac{(d_{50a})_{\max}}{d_{50a}} = 1.8 \left( \frac{U_{*a}}{U_{*ac}} \right)^{-2} \quad (18)$$

where  $U_{*a}$  is the shear velocity for formation of a given armor, and  $U_{*ac}$  is the shear velocity condition for formation of the critical armor condition (or maximum possible armor), or by the following relationship that is similar to the equations proposed by White and Day (1982):

$$\frac{\theta_{ca}}{\theta_c} = \frac{\theta_{ca}}{0.05} = (0.4d_{ar}^{-0.5} + 0.6)^2 \quad (19)$$

where  $\theta_c$  is the critical Shields parameter for formation of a given armor layer, and  $\theta_{ca}$  is the critical Shields parameter for formation of the critical armor layer, and  $d_{ar}$  is size ratio given by  $d_{ar} = (d_{50a})_{\max}/d_{50a}$ .

If the bed shear stress exceeds the value for the limiting, or critical, armor layer, all sizes of bed material are mobile. In some cases, a riverbed becomes covered with armor stones that do not move even during large floods if these floods do not exceed the  $U_{*ac}$  condition. Marked cobbles can be found at their locations even after major floods. In such cases, the channel acts as a

conveyor for materials finer than those lining the bed; these materials are supplied from upstream reaches or from tributary sources. Also, the bed material below the armor lining plays no part in transport processes (Raudkivi 1998).

Armoring of an eroding bed is probable when the threshold size is smaller than the  $d_{95}$  size of the bed-material composition representative of the depth of possible degradation (Little and Mayer 1972). The  $d_{90}$  or  $d_{95}$  size of this material is frequently found to be the size of the particles forming the armor layer. In other words, at least 5 to 10% of the original bed material must be immobile at a given flow condition for the armor to develop. More conservative estimates place the quantity of immobile material required at 15% (Strand and Pemberton 1982, Lagasse et al. 1991). In other words, if incipient motion computations indicate that the  $d_{85}$  size is at the condition of incipient motion, then at least 15% of the bed material will be immobile and armor could develop. We used this more conservative estimate to determine the stability of armor in the Snake River.

Several aspects of the process of streambed armoring have been investigated and reported in the literature (Lamberti and Paris 1992). First, the sediment and hydraulic conditions under which the coarse surface layer develops have been investigated since 1953. Second, the effects on incipient motion and on sediment transport induced by the nonuniformity of grains have been studied since 1950. Third, the relation between the final grain-size distribution of the coarse surface layer and the characteristics of the subsurface material from which it is derived has been investigated since 1965. Fourth, the erosion or channel degradation associated with the development of the armor layer has been studied since 1972. Fifth, the temporal evolution of the armor layer and the transport rate during the armor-formation process have been assessed since 1972. Mathematical modeling of the armoring process has been proposed in various forms since 1970. The numerous aspects of the armoring process offer a clue to the complexity of the processes involved in armor development and characterization.

#### **9.4.2. Armoring in the Mainstem Snake River**

The existing armor in the mainstem Snake River in Hells Canyon is characterized by particle sizes estimated from photographic sampling of the riverbed. Comparing PSD properties of this surface layer with PSD properties of the underlying bed materials shows that the existing surface layer is indeed an armor layer. The median size of the surface layer material is much larger than the median size of the subsurface materials. Also, the geometric standard deviation,  $\sigma_g$ , of the surface layer is significantly smaller than that of the subsurface materials, indicating a more consistent gradation of particle sizes in the surface layer. However, this characterization of the existing armor may not be the characterization of the limiting, or maximum size, armor layer, which could develop at flow conditions greater than those reflected in the existing armor layer.

To assess the ability of the riverbed to supply sediments for transport, we need an evaluation of the stability of the surface bed materials. Under armored conditions, very little if any of the underlying bed material is available for transport. On the other hand, if the armor layer can be moved under flows within the range of possible conditions, then the underlying bed materials would be available for transport and would constitute an additional supply of sediments to downstream reaches of the river.

Our evaluation of the stability of the surface bed materials is based both on the stability of the existing armor layer, as characterized by PSD data developed using the photographic method, and of the limiting armor layer, as characterized using the mathematical modeling approach suggested above in Section 9.4.1. The stability assessments are based on routine, well-established incipient motion computations involving comparison between the critical Shields parameter for a given particle size and the Shields parameter for the assumed flow conditions.

Incipient motion computations for the existing armor layer are based on the  $d_{84}$  particle size in the surface layer. The selection of this size is based on the assumption that at least 15% (represented by  $d_{84}$ ) of the larger particle sizes in the surface layer would need to be immobile to provide sufficient material for a limiting armor layer to develop (Strand and Pemberton 1982, Lagasse et al. 1991). Because the surface layer bed materials exhibit a relatively consistent size distribution, there is actually little difference between using the  $d_{84}$  particle size in the surface layer and the  $d_{50}$  particle size in the surface layer.

## 9.5. Calculations of Incipient Motion

Water flowing down a river exerts forces on the riverbed material. When these forces exceed the sum of the forces holding the material in place, the material begins to move. The beginning of bed-material movement is called *incipient motion*. This section describes the theory and procedure we used to determine the stability of the existing armor layer in the Snake River study area. A stable armor layer does not indicate zero sediment transport, as sediments can be transported over a stable riverbed. To evaluate the stability of the armor in the Snake River and assess the availability of bed materials for downstream transport, we must understand under what flow conditions sediment will begin to move in the Snake River. We must also understand the spatial variability along the channel of this initial motion to evaluate whether sediments (once they begin to move) will likely redeposit in other locations along the river or whether they might be completely removed from the system.

Incipient motion in the mainstem Snake River was calculated using the procedure outlined in this section, but incipient motion in the tributaries is presented implicitly within the transport equations by allowing transport only when at least 85% of the bed-material sizes are mobile.

### 9.5.1. General Background

The relevant technical literature describes different methods for predicting the initiation of motion. Most of the laboratory and theoretical developments have focused on uniform sediments in laboratory flume environments. The most widely studied sediment sizes are sands because of their relative abundance in mature streams and their ease of study in laboratory experiments. Unfortunately, uniform sediments behave similarly to rigid boundaries with regard to the boundary flow resistance because of the uniform grains. In heterogeneous or mixed sediments, the effects of sorting alter the boundary flow resistance and cause instantaneous velocity fluctuations through and around the bed material; these alterations cause undulating bed forces. Larger particles may shield smaller particles while being exposed to higher drag forces as they are “lifted” into the flow. Therefore, greater drag forces on larger particles in the mixture may

counter increased weight. As such, particles in heterogeneous mixtures typically exhibit different points of incipient motion than would be predicted for the same size particles in a uniform mixture (Raudkivi 1998).

An important feature in this discussion is the concept presented by Stelczer (1981) that “to each particle size a lowest bottom velocity...exists, below which there is no movement... On the other hand, there exists also a bottom velocity at which all particles belonging to this fraction will move.” Therefore, the concept of a unique critical Shields stress, or critical dimensionless shear stress, is inherently a statistical value that attempts to convey these two points. Buffington et al. (1992) also present data to show that shear stress fluctuates based on particle sorting, hiding, and packing.

Therefore, the problem of bed features in gravel-bed rivers is more complex than in sandy streams. A major factor in this additional complexity is the difference in sediment structure (Raudkivi 1990). In general, sands form beds of almost uniform grain size, whereas gravel beds usually contain a broad range of grain sizes, at times from fine sand to large boulders. Consequently, there is a *preferential transport* as well as *armor*ing of the bed surface. The different grain sizes also lead to the applied shear stress excess,  $(\tau_0 - \tau_c)/\tau_c$ , in gravel-bed rivers being less than in sandy beds. The equivalent of transition flat-bed conditions in sandy rivers rarely if ever exists in gravel-bed streams. The movement of grains in a gravel bed is somewhat more selective and associated with the breakdown of grain clusters on the surface. In these clusters, grains mutually support each other and armor the surface. Indiscriminate transport occurs only at shear stresses greater than those for the limiting armor layer (i.e., at stresses at which no armor layer can reform). In principle, the complexities arise from the grading of the sediment and relative flow strength. Regular 2-D bed features can be generated in the laboratory for uniform gravels (i.e.,  $\sigma_g < 1.3$  to 1.5) (Raudkivi 1990).

The formation of mutually supporting grain clusters leads to local three-dimensional flow. The cluster protects the surface locally, but the bed erodes at the periphery of the cluster until it fails through undermining and a new cluster begins to form. This armor ing process also affects the large-scale bed features in gravel-bed rivers. When these features are relatively flat in comparison to sand dunes, they are referred to as bars. The bars have a multitude of forms, and their lengths often equal or exceed the width of the channel. Bar features result in nonuniform flow conditions in the channel.

### 9.5.2. Incipient Motion for Uniform Sediments

Shields (1936) introduced the now classical definition of the point at which particle sizes become entrained. A relationship between the boundary Reynolds number and a dimensionless shear stress was found to convey a consistent relationship similar to that found in the Moody diagram for laminar-turbulent flow in rigid boundary pipelines (Yang 1996). When using the Shields diagram, the following definitions apply:

$$Re_b = \frac{U_* d_s}{\nu} = \frac{(g R S)^{0.5} d_s}{\nu} \quad (20)$$

where  $Re_b$  is the boundary Reynolds number,  $U_*$  is the shear velocity,  $d_s$  is the particle diameter,  $\nu$  is the fluid kinematic viscosity,  $g$  is the acceleration due to gravity,  $R$  is the hydraulic radius, and  $S$  is the streambed slope (or energy slope under uniform flow conditions). And

$$\theta_* = \frac{\tau_c}{(\gamma_s - \gamma) d_s} = \frac{\gamma R S}{(\gamma_s - \gamma) d_s} \quad (21)$$

where  $\theta_*$  is the Shields parameter or dimensionless shear stress,  $\tau_c$  is the critical shear stress at incipient motion,  $\gamma_s$  is the specific weight of the sediment, and  $\gamma$  is the specific weight of water.

In the Shields diagram, the boundary Reynolds number is plotted against the dimensionless shear stress to show the particle and flow conditions at incipient motion.

The Shields diagram may be used for different particle sizes when using a modification presented by Vanoni (1975). Therefore, the diagram could be used to develop different critical shear stresses for nonuniform sediments, a practice that is in fact common among engineers. Under hydraulically rough boundary conditions, the dimensionless shear stress reaches a constant value for uniform sediments. Shields used a value of 0.060. However, further work by Gessler (1971) indicates a dimensionless shear stress of 0.047 for nonuniform material. Using the concept of the Shields diagram and assuming a hydraulically rough boundary (valid for most gravel-bed river conditions), the expression for critical shear stress at incipient motion becomes

$$\tau_c = 0.047 (\gamma_s - \gamma) d_s = \gamma R S \quad (22)$$

where variables are as previously defined and the value of  $\theta$  is taken as 0.047.

Based on this formulation, a direct relationship between particle size and shear stress is predicted.

There are several deficiencies in the Shields diagram approach for dealing with nonuniform sediment mixtures. Assuming that the shear stress is based on a depth-slope product does not account for velocity profile distributions that vary greatly from the assumed log-linear relationship. Actual velocity profiles observed in some gravel-bed stream situations vary drastically from the assumed form. Also, local instantaneous turbulent effects are ignored, as are temporal and spatial fluctuations in shear stress.

We must give further notice to the definition of incipient motion. Incipient motion should be regarded as a probabilistic distribution for which  $x\%$  of the sediment particles are in a state of active transport. A Shields parameter of 0.047, according to Gessler (1971), corresponds to a 50% probability of movement in hydraulically rough turbulent flow. Several means have been used to define the beginning of particle motion (Buffington and Montgomery 1997):

- Visual observation—visual determination of the point of motion
- Reference transport—extrapolation of transport rates to zero or near-zero point (this is the Shields method)

- Competence functions—functions that relate shear stress to the largest mobile grain size from which one can establish the critical shear stress for a given size of interest
- Theoretical calculation—based on resolution of force balance as suggested earlier

Buffington and Montgomery (1997) note that considerable deviation exists among the four methods based on an examination of incipient motion data gathered to date:

- Under visual determinations, the rate that determines “transport” is highly subjective. A strict definition regarding the point of incipient motion is the point when one particle moves. Given that instantaneous fluctuations exist in natural channels or even laboratory flumes, this definition is inherently flawed. Standardized means of quantifying incipient motion for visual testing have been proposed, but they have not been widely accepted.
- Critical shear stress calculated with the reference transport rate is subject to the method of extrapolation.
- Competence functions are sensitive to the size and efficiency of the sediment trap, sampling size, sampling strategy, availability of coarse grain sizes, and curve fitting method. Furthermore, competence functions necessarily assume selective transport and not equal mobility. Therefore, they may not be applicable for all bed-size distributions.
- A theoretical model is sensitive to model parameters such as grain protrusion, packing, and friction angle.
- Because most gravel-bed rivers are armored, all conclusions regarding gravel-bed rivers should be based on the surface distribution and not the subsurface distribution.

Buffington and Montgomery (1997) gathered 613 critical shear stress values, but they selectively discarded data sets with poorly sorted bed material. They discarded these data sets to minimize the reworking of the bed under nonsteady-state conditions that could cause conflicting results. They also eliminated data with a small relative roughness (height of sediment protrusion:flow depth  $\leq 0.02$ ), to preclude flows with velocity profiles that vary drastically from the assumed log-linear relation, and data from studies using convergent-wall flumes. Based on the resulting data, a Shields parameter of 0.052 to 0.086 for reference-based transport and 0.030 to 0.073 for visually based transport was found. However, very few data are available for high boundary Reynolds numbers. The remaining scatter presumably can be attributed to:

- Grain sorting, packing, and particle shape differences
- Neglect of roughness elements such as side walls, form drag, and others
- Method of shear stress measurement
- Sampling technique used to characterize the grain-size distributions
- Differences in scale and duration of sediment transport

- Previously discussed considerations in defining the point of incipient motion

Buffington and Montgomery (1997) provide a thorough discussion of each element of scatter with suggestions for engineering applications. One recommendation of note regards the use of the definition for incipient motion. Visually based transport results may prove more useful when identifying the mobility of discrete particles; reference-based results may prove more accurate when used in a transport equation. Regardless of application, an appropriate value for  $\theta_c$  must be carefully chosen from an investigation with similar flow and sediment characteristics.

### **9.5.3. Use of Shields Diagram for Nonuniform Sediments**

The most serious limitation in using the Shields diagram is the requirement for a uniform sediment gradation. Gravel-bed rivers often have armor layers that are coarser than the underlying subbase or bedloads, yet they may have a portion of fines represented in the active beds. In the simplest case, an investigator could presumably apply the Shields diagram to individual particle sizes to determine the point at which each size fraction becomes mobile. However, larger grains act to shield the smaller grains from the fluid forces, thereby lessening their likelihood of becoming entrained and raising the critical shear stress for motion of the fines. On the other hand, smaller particles also affect the incipient motion condition for the larger particles by “lifting” the larger particles higher into the flow and reducing the interparticle friction angle. This lifting is not a physical lifting of larger particles by smaller particles, but rather an increased exposure because of the winnowing away of surrounding smaller particles. Therefore, larger particles may experience additional drag forces because of the greater exposed area and an increased tendency to roll over the finer material if unbalanced. Consequently, it is difficult to use a Shields diagram to assess the definition of incipient motion for bed material with a wide PSD because the diagram was based on uniform particle sizes in which hiding, sorting, and angles of repose do not vary widely.

Kuhnle (1993) conducted experiments on uniform and nonuniform sediments in a laboratory flume. Kuhnle used uniform sand with a  $d_{50}$  of 0.476 mm (0.019 inch) and a particle-size range of 0.177 to 2 mm (0.7 to 0.07 inch); he also used a uniform gravel with a  $d_{50}$  of 5.579 mm (0.22 inch) and a particle size range of 2 to 8 mm (0.07 to 0.31 inch). By mixing sand:gravel at 90:10, 75:25, and 55:45 ratios, nonuniform particle-size sediments were developed that showed uniform, skewed, and bimodal distributions. The uniform sediments were found to exhibit nearly constant critical shear stresses with the sand fractions moving at approximately  $0.25 \text{ N/m}^2$  and the gravel at  $3.5 \text{ N/m}^2$ . However, with nonuniform sediments, the critical shear stress for the sands *increased* to approximately 0.30, 0.35, and  $0.7 \text{ N/m}^2$  for 90%, 75%, and 55% sand, respectively. The critical shear stress for the gravels *decreased* to approximately 0.4 to 1.0, 0.6 to 1.0, and  $1.5 \text{ N/m}^2$  for 10%, 25%, and 45% gravel. The following conclusions may be drawn:

- Nonuniform sediments exhibit widely ranging critical shear stresses depending on the PSD.
- The critical shear stress for size ranges in nonuniform mixtures is not equal to the critical shear stress of the same size range in a uniform mixture.

- Under skewed distributions (i.e., 90:10 for sand:gravel), the critical shear stress will vary considerably from the smallest to largest particle sizes.
- Under bimodal distributions (i.e., 55:45 for sand:gravel), the critical shear stress will vary from the smallest to the largest particle size, but it will be in a closer range than in a skewed or normal distribution.
- As a general observation, the larger particle sizes dictate the shear stress for the entire bed (i.e., a low percentage of gravel tends to yield a lower critical shear stress for the sand fraction), whereas more gravel yields a higher critical shear stress for the sand fraction.
- The critical shear stress for the  $d_{50}$  for each sediment mixture was found to lie close to the Shields critical shear stress. Furthermore, using the critical shear stress for the  $d_{50}$  was accurate in predicting the initiation of motion for the sand fractions, but not for the gravel fractions.
- Sand fractions exhibit nearly a 1:1 relationship between critical shear stress and particle size when plotted on log-log paper. Gravel fractions have a slope of 0.24:1. These findings indicate that the sand fraction exhibits equal mobility, while the gravel fraction undergoes selective transport.
- A critical shear stress model developed by Wiberg and Smith (1987) can predict the trend, if not the actual values, for incipient motion of the size fractions in a nonuniform mixture. However, the Wiberg-Smith technique tends to underestimate shear stress increases with increasing sediment size for the gravel sizes when compared with data from Kuhnle's study.

Therefore, we conclude that the Shields criterion for incipient motion is not applicable for individual size fractions within a nonuniform sediment mixture. The ability of the Shields diagram to predict the point of incipient motion for the  $d_{50}$  size of the sediment mixture does offer reassurance to account for the variations found in sediment mixtures. If further modifications of the Shields diagram could be developed to account for the variations found in sediment mixtures, a Shields relation might prove useful for nonuniform mixtures.

As we mentioned earlier, Wiberg and Smith (1987) did develop a model that modified the existing Shields curve to account for some of the effects discussed earlier—primarily the influence of sorting and hiding of bed materials. After developing a theoretical model for describing sediment entrainment and comparing it with experimental laboratory data and the existing Shields diagram, we developed a graph that yields critical shear stress values for heterogeneous sediment mixtures. The dimensionless particle parameter,  $K_s$ , and relative particle size,  $d_i/k_s$ , where  $k_s$  is the bed roughness length assumed to be the  $d_{65}$ , are used in the relationship for dimensionless critical shear stress  $\tau_{c^*}$  with definitions as follows for the functional relationship:

$$\tau_{c^*} = \frac{\tau_c}{(\rho_s - \rho) g d_s} \quad (23)$$

where  $\rho_s$  is the sediment density and  $\rho$  is the fluid density. Other terms were previously defined.

And the dimensionless particle parameter,  $K_s$ , is given by

$$K_s = 0.0047 \left[ \frac{k_s^3 (\rho_s - \rho) g}{\nu^2 \rho} \right]^{1/3} \quad (24)$$

where  $k_s$  is the  $d_{65}$  size of the bed material and  $\nu$  is the kinematic viscosity of the water. Other terms were previously defined.

Figure 12 shows the relationship between these two parameters under varying values of bed roughness scale,  $D/k_s$ , where  $D$  is flow depth.

As seen in Figure 12, the incipient motion condition follows the same general pattern as the Shields curve. The exceptions are the multiple parallel lines for the bed roughness parameter  $D/k_s$ . The Shields diagram would indicate that, for high boundary Reynolds numbers, as the particle size increased, the dimensionless shear stress would remain constant at 0.060 for uniform particles or at 0.047 for mixed sediment sizes. From the Wiberg and Smith model, for an increase in particle size for the hydraulically rough boundary condition with the bed roughness parameter  $D/k_s$  varying from, for example, 1.0 to 2.0, the dimensionless shear stress would be in the range of 0.060 to 0.030. Therefore, the dimensionless shear stress decreases by a factor of 2. Consequently, the range of critical shear stresses for the sediment mixture is very close; small increases in flow may considerably increase sediment entrainment because of the narrowing “band” of critical shear stress.

As a consequence of bed-particle interactions, fine materials tend to become less easily entrained, while larger particles become more easily entrained. Two possibilities exist:

1. The fine material may not be entrained until the larger particles have moved. In other words, once the larger particles move, the fine material is no longer hidden and is therefore available for transport. This condition may be assumed to be instantaneous once the larger particle has moved, such that the flow conditions will not change. Therefore, the shear stress that moved the larger particle would also move the smaller particle. Critical shear stresses for the range of particle sizes would then be nearly uniform, despite the bed-size distribution.
2. Interactions between coarse and fine materials of the bed—specifically the effects of hiding, protrusion, and weight differences—may balance each particle’s tendency to move, forcing a narrow band of flow conditions describing the point of incipient motion.

Therefore, equal mobility may be defined as a condition under which heterogeneous sediments exhibit equal or nearly equal critical shear stresses. Andrews and Parker (1987), Wiberg and Smith (1987), Ashworth and Ferguson (1989), Church and Wolcott (1991), and Kuhnle (1993), among others, report some level of equal mobility in data sets. Andrews and Parker (1987) also discuss a condition commonly referred to as near-equal mobility. This condition exhibits a

selective transport phenomenon under which the fines are slightly more likely to move than the coarse materials are.

Based on an evaluation of multiple data sets, Andrews (1983) found a critical shear stress relationship in the form of

$$\tau_{ci}^* = \tau_{c50}^* \left( \frac{d_i}{d_{50}} \right)^m \quad (25)$$

where  $\tau_{ci}^*$  is the dimensionless critical shear stress for the  $i$ th particle size in question,  $\tau_{c50}^*$  is the dimensionless critical shear stress for the  $d_{50}$  sediment particle size,  $m$  is an exponent to be discussed later, and  $d_i$  is the particle size in question.

The dimensionless critical shear stress is further defined as

$$\theta = \tau_{ci}^* = \frac{\tau_c}{(\gamma_s - \gamma) g d_i} \quad (26)$$

Combining equations 27 and 28 lets us visualize how increasing particle sizes affects the critical shear stress. Doing so results in the following:

$$\theta = \tau_{ci}^* = \frac{\tau_c}{(\gamma_s - \gamma) g d_i} = \tau_{c50}^* \left( \frac{d_i}{d_{50}} \right)^m \quad (27)$$

If we allow that  $\beta = -m$ , where  $m \leq 0$ , then any increase in  $d_i$  is negated by the relationship on the right side of equation 29. In other words, the critical shear stress for any particle size will be constant if  $m = -1.0$  or  $\beta = 1.0$ . Equal mobility may be defined, then, as that condition where  $m$  reaches a value of -1.0. The value of the exponent  $m$  and its divergence from unity indicate whether equal mobility occurs or to what degree selective transport occurs.

Kuhnle (1993) suggests that the value of the exponent  $m$  is very nearly equal to unity for particle sizes less than about 1.5 mm (0.06 inch), indicating equal mobility for the fine fraction. The value of the exponent is much less at particle sizes larger than 2 mm (0.07 inch), suggesting selective transport for the coarser materials. These results are consistent with the work of Church and Wolcott (1991), who found that fine fractions (fine and medium sand) move in approximately the same proportion as that found in a bed where no selective transport is evident.

Andrews (1983) proposed a constant value for  $\tau_{c50}^*$  of 0.0834 and a value for the exponent  $m$  of  $-0.872$ . Applicable values for  $d_i/d_{50}$  were 0.3 to 4.2 with a coefficient of determination  $r^2$  equal to 0.980. For values of  $d_i/d_{50}$  greater than 4.2,  $\tau_{ci}^*$  appears to reach a minimum value of 0.020. The value of the exponent  $m$  equal to  $-0.872$  indicates that the bed material will show some selective transport, but it will almost conform to equal mobility. This indication means that the initiation of motion condition for different particle sizes in heterogeneous streambed materials will not vary greatly with particle size.

Andrews and Parker (1987) studied the classic Oak Creek data set from Milhous (1973) to determine values for  $m$  and  $\tau_{c50}^*$ . Although using the subsurface bed material is counterintuitive

for incipient motion criteria, they found a good correlation in both the point of incipient motion and in gravel transport. Based on the subsurface data, they recommended values of the exponent  $m$  equal to -0.982 and  $\tau_{c50}^*$  equal to 0.0876. Based on the armored surface material, the resulting values were  $m$  of -0.9067 and  $\tau_{c50}^*$  of 0.0455. The inference here is that the surface material is often much coarser than the subsurface material and will exhibit different incipient motion characteristics (as well as different transport characteristics). For example, the surface material shows a higher level of selective transport based on values of  $m$  and also a lower dimensionless shear stress of similar magnitude to the results of Gessler (1971) and Buffington and Montgomery (1997).

Ashworth and Ferguson (1989) studied three high-energy streams in Scotland and Norway for entrainment characteristics. After averaging all the data for the three streams, they determined the values were  $m$  of -0.74 and  $\tau_{c50}^*$  of 0.089, values that indicate more selective transport and a wider range of incipient motion conditions over the range of particle sizes than those proposed by Andrews (1983).

#### 9.5.4. Procedure

Riverbed stability (as indicated by flow being either below (stable) or above (mobile) the flow required for incipient motion) was calculated at each model cross section on the Snake River from HCD to just above Lewiston for flows of 30,000, 39,670, and 100,000 cfs. We selected the flow of 30,000 cfs because it is approximately the hydraulic capacity of the HCD power plant. We selected the 39,670 cfs flow because it is the “bankfull” flow as estimated by the 1.5-year return interval. Finally, the 100,000 cfs flow is approximately the maximum recorded flow at the USGS gauge immediately below HCD.

There are a total of 738 cross sections in this reach, with 566 cross sections located above the confluence with the Salmon River and 172 cross sections below the confluence. It should be noted that each cross section has been located by a chainage and by RM. *Chainage* is the term used in the MIKE 11 model to define the length of the river with units in meters. In the Hells Canyon application of the MIKE 11 model, chainage begins at the HCD and increases in the downstream direction. This order is opposite to river miles, which increase in the upstream direction. For example, the chainage at RM 247.7 is 0.0 m, while the chainage at the Salmon River confluence (RM 188.2) is 96368.60 m. Also important, because chainage and river miles are not based on exactly the same river thalweg, accurately computing river mile from chainage or vice versa is impossible.

Shear stress values were computed for each cross section using MIKE 11. MIKE 11 is a 1-D hydraulic modeling program described in detail in Parkinson (2002). MIKE 11 uses the following equation to compute the shear stress at a cross section:

$$\tau_b = \gamma RS \quad (28)$$

where  $\tau_b$  is average bed shear stress in  $\text{N/m}^2$ ,  $\gamma$  is specific weight of water in  $\text{N/m}^3$ ,  $R$  is the hydraulic radius of the cross section in meters, and  $S$  is the slope of the energy grade line.

Table 5 shows an example of tabulated shear stress values as calculated by the MIKE 11 model.

The second step involved computing the dimensionless shear stress value for each cross section. Dimensionless shear stress ( $\theta_*$ ) is often referred to as the Shields parameter, as explained in Section 9.5.2. The equation used to compute dimensionless shear stress is

$$\theta_* = \frac{\tau_b}{(\gamma_s - \gamma)d_{84}} \quad (29)$$

where  $\theta_*$  is the dimensionless shear stress,  $\gamma_s$  is the specific weight of sediment in  $\text{N/m}^3$ , and other terms are as previously defined.

The  $d_{84}$  size of the bed material was based on the existing armor layer and acquired from the PSD data derived from the photographic sampling of the riverbed. To obtain the  $d_{84}$  particle size at each cross section, we used the PSD data nearest the cross section. Some cross sections were evenly spaced between two or more sample points. For these cases, the particle sizes may have been averaged between the points, based on professional judgment.

Table 6 displays an example of the calculated dimensionless shear stress ( $\theta_*$ ) for the various flows. These dimensionless shear stress values are compared with the Shields critical dimensionless shear stress values of 0.030 and 0.047. These values were selected as a reasonable range for the critical Shields parameter for armored bed materials that are nearly uniform in size distribution. If the calculated dimensionless shear stress value for a given flow condition and location is less than critical value, then the bed at that location is considered to be stable. If it is greater than critical value, then the bed at that location is initially considered to be mobile (i.e., the given flow conditions are competent to move the bed material).

Several conditions must be met for this analysis to be valid. These conditions include the flow depth being governed by a resistance relationship and the  $d_{84}$  particle size properly representing the bed-material size. Pool reaches were considered to be stable because the energy gradient in the pools would be less than indicated because of downstream control. Rapids were considered to be stable because the bed-material particle sizes in the rapids, though not sampled, were visually determined to be much larger than the particle sizes used to characterize the reach, based on the sampling of surface material. Therefore, the preliminary determination of stable or mobile bed was modified using channel classification to determine whether mobile locations were in pool or rapids areas where the previously mentioned assumptions are invalid. We used the river channel classification presented in Miller et al. (2003) to determine whether areas with a preliminary indication of mobile were actually pools or rapids. Pools or rapids with a preliminary classification of mobile were reclassified as stable.

### **9.5.5. Incipient Motion Analysis of Fall Chinook Spawning Sites**

IPC biologists modeled 17 spawning sites for fall chinook salmon in the Snake River below HCD (Groves and Chandler 2001). These spawning sites are scattered throughout the river, with 12 sites located above the Imnaha River, one site between the Imnaha and Salmon rivers, and the remaining 4 sites below the Grande Ronde River. The riverbed material was analyzed at each

spawning site to determine whether the flows experienced in this reach would mobilize the material. The theory, procedure, and equations used to analyze the movement of bed material are detailed in Section 9.4. In summary, bed material mobilizes when the shear stress exerted by the water is greater than the shear stress holding the material in place. To determine the shear stress at each spawning site, a slight modification of equation 30 was used. As it is, equation 30 uses the energy slope, specific weight of water, and hydraulic radius ( $R$ ) to calculate average shear stress. For the calculations of stability at specific spawning sites, the depth of the water over the spawning site was substituted for the hydraulic radius, resulting in a shear stress at a specific location in the channel section. To acquire the depth, the location of each spawning site was determined. The datum of the associated cross section of the river channel, mapped at these sites by IPC or the USFWS, was adjusted to the same elevation datum as the river model. Then the depth of water over the spawning site for the corresponding flow was determined using water surface elevations obtained from the MIKE 11 model. Energy slopes used in the shear stress calculations were also determined using the MIKE 11 model.

After the shear stress was computed, the dimensionless shear stress at each site was calculated using equation 31 and compared with a range of critical dimensionless shear stress values of 0.030 and 0.047. If the calculated dimensionless shear stress was less than the critical value, then the material was considered to be stable. The median particle size used in this analysis was obtained from data presented by Groves and Chandler (1999). This study reported that redd substrate sizes range from small gravel (0.6 cm–2.5 cm) to large cobble (15.1 cm–22.5 cm). Of the redds studied, more than 80% of the sites were dominated with substrate sizes that ranged from medium gravel (2.6 cm–5.0 cm) to small cobble (7.6 cm–15.0 cm), so median particle sizes ( $d_{50}$ ) would range from 5.0 cm to 7.5 cm for these redds. However, a few (5%) of the sites they observed were dominated with much smaller size substrate, with the smallest particle size distributions ranging from small gravel (0.6–2.5 cm) to medium gravel (2.6–5.0 cm), which would yield a median particle size ( $d_{50}$ ) of approximately 2.5 cm (1 inch). The most conservative approach possible was used and the smallest median particle sizes (2.5 cm and 5.0 cm) were applied in the calculations of incipient motion at all of the 17 sites. Results of this analysis are discussed in Section 10.

## 9.6. Transport Modeling for Tributaries

For sand-bed streams, where the range of particle sizes represented in the bed materials is fairly narrow, reasonable estimates of transport capacity may be obtained by applying the transport equations and using a single characteristic particle size, such as the  $d_{50}$  size. On the other hand, for gravel-bed streams, an estimate of transport capacity based on a single characteristic particle size rarely gives a correct estimate of transport capacity because the estimate does not normally account for the likelihood that some of the larger sizes may experience very little or no motion under certain flow conditions. This lack of motion of larger particles gives rise to the possibility of armor development. If armor develops on the surface of the streambed, very little bed material can be transported, even if the flow conditions are such that a capacity for transporting smaller sizes exists. Transport capacity for streams with coarse bed materials should always be based on a particle-size class rather than on a single characteristic size. By using this rule, it becomes apparent when some sizes are not transported and armor may begin to form. This occurrence causes the investigator to consider the possibility of armor development along with the likely

result of little or no actual transport, with transport limited to the quantities of materials supplied from sources other than from the bed materials.

Molinas (1998) concluded that a single fixed size, such as  $d_{35}$  or  $d_{50}$ , could not appropriately reflect the effects of bed-material size gradation on the transport of sediment mixtures. Many bed-material load formulas—such as those developed by Engelund and Hansen (1967), Ackers and White (1973), and Yang (1996)—are based on a single representative size of bed material. They may generate significant scatter when applied to nonuniform sediment mixtures. Considering the physical processes governing the transport of sediment mixtures, the geometric standard deviation,  $\sigma_g$ , which represents the range of particle sizes in the bed material, is a significant additional parameter. For the same flow condition and the same  $d_{50}$ , the sediment size in transport and the transport rate of sediment mixtures differ for different sediment-size gradations. For a given flow condition and median bed-material size, as the size gradation increases, the size of sediment in transport decreases, resulting in higher sediment transport rates. The effects of size gradation of sediment mixtures can be compensated for by a size gradation compensation factor. The compensation factor allows the investigator to obtain an equivalent representative diameter for computing the size of sediment in transport and improving the accuracy of the transport equations. Alternatively, the transport may be calculated for each size fraction. Total transport is then obtained by summing the transport in each size fraction weighted by the availability of each fraction in the bed materials. In modeling the transport in the Hells Canyon tributaries, we elected to use the alternative approach, namely calculation of transport for each size fraction and summing the total weighted values. This method not only helps investigators avoid the need to select a single representative size class and associated compensation factor, but it also allows them to determine when the bed is likely to mobilize and allow bed material to contribute to the sediment supply.

### **9.6.1. Equations for Transport of Gravel Beds**

A few equations, such as the bedload equation of Smart and Jaeggi (1983) or Smart (1984), have been developed specifically for gravel-bed stream conditions. Other equations, such as the Ackers and White (1973) equation, have modified forms suitable for limited application in cases of coarse streambed materials. The Meyer-Peter and Muller equation (1948) is often used in the case of coarse streambed materials because the original data set used in developing this transport equation included bed-material sizes in the gravel range. The bedload equation of Smart (1984) is basically a form of the Meyer-Peter and Muller equation with the incipient motion condition modified for high stream gradients. Each of these equations can be applied on a size-class basis. Yang's equation for gravel transport (1984) was developed specifically for application with coarse streambed materials. While this equation can be applied on a size-class basis, its practical use in doing so is cumbersome. Bathurst et al. (1987) suggest that a modified version of the Schoklitsch equation is well suited for predicting sediment transport in the gravel-bed stream environment, and it can be applied by size class.

The total load equation of Ackers and White (1973) has a modified form for application to coarse streambed materials. In the version recommended for coarse sediments, this form is

$$q_{st} = 0.025 \frac{qD}{d} \left[ \frac{F_{gr}}{0.17} - 1 \right]^{1.5} \quad (30)$$

where  $q_{st}$  is the total volumetric sediment discharge per unit width,  $D$  is the flow depth,  $d$  is the particle size (geometric mean for the size class),  $F_{gr}$  is a sediment mobility term given in the following form for coarse sediments:

$$F_{gr} = \frac{1}{\left[ gD \left( \frac{\rho_s}{\rho} - 1 \right) \right]^{1/2}} \left[ \frac{U}{\sqrt{32} \log \left( \frac{10d}{D} \right)} \right] \quad (31)$$

where  $U$  is the mean velocity,  $\rho_s$  is the particle density, and  $\rho$  is the fluid density.

This equation is one of the more reliable equations for application to coarse streambed sediments (Bathurst et al. 1987), but it should not be applied to flows with Froude numbers above about 0.85. This value may be typical of sediment-moving conditions in some gravel-bed streams, including many of the Hells Canyon tributaries. Note that the transport is zero if the value of  $F_{gr}$  is less than 0.17, a coefficient derived from incipient motion conditions.

The bedload equation of Meyer-Peter and Muller (1948) may be given in the form

$$q_{sb} = g \sqrt{g \left( \frac{\rho_s}{\rho} - 1 \right) d^3} \left[ \left( \frac{K_s}{K_r} \right)^{3/2} (\tau_* - \tau_{*c}) \right]^{3/2} \quad (32)$$

where  $q_{sb}$  is the volumetric bedload discharge per unit width,  $K_s/K_r$  is a correction factor for bedform roughness,  $\tau_*$  is the dimensionless shear stress, and  $\tau_{*c}$  is the critical Shields parameter or critical dimensionless shear stress. The parameter  $d$  is the geometric mean size for each size class for transport calculations by size class, or the mean particle size if transport calculations were based on a single representative size.

In the original form of the Meyer-Peter and Muller equation, the value of  $\tau_{*c}$  is given as 0.047, but in coarse-bed materials or high-gradient channels, this value may need to be adjusted. Smart (1984) showed that the original value underestimates transport rates at slopes steeper than 3%.

The bedload equation of Smart (1984) represents transport for gravel-bed streams as a shear stress excess in the form

$$q_{sb} = 4 \sqrt{g \left( \frac{\rho_s}{\rho} - 1 \right) d^3} \left[ \left( \frac{d_{90}}{d_{30}} \right)^{0.2} S^{0.6} \frac{U}{U_*} \tau_*^{0.5} (\tau_* - \tau_{*c}) \right] \quad (33)$$

where terms were previously defined and  $U_*$  is the shear velocity ( $U_* = (g R S)^{0.5}$ ).

Another form of the transport formula of Smart and Jaeggi (Smart and Jaeggi 1983, Smart 1984) is given as

$$q_{sb} = \frac{4}{(SG-1)} \left( \frac{d_{90}}{d_{30}} \right)^{0.2} q S^{0.6} (S - S_c) \quad (34)$$

where  $SG$  is the specific gravity of the sediment,  $q$  is the water discharge per unit of width,  $S_c$  is the channel slope for incipient motion conditions, and other terms were previously defined.

Still another form of the Smart and Jaeggi transport formula is expressed as

$$q_{sb} = \frac{4}{(SG-1)} \left( \frac{d_{90}}{d_{30}} \right)^{0.2} q S^{1.6} \left[ 1 - \frac{\theta_c (SG-1) d_m}{DS} \right] \quad (35)$$

where  $\theta_c$  is the critical Shields parameter,  $d_m$  is the mean grain size,  $D$  is the mean flow depth, and other terms were previously defined.

Smart's equation was developed on the basis of flume measurements with sediment sizes of up to 29 mm (1.14 inches) and slopes of up to 20%. It is basically a modified version of the Meyer-Peter and Muller equation designed for application on steep slopes. Whittaker (1987) suggests that the Smart and Jaeggi transport equation is appropriate for calculating transport in step-pool streams because it was developed for steep channels.

The bedload equation of Schoklitsch (1962) provides reasonable estimates of transport capacity in gravel-bed streams and presents the advantage that a flow depth is not required as a parameter in the equation (Bathurst et al. 1987). Flow depth is sometimes difficult to measure in streams with coarse bed materials, thereby making it difficult to apply transport equations that are based on shear stress excess. Lopes et al. (2001) evaluated seven different transport equations by comparing modeled results against measured results for 22 streams, including 10 streams in Idaho, over a range of sediment supply conditions. They concluded that, on the basis of the number of streams for which an equation performed well, the best equations were those of Schoklitsch and Bagnold. The basic form of the Schoklitsch transport equation is

$$q_{sb} = \frac{2.5}{\frac{\rho_s}{\rho}} S^2 (q - q_c) \quad (36)$$

where  $q$  is the unit discharge and  $q_c$  is the critical unit discharge at which bedload transport begins. Other terms were previously defined. The original expression for  $q_c$  is given as

$$q_c = 0.26 \left( \frac{\rho_s}{\rho} - 1 \right)^{\frac{5}{3}} \frac{d_{40}^{\frac{3}{2}}}{S^{\frac{7}{6}}} \quad (37)$$

A more satisfactory agreement with transport data for gravel-bed streams with uniform sizes is achieved with the empirical expression for  $q_c$  given as

$$q_c = 0.15 \frac{\sqrt{gd_{50}^3}}{S^{1.12}} \quad (38)$$

This expression applies essentially to uniform sediments for the range of slopes between 0.25 and 20%. For streams with nonuniform coarse sediments, the recommended calculation for  $q_c$  uses a coefficient of 0.21 instead of 0.15 and replaces the  $d_{50}$  size with  $d_{16}$ , where  $d_{16}$  is for the surface layer rather than for the underlying parent bed material. Note that when calculating the transport by size fraction using the Schoklitsch equation, the critical conditions predicted by the modified form of equation 38 (using a coefficient of 0.21 and  $d_{16}$ ) do not necessarily apply to all fractions of the sediment-size distribution where that distribution is wide. In other words, the equation predicts the conditions for initial movement of bedload, but this movement may consist of the smaller sizes while the larger sizes are still stationary. To predict the initiation of motion of each size fraction, equation 38 (as presented and not the modified form) should be applied separately to each size fraction, taking the size  $d$  as the geometric mean of the size class.

The discussed transport equations for streams with coarse bed materials were tested by Bathurst et al. (1987) for a range of slope conditions from 0.27% to 9% and for sediment mixtures with median sizes in the range between 3.3 and 43 mm (0.13 and 1.69 inches). Results of these tests indicate that the Schoklitsch equation produced results with the smallest mean errors and smallest root mean square errors, followed by Ackers-White, Meyer-Peter and Muller, and Smart, respectively. The Smart equation considerably overpredicted the sediment discharge because the value of the critical Shields parameter of 0.047 underestimates the shear stress at which transport begins under conditions of wide particle gradation. There was considerable scatter in the predictions by the Ackers-White and Meyer-Peter and Muller equations, affirming that these equations are not adapted to high-gradient stream conditions that are often found in streams with coarse bed materials. Performance of the Smart and Meyer-Peter and Muller equations can be considerably improved when the definition of incipient motion conditions is improved and an appropriate flow resistance relationship is used to determine the normal flow depth. Note that all of the above transport equations predict a maximum sediment discharge rather than a mean sediment discharge because of complexities related to sediment supply in the stream reach in question (Bathurst et al. 1987).

For modeling transport in the tributary streams flowing into Hells Canyon, we developed an additional transport equation by modifying the Meyer-Peter and Muller equation to use a critical dimensionless shear stress other than the 0.047 value originally indicated by Meyer-Peter and Muller (1948). We refer to this equation as the modified Meyer-Peter and Muller equation. Modifying the Meyer-Peter and Muller equation to reflect a different incipient motion condition is not an original idea; it was the concept behind the Smart and Jaeggi (Smart and Jaeggi 1983, Smart 1984) equation. We modified the Meyer-Peter and Muller transport equation by using the critical dimensionless shear stress as suggested by Andrews (1983), who proposed that the critical dimensionless shear stress for each particle-size class, be determined using the equation

$$\theta_{ci}^* = \tau_{c50} \left( \frac{d_i}{d_{50}} \right)^m \quad (39)$$

The Andrews (1983) method for adjusting the critical shear stress values was discussed earlier in this section.

Each of the four transport models described was applied to determine the transport capacity of the Snake River tributaries studied. Based on a comparison of the results and the recommendations of Bathurst et al. (1987) and Lopes et al. (2001), we reported values for sediment transport capacity based on the Schoklitsch equation (equations 36 and 38), which yielded values that were, for most discharges, between the values predicted by the other equations. Appendix E provides the capacities predicted by all four transport models. Results from the Schoklitsch model were used to determine the quantities of sediment contributed from the tributaries to the mainstem Snake River.

### **9.6.2. Special Considerations**

Several consistent features emerge from studies of sediment transport in steep mountain streams. First, sediment transport is derived from sediment supplied by a limited number of sites within a given catchment. Sources of sediment supplied to the stream channel include surface erosion of bare slopes, landslides, debris flows, and erosion of the channel bed and banks. For many mountain catchments at higher elevations, debris flows of glacial or other deposits that are activated by spring thaw constitute a major source of sediment. Often the major source of sediment in a mountain stream may be from a single contributing location within the catchment.

Second, because the input of sediment from the supply sites occurs at random intervals—depending on such factors as antecedent conditions, weather, and others—sediment transport in mountain streams typically varies both spatially and temporally. Sediment supplied to the channel may be moved quickly through the stream by a flood condition, or it may be stored within the channel until a flow occurs that is capable of moving it. This storage/transport interaction is modified at lower slopes (less than about 5%) where the bedload and armor layer interacts under high-frequency, low-intensity events. Milhous and Klingeman (1973) assert that, for these lower gradient streams, the armor layer is the most important single factor in limiting the availability of sediment and in controlling the relationship between stream flow and bedload transport. This interaction of the channel structure with the bedload transport process occurs much less frequently in step-pool channels because of the inherent stability of the step-pool structure.

Most sediment transport occurs over relatively short time periods. Hayward (1980) calculated that 90% of the sediment transport occurred in 1% of the total time. Bedload transport yield in step-pool streams is therefore regulated by supply and not controlled by bed and hydraulic variables reflected in most transport equations. This supply-limited transport condition is referred to by Hayward (1980) as a phase 1 condition, while the non-supply-limited condition is referred to as a phase 2 condition. Storage in the pools causes complex hystereses in the sediment transport process. On the other hand, if the armored surface in the channel is mobilized or if sediment is stored in the channel bed and readily available for transport, sediment discharge

increases rapidly to the transport capacity indicated by the transport equations in a phase 2 condition.

In light of these factors, considerable difficulties lie in the way of measuring or predicting sediment transport in steep mountain streams without extended periods of intensive sampling. Our estimates of sediment transport in the tributaries are based on field observations that indicated a lack of armoring in those reaches for which the transport modeling was applied. In our estimates of sediment transport, however, we allowed no transport until at least 85% of the bed material was mobilized. Furthermore, field investigations on several of the tributary streams by Miller et al. (2003) (UI and CH2M HILL, respectively, pers. comm., 2000) revealed that supplies of readily transportable sediments were available and stored on the streambed for a short time after the major transport event of 1997. These observations indicate that the tributaries are not likely to be supply limited.

## **9.7. Estimation of Sediment Supply to the Snake River**

IPC's preferred approach would have been to use an extended record of empirical data to estimate sediment supplies to the Snake River including the Hells Canyon Reach. However, given that this record does not exist, IPC opted to develop sediment supply estimates based on analyses using established principles of sediment transport. This conceptual approach is supported by Andrews who states that "In short, direct field measurement of sediment transport in streams with poorly sorted bed material and highly variable discharge is unlikely to be substantially better than established computational methods." (Andrews 2000).

Estimation of the sediment supply to the mainstem Snake River involves several steps. Each of these steps is discussed in separate sections below.

### **9.7.1. Development of Flow-Duration Curves for Tributaries**

Of all the tributaries to the Snake River within the study reach below HCD, only the Salmon, Imnaha, and Grande Ronde rivers have flow records. Pine Creek, Oregon, and the Wildhorse River, Idaho, are gauged, but both of these streams flow directly into the HCC. There is no record of any of the smaller tributaries below the HCC being gauged. Therefore, to get flows associated with the transport of sediment, we had to estimate the flow-duration curves for these tributaries. The USGS completed the development of regression equations for estimating flow durations on ungauged streams in Idaho in 2001 (Hortness and Berenbrock 2001). The flows estimated are daily average flows. Idaho was divided into eight regions for that study. All of the tributaries in the Hells Canyon reach of the Snake River fall into Region 4. The USGS study developed an equation to calculate the 20, 50, and 80% exceedance daily average flows for each month and the average annual daily average flow. For Region 4, the standard error of estimate ranged from -58 to 136%. The highest standard errors of estimate were in the low-flow months of July, August, and September and in the low-flow estimates (80% exceedance) of those months. During these months, it is unlikely that much sediment is transported in any event, so the errors in flows important to this study should be well under these values. Also, little sediment

is transported in the low flows. During the spring when sediment is more likely to be transported, the standard error of estimates were lower, ranging from -46 to 85%.

Using the same base data as the USGS used in its study, IPC developed flow estimates for the selected tributaries at the 20, 50, and 80% exceedance intervals for each month. A log curve was then fitted through each set of three points, and the equation of this log curve was used to develop a flow-duration curve for each month in 5% increments. Appendix F shows the data used in developing these flow-duration curves.

### **9.7.2. Transport Calculations for Tributaries and Application of Flow-Duration Curves to Estimate Annual Sediment Yield to Snake River**

We developed a flow-versus-sediment transport curve (transport-rating curve) for each tributary by calculating sediment transport at several different flows. The range of flows selected was based generally on a high flow equal to or greater than the 100-year flow and the low flow, at about the minimum flow to mobilize armor in the stream. This flow range was then divided into about 10 increments, with flows in the lower part of the range spaced closer together and flows in the higher part of the range spaced farther apart.

We calculated sediment transport by sediment size class. Size classes were determined by the sieve analysis with the size classes defined by the differences between each adjacent sieve size.

Sediment transport was only allowed when at least 85% of the bed material was mobilized based on that transport equation. In other words, if 15% or more of the bed material was immobile, the streambed was considered to be armored and therefore supply limited. Under these conditions, no significant transport would occur. See Sections 9.4. and 9.6. for more detailed discussions on the armoring and transport processes.

We calculated transport using a Mathcad<sup>®</sup> workbook for each of the selected transport equations. Appendix G includes a sample workbook for each of the selected transport equations.

Using the 5% increments of the flow-duration curve, we calculated a geometric mean flow for each flow increment and, using linear interpolation, we calculated the sediment transport rate associated with each flow. This incremental sediment transport rate was multiplied by its corresponding probability from the flow-duration curve, and these increments were summed to generate a sediment transport yield.

The flow-duration curves developed following the USGS methodology have a monthly basis. That is, there is a separate flow-duration curve for each month. The transport calculations give a daily average transport based on the given flow. Therefore, the average daily transport rate was multiplied by the number of days in the month to get a monthly sediment transport quantity. These quantities were then summed over the year to get the annual sediment transport quantity.

It should be noted that using daily average flow values instead of instantaneous or 15-min flow values underestimates the true flow values available to transport sediment. As an example, the 100-year flow value for Pine Creek from USGS (Kjelstrom et al. 1996) based on daily average flows is 1,940 cfs. The 100-year flow value for the same creek from the same source based on

instantaneous peak flow measurements is 10,400 cfs. The median flow values (2-year return interval) using the same comparison (daily average vs. instantaneous peak) are 159 cfs and 2,810 cfs, respectively. The result of this discrepancy is that flow estimates used in the transport calculations are almost certainly substantially lower than the true flows available to transport sediment.

### **9.7.3. Reference Values for Sediment Yield**

Sediment yield values from various literature sources were summarized and compared with calculated sediment yield values to confirm that the calculated values are consistent with other work. To be able to compare these literature values with our values, we converted all values to a per-acre basis. Table 7 shows these values from a variety of sources. The sources included textbooks; USGS and other agency reports; and preliminary, unpublished data. In general, these values showed that the calculated sediment yields for tributaries in Hells Canyon are on the high end of the range of published values. We would expect this result because the tributaries in Hells Canyon are smaller and steeper than the drainages represented by most published data.

### **9.7.4. Measured Quantities of Sediment Yield from Tributaries**

Measured data are limited on the transport of sediment in the tributaries. Samples of suspended sediments have been collected on various tributaries since 1998. In January 2001, sampling locations on the 17 tributaries were established. Bedload sampling on the tributaries also began during 1998 and continued through 2001. These tributaries were sampled regularly during the spring of 2001. Unfortunately, flows were low that spring, and very little bedload transport occurred from any of the tributaries in the study area. Many of the suspended sediment samples collected during low-flow periods returned results indicating concentrations below detectable limits.

## **9.8. Sediment Source Analysis of Bed Materials in the Snake River**

One of the questions regarding sediment supply and stability in Hells Canyon is where the sediment supply historically originated. Did it come primarily from upstream of the HCC, from downstream, or from a combination of the two? One of the ways to address these questions is to determine whether the character of the existing sediments in the canyon matches potential sources upstream and downstream of the HCC. Therefore, the bed-material samples collected in the Snake River were not only analyzed for PSD, but they were also analyzed to determine whether any conclusions could be reached regarding the source of these sediments. Results of this analysis are discussed in Section 10.4.4. (A complete report of this analysis is included as Appendix F in Miller et al. [2003].)

## 9.9. Changes in Sandbars Based on Analysis of Aerial Photographs

We used two methods of analyzing aerial photographs to evaluate changes in sandbars. One method was based on measuring the area of selected sandbars from photographs taken in different years. The other method was based on counting the number of sandbars visible in photographs taken in different years.

### 9.9.1. Area Method

Aerial photographs were geo-referenced for 10 sites along the Snake River in Hells Canyon for this analysis. These sites are located at RM 229.8 (Johnson Bar), RM 227.5 (Pine Bar), RM 222.35 (Salt Creek), RM 216.35 (Fish Trap), RM 208.25 (Lookout Creek), RM 204.25 (Fence Hole), RM 201.05 (Flying H), RM 196.75 (Dug Bar), RM 193.8 (Lower Zig Zag), and RM 193.4 (China Bar). Figure 5 shows their location within Hells Canyon. Aerial photographs were researched and selected that had sufficient spatial and temporal coverage at each site. The locations of the sites used in this analysis, along with the years of coverage are the same as those used in the sandbar count analysis.

Rectified aerial photographs were used to analyze surface areas of 10 major sandbars within Hells Canyon. The sandbar areas were digitized using ArcInfo™ software. ArcInfo is a GIS software that was developed and is maintained by the Environmental Systems Research Institute (ESRI®).

To rectify aerial photographs, IPC technicians first optically scanned aerial photographs from selected years to be used for sandbar assessments. These photographs were scanned at a resolution of 600 dots per inch (dpi). Where aerial photography film was available, direct scans were obtained from the film negatives at 28 microns or approximately 900 dpi.

Aerial photos inherently contain spatial distortions due to factors associated with camera angle, lens properties, and relief displacement. To minimize incorrect measurements of area, these distortions must be addressed in the rectification process. Although a tremendous amount of relief is found in each photo, relief was less critical since the bars are generally flat relative to the surrounding topography. A digital elevation model is normally required to ortho-rectify aerial photos to minimize relief distortions. Because of the nominal relief at the bars and water's edge, the need for ortho-rectification was avoided by focusing our rectification to a specific site within a photo. Images were selected that were centered nearest the site. This helps reduce camera angle distortions found toward the edges of the photos.

High resolution scans of the photos were imported into ArcGIS software where common ground control points were used to warp the images to fit real world coordinates. GPS coordinates were collected for each corresponding ground feature. Control points were selected near the study sites to minimize the field collection effort of the GPS coordinates. We selected points such as rock outcrops, trails, roads, buildings, and geomorphic features along the riverbank. Other GPS data of historic trail systems and disturbed areas also contributed accurate control for the rectification process. High resolution scans of the photographs and GPS data were imported into the ArcGIS

software where the images were rectified using a first order polynomial transformation. Root Mean Square (RMS) errors were closely monitored and recorded during the image rectification to make certain that the images are all georeferenced with acceptable spatial errors.

The available media of the aerial photos varied from positives, negatives, prints, to scans of positives, negatives, and prints. The individual image quality of the photographs of each year varied based on the available media. As photography technology improved over the years so did the quality of the aerial photography. Because of the media quality, shadows, vegetation, and scale of the photographs, we had difficulty distinguishing the precise boundaries of each sandbar. It was determined that the approach of digitized surface area was too subjective to calculate 'exact' sand bar surface area with an adequate level of confidence. The study used the digitized areas to assist in analysis of noticeable changes in sandbar surface shape and area.

In an effort to standardize the delineation of sandbar areas, criteria were developed to minimize subjectivity. Areas were delineated based on: areas of visible contiguous sand, detached bar areas were included, and did not include gray areas, which were considered to be either vegetation or gravel deposits (not parts of sandbars). For example, as illustrated by Figure 13, the area delineated at Johnson Bar varied with time. Questions arise regarding why there is a variation in the delineation of bar edges. Is this a result of the bar boundaries changing, or differences in vegetation cover (resulting from growing conditions, removal of vegetation by human activities, cattle/sheep grazing, camping, etc.), time of year of the photo, or errors associated with photo rectification. At the scale of the available photographs, the surface materials at the sites other than large cobbles or boulders were indistinguishable. With limited ability to distinguish between surface materials, the delineation between upland areas and sandbars was difficult to define.

Another source of error is the variation in water levels between photographs. To address this, the length of water's edge was used to adjust the surface area. To make this adjustment, we used the slope of the submerged portion of the sandbar to estimate the horizontal variation of the water's edge for a vertical change in water surface elevation. The average slope angle used was 9.13 degrees. The average slope angle was based on survey data collected at Pine Bar, Salt Creek, Fish Trap, and China in 1998 and 2000. The slope angles ranged from 7.7 to 10.4 degrees. Values for the change in water surface elevation (from the MIKE 11 model), length of water's edge along the sandbar, and average slope angle were all used to determine the adjusted sandbar surface area. The equation for this procedure is

$$A_T = \left( \frac{\Delta WSE}{\tan(\theta)} \right) L + A_o \quad (40)$$

Where  $A_T$  is the total adjusted area,  $\Delta WSE$  is change in water surface elevation computed from MIKE 11 model,  $\theta$  is the average angle,  $L$  is the length of the sandbar along the water's edge, and  $A_o$  is the original scaled sandbar area.

If the water surface is higher than the reference surface (i.e.,  $\Delta WSE$  is a positive value), then the visible area of sand shrinks. This difference must be added to allow comparison with the reference water surface. Likewise, if the water surface is lower than the reference water surface

(i.e.,  $\Delta WSE$  is a negative value), then the opposite is true and the difference is subtracted. All sandbars surface areas were adjusted and compared to common flow equal to 11,000 cfs. The adjusted sandbar surface areas were used to compare how the sandbars might have changed over the period of aerial photograph records that we have for each site.

### **9.9.2. Sandbar Count**

Ideally, a complete series of aerial photographs spanning a period of several years prior to the construction of the HCC, would be used to establish pre-HCC conditions in Hells Canyon. Without two or more complete series of photographs to determine pre-construction trends, it is impossible to define changes caused by disturbances within Hells Canyon or the upstream watershed. The only pre-HCC complete series IPC was able to locate was 1955. Partial coverage of small reaches in Hells Canyon was found (1946). This lack of coverage, prior to the construction and operation of the HCC, makes it difficult to differentiate between changes to sandbars caused by disturbances within Hells Canyon, the upstream watershed, or the construction of the HCC.

A pre-dam sandbar count analysis was conducted for the Snake River in Hells Canyon. This analysis contained aerial photographs from 1946 and 1955, and covered two segments of the Snake River (1) from RM 190.6 to 199.0 and (2) from RM 201.5 to 205.6 because full coverage of the river before 1955 is not available.

A more comprehensive analysis was also conducted, and it included aerial photographs that covered the entire river reach (HCD to Salmon River) for the following years: 1955, 1964, 1973, 1977, 1982, and 1997. The 1955 and 1964 photographs were obtained from the USDA APFO. The 1973, 1977, and 1982 aerial photograph flights were obtained from the USACE. The 1997 photographs are available at IPC. The 1973 photographs consisted of four flights that occurred on four subsequent days, each representing a different flow (5,000 cfs, 7,700 cfs, 12,000 cfs, and 18,000 cfs). Table 2 contains the dates, scales, and coverage of the flights used in the pre-dam and post-dam sandbar count analysis.

The post-dam analysis consisted of counting all sandbars that occurred within the study reach for each series of aerial photograph flights. These separate counts allowed for the comparison of sandbar frequency totals between each aerial photograph flight. They also leave open the possibility of sandbars shifting position along the river, as well as the formation of new bars. Previous researchers (Grams and Schmidt 1991) conducted a similar study, however, they used the 1964 aerial photographs as a baseline for their sandbar counts. They counted each visible sandbar in the 1964 series of photographs, and only checked these same locations during subsequent years. If the sandbars were still at the original river mile (as identified in 1964) then they were counted; if a sandbar was not identifiable at the original river mile then it was not counted. Grams and Schmidt's methodology essentially eliminates any potential for an increase in the number of bars and shows any shifting in location of a sandbar as absolute loss; therefore, this methodology appears to bias the results toward a net loss of sandbars.

It is important to explain the criteria and methods used in the sandbar frequency study to accurately reproduce the results. The criteria and methods used for this study are as follows:

- Scanned images were used for the sandbar counts because they provided a higher quality picture than the paper prints. Scanned images also allow the viewer more zooming options to help with the identification of sandbars.
- Sandbar counts began at Hells Canyon Dam (RM 247.6) and ended at the Salmon River Confluence (RM 188.28).
- The same river mile map was used for each photograph series to help maintain numbering consistency.
- Sandbars were counted and labeled to at least the nearest one-tenth (0.1) of a river mile.
- Any sandbar that extended to the river's edge or was a large deposit of sand occurring just off of the river's edge was counted.
- If a sandbar was completely submerged, then it was not counted for that specific year. However, it was noted that the bar was submerged to help identify a reason why it did not show up in subsequent counts.
- If a sandbar occurred in the middle of the river, then it was recorded as an Idaho bar (river right) and noted that it occurred in the middle of the river.
- Sandbar counts were adjusted for flow effects by using the 1973 series of photographs (photographs taken on four consecutive days at various flows) to estimate the change in sandbar counts based solely on flow and applying this change (pro-rated for flow) to counts taken in other years to adjust all counts to 12,000 cfs. IPC analyzed three of the four flows available in 1973 (5,000 cfs, 12,000 cfs, and 18,000 cfs), and used the difference in sandbar counts to establish the 12,000 cfs adjusted sandbar total line that is seen in Figure 14. The analysis of the 1973 photographs shows that 31 bars were covered by water between 5,000 cfs and 12,000, and that 18 more bars are covered by water between 12,000 cfs and 18,000 cfs. This 49 bar difference was extrapolated over the 13,000 cfs change (5,000 cfs to 18,000 cfs), which lead to 3.77 bars being covered up for every 1,000 cfs flow change (three bars per 1,000 cfs was used for the adjustments to be conservative). This value was then applied to each year to create the adjusted line in Figure 14.
- To develop sandbar counts on a reach basis rather than including the total reach, a similar methodology was used in 5-mile increments to adjust sandbar counts to the 12,000 cfs flow. The difference was that fractional bar numbers were allowed in adjusting bar counts and a separate adjustment factor was calculated for each 5-mile segment and for positive and negative flow changes. Note that because this adjustment introduces fractional values for the number of bars, rounding off can cause the total number of bars in a reach to be different than the summation of the rounded off number of bars.

The results of this analysis differ from the results obtained by previous researchers (Grams and Schmidt 1991, 1999a) primarily because of two reasons, [1) IPC used a methodology that allows bars to be included independent of whether they are evident in the 1964 series of photographs and 2) IPC evaluated changes relative to pre-HCC conditions (1955) rather than 1964 because it is probably more representative of pre-HCC conditions than 1964.]

## 9.10. Reservoir Trapping Efficiency

Reservoirs and diversions impound water and reduce the flow velocity through the water body. This reduction in flow velocity means that some of the material that is being transported by the flow is deposited in the reservoir. This trapping effect is primarily a function of the size of the reservoir in relation to the flow into or out of the reservoir. We used two methods to estimate reservoir trapping efficiency: Churchill and Brune (Morris and Fan 1997).

The Churchill method involves estimating the sedimentation index of the reservoir that is described as the period of retention divided by the mean velocity. Either the average inflow or outlet capacity can be used to evaluate these terms. Using the sedimentation index, a plot is entered and provides a number representing the percentage of sediment passing through the reservoir. This number subtracted from 100 is the percentage of material trapped in the reservoir.

The Brune method is similar in that the graph is entered based on an inflow ratio and the trapping efficiency is read off the other axis. Brune's method shows an envelope of values based on the size of the suspended material, ranging from colloidal, dispersed fine-grained sediment to highly flocculated and coarse sediment. We used the median curve.

# 10. RESULTS AND CONCLUSIONS

This section summarizes the results of the different analyses and presents relevant conclusions based on these results. The results specific to sandbars, mainstem bed stability, bank stability, and sediment supply to the mainstem are each discussed in their own sections. Finally, the proposed operating scenarios and effects associated with these scenarios are discussed.

Each of the sections presents a summary of the findings and important points associated with the sediment investigation. Additional discussion, detail, and specific results follow in each section. It is not the purpose of this section to include interpretations regarding specific aquatic, terrestrial, recreational, cultural, or aesthetic resources that may depend on or be affected by sediment-related processes.

## 10.1. Sandbars and Terraces

We used two approaches to quantify changes in sandbars:

- Physically surveying selected sandbars

- Counting the total number of sandbars identifiable on aerial photographs within a selected reach of river

Additional information using surface area measurements from aerial photographs and distance measurements using aerial photographs were used primarily to reinforce the quantitative results from the sandbar count and physical survey methods. This section discusses the results of each of these methods.

### **10.1.1. Sandbar Material**

#### **10.1.1.1. Sandbar Material Particle Size**

We collected bulk material samples from both the depositional area of the sandbars and adjacent cutbank areas. PSD data from the sandbar cores is presented in Appendix F in Miller et al. (2003).

PSD data are available on the same four sandbars that we monitored by surveying: Pine Bar at RM 227.5, Salt Creek Bar at RM 222.4, Fish Trap Bar at RM 216.4, and China Bar at RM 192.3. Figures 15 through 18 show particle-size data for these four sandbars. Because the #200 sieve (0.074 mm [0.003 inch]) is slightly larger than the break between very fine sand and silt (0.062 mm [0.002 inch]), particle sizes smaller than the #200 sieve were not analyzed. Even using this slightly larger size as the break point, 7% or less of any of the sandbar material is smaller than sand sizes. This finding indicates that, for the sandbar areas to be maintained, the sediment supply has to have significant material in the sand-size range.

Figure 19 compares the material found in Brownlee Reservoir with the material found in the sandbars in Hells Canyon. This figure shows that almost none of the material trapped in Brownlee Reservoir is in the size ranges necessary to maintain the sandbars.

The data shown in this figure have been normalized so that the percentages shown are percentages of sand sizes only, not percentages of the total sample. For example, the Brownlee Reservoir sediments are about 86% silt/clay sizes. In Figure 20, the silt/clay sizes are not considered and all sand classes are increased proportionally so that they add up to 100%. This figure shows that on average the sand materials in the sandbars in Hells Canyon are coarser than the sand size sediments trapped in Brownlee Reservoir. Twenty seven percent of Brownlee Reservoir sand sizes are in the very fine sand (<0.125 mm [0.005 inch]) class while the sandbars have only about 8% in this size class. The bulk of sandbar sands (about 65%) fall into the medium and coarse sand class (0.25 to 1.0 mm [0.01 to 0.04 inch]) while only 25% of the sand sizes in Brownlee Reservoir are in this class.

Figure 21 shows the full range of sediments sampled in Brownlee Reservoir. Samples taken from sandbars in Hells Canyon show a very different PSD with a wide range of sand sizes that are better characterized as medium and coarse sands. Since the sandbars are not made up of material similar in size to the material trapped in Brownlee Reservoir, IPC concludes that the sediments trapped by Brownlee Reservoir would not have prevented erosion of the bars.

A reasonable question that arises in examining the data associated with the sandbars is: Have the particle size characteristics of the sandbars changed over time as sediments have been trapped by upstream projects? Particularly given that the sediments trapped in Brownlee Reservoir are largely in the fine and very fine sand size classes, is the surface texture of the bars coarser than would otherwise be the case? Given that there are no data on PSD of the sandbars from before the HCC (or other upstream projects) was constructed, the most reasonable way to answer this question is by looking at the sandbar PSD with depth. Since it is unlikely that the sandbars have been completely eroded and re-worked to their full depth since construction of the HCC, one would expect to find a difference in PSD near the surface of the bars compared with the sub-surface if sediment trapping upstream is modifying the PSD of the sandbars. This difference should show up more strongly the deeper the sample. The cores taken during the provenance sampling allow evaluation of this hypothesis. Figures 22 through 28 show the PSD by size class with depth at Fish Trap and Pine Bars. With the possible exception of P2, none of these cores show the expected trend of fining with depth. Although there is some variation between cores, particle sizes are all relatively consistent with depth. None of them (with the possible exception of P1) show any resemblance to the distribution of sands in Brownlee Reservoir. P2 does show more coarse material (>1 mm [0.04 inch]) toward the surface of the bar but the percentage of finer material (<0.25 mm [0.01 inch]) remains relatively constant. That is, the coarse sand size class appears to be partially replaced by even coarser material in the 1- or 2-foot surface of the sandbar. Visual observations of the eddy bar from which P2 was collected indicate that more gravel-sized materials were present at the surface of the bar following the 1997 and 1998 floods. Tables 8 and 9 show numerical values of PSD for core samples taken at Fish Trap Bar and Pine Bar respectively. Figures 29 and 30 show the locations of the core samples taken at each bar.

P1 appears to be something of an anomaly with noticeably finer sediments than the other cores. This finer material is not limited to a single layer or just the surface. In fact, at about 5 feet and lower, the material appears to be finer than the upper layers but given that the bar was likely deposited more than 2,000 years ago (see Miller et al. [2003]), this is unlikely to be an artifact of anthropogenic effects in the last 100 or 200 years.

#### **10.1.1.2. Sandbar Material Provenance**

This section summarizes results that are presented more completely in Miller et al. (2003).

IPC used X-Ray Diffraction (XRD) and PSD information to address an essential question: If the sediments trapped within the HCC (both from upstream sources and from within the reservoir reach itself) previously contributed to the sandbars in Hells Canyon, what changes in the sandbars would we expect to see as a result of the construction of the HCC? Fundamentally, if the sediments traveling through the HCC reach before impoundment were a significant component of the sandbars in Hells Canyon, the trapping of these sediments should result in a different mineralogical composition and grain-size distribution of the sandbars at depth. In other words, if the sandbar materials were comprised originally of predominantly upstream sources (vs. sources from the local tributaries or hillslopes), then the cutoff of this material by the HCC should result in a surface layer from local sources that have a distinctly different mineralogical composition. Similarly, if the sandbar materials were composed originally of predominantly upstream sources, then after the cutoff of finer material (found in HCC) the fine materials

remaining in the sandbars would be “winnowed” away and the current surface material in the sandbars would be coarser than at depth.

The results of the sediment analysis indicate that neither of these cases exists. From a mineralogical perspective, sediments within each individual sandbar are similar in composition throughout the vertical profile (there is minor variability between sandbars discussed in more detail below). Although XRD is a semi-quantitative method with a laboratory precision of about 2 to 3%, the averages of the three indicator minerals (quartz, plagioclase, and potash feldspar) are similar for each of the bars. Thus, the mineralogical signature of surface materials is similar to the mineralogical signature of subsurface materials at these bars.

Thus, the sandbars are very consistent in mineralogical composition in addition to grain size and the expected responses to upstream sediment entrapment by the HCC do not appear to be evident.

Other research has shown that sandbar formation in bedrock canyons is often driven by rare catastrophic floods (Schmidt and Rubin, 1995). The XRD and grain size data together suggest that the original bars (including terrace areas) in Hells Canyon were probably deposited during either a single event or several events under hydrologically similar conditions. Based on archaeological dating of artifacts found in Tin Shed sediments, this bar is believed to be more than 2,500 years old. Because of the similarity in mineralogy and grain sizes between the three bars, Pine Bar and Fish Trap are likely as old as Tin Shed. The mineralogical signature of all three sandbars indicates upstream sediment (vs. sources from the local tributaries or hillslopes) contributed between 50% (Pine Bar) and 85% (Tin Shed Bar) of the original bar materials. This suggests that, unlike coarser bed materials within Hells Canyon, local sources of sediment do not appear to have contributed as much to the finer-grained sandbars as previously thought from visual estimates of mineralogical signatures. Stated another way, local sources only contributed between 15 and 50% of fine-grained sediments in the original depositional environment of these ancient sandbars. Since the sandbars were originally deposited, these fine-grained sediments undoubtedly have been reworked through aggradation and erosion.

As an example within Hells Canyon, a core collected from an active area of Pine Bar indicates a similar mineral composition to that of nearby fine-grained subsurface bed materials (both with upstream mineralogical signatures). This suggests that upstream materials were deposited under pre-impoundment conditions downstream of HCD. These materials were probably stored either in the channel bed or upstream sandbars and are still in transit at least as high as Pine Bar (RM 227). Of even more importance, the grain sizes from the core representing the active portion of Pine Bar are coarser-grained than those currently being deposited in Brownlee Reservoir. This appears to be another piece of evidence suggesting that these active bar sediments originally entered Hells Canyon from upstream before the regulation of the upper tributaries (e.g., Boise and Payette).

Because the upstream sediment appears to have a large influence on the sandbars, it is important to understand the relative effects of the HCC in cutting off these sediments. From a mineralogical perspective, sediments from the upstream Snake River Basin are distinct from local sediments within Hells Canyon based on their respective quartz, plagioclase, and potash feldspar (k-spar) composition. K-spar is essentially limited to the rocks of the Idaho Batholith

and provides a unique chemical signature in the fine-grained bed sediments in the Boise and Payette Rivers (the two tributaries with the largest input, in terms of discharge, to the mainstem upstream of Brownlee Reservoir). Because the Boise and Payette watersheds both have regulation projects that cut off their sediment-producing headwater areas (primarily Idaho Batholith sediments), the downstream Idaho Batholith sediment signature represents either sediment loads that reached the mainstem Snake River prior to these regulation projects, or sediments deposited downstream of the tributary reservoirs that are still in transit. Based on their mineralogical signatures, the sediments found in Brownlee Reservoir appear to be mainly from the upper mainstem channel (70%), with a relatively smaller contribution of upper tributary sediments (e.g., from the Boise and Payette and Weiser; 30%). These results are consistent with the conclusion that over 87% of the sediment-producing upper watershed, including the upper tributary basins, was cut off from the mainstem Snake River above Brownlee Reservoir prior to the construction of the HCC.

To summarize, the XRD and grain size data suggest that sandbars in Hells Canyon were formed primarily from upstream materials that were deposited within the canyon more than 2,500 years ago. Since the original depositional event(s), the watershed has not experienced flood conditions that have changed the original depositional signature. XRD analysis suggests that the Idaho Batholith was an important source of material for the original sandbars formed in Hells Canyon. This source was cut off by water storage projects prior to and upstream of the HCC. While the HCC has cut off supplies of sediment from Hells Canyon, grain-size data suggest that Brownlee Reservoir has not trapped sediments in the size range necessary to maintain sandbars in the condition observed prior to construction of the HCC.

### **10.1.2. Sandbar Monitoring**

#### **10.1.2.1. Background**

IPC surveyed four sandbars on the Snake River in Hells Canyon to evaluate the changes in size and shape of the bars. We also conducted transect surveys in 1998 and 2000 to monitor each of the bars. In addition to the monitoring data, there are limited amounts of survey data available for 1997 and 1999. The 1997 surveys were skeleton surveys that covered the major features of each bar. In 1999, IPC conducted additional surveys on Pine Bar and Fish Trap Bar to help collect topographical 2-D modeling data. The additional surveys were included with the monitoring data when appropriate.

#### **10.1.2.2. Hydrology**

Before monitoring of the four bars, the Snake River in Hells Canyon experienced both the highest and second-highest peak discharges on record for the USGS Hells Canyon gauge (13290450). In 1997, the daily average peak flow was the highest on record at 98,000 cfs (15-min peak was 103,000 cfs). During the spring of 1998, the Snake River at HCD experienced the second-highest daily average flow on USGS record at 93,400 cfs. Following the peak discharge of 93,400 cfs, the recession limb of the hydrograph stayed above the hydraulic capacity of HCD (30,000 cfs) for 25 days. The average discharge during this period was 51,476 cfs. Also, during the springs of 1997 and 1998, several of the Hells Canyon tributaries experienced “blow outs” (high sediment loads as demonstrated by large new deposits on the

fans). Several of these tributaries are located upstream of all of the major sandbars. For additional information on the historical and current hydrology, see Parkinson (2002).

### 10.1.2.3. General

Figures used to show the results of the sandbar monitoring include a plan view of each bar showing the location of the surveyed transects, a cross section of the bar at selected transects, and the approximate water surface elevation for several different flows at each sandbar location. The water levels were generated based on MIKE 11 model runs. The MIKE 11 model setup and calibration is described in Parkinson (2002). The flows shown on the cross sections include 12,000, 22,000, 30,000, and 98,000 cfs. The discharges of 12,000 and 22,000 cfs fall near the middle of the range of normal flow fluctuations. The 30,000 cfs is approximately the hydraulic capacity of the power plant at HCD. Flows are held to less than 30,000 cfs as much as possible because flows above plant capacity do not generate any electricity. The 98,000 cfs is the highest average daily flow recorded at the gauging station downstream of HCD (Snake River at HCD, ID-OR 13290450).

#### *Pine Bar*

Pine Bar is located on the Idaho side of the Snake River at RM 227.5. Figure 31 shows a plan view of Pine Bar and the location of transects. The bar is protected by a bedrock outcrop on the upstream end, with the downstream end fading into a debris fan. The east side of the bar (bank side) is composed of a landslide that transitions into the high sand terrace. Two house-size rocks (bedrock outcrops) that are approximately 20 by 14 m (66 by 46 ft) and 14 by 8 m (46 by 26 ft) in size are located in the center of the river channel approximately across from the bar. At least 3 m (11 ft) of the largest rock is exposed under normal operational flows. This pair of rocks strongly influences flow patterns in this reach of the river.

IPC survey data for Pine Bar are available for the following dates: November 17, 1997; November 3, 1998; November 9, 1999; and December 5, 2000. The data collected in 1997 and 1999 provide general information about the shape and size of the banks and bar, but the transect lines do not exactly match the transect lines from the other surveys. Survey data from the 4 years demonstrate that Pine Bar experienced almost 0.46 m (1.5 ft) of deposition in 1998. This period of accretion on the bar included the peak flow of record and the sustained high flows in the spring of 1998.

There was some localized erosion on the upstream end of the bank and bar ranging from 10 to 46 cm (0.33 to 1.50 ft) between 1998 and 2000. Other than the localized site of erosion, the bank and bar has not changed substantially between 1998 and 2000. Figures 32 through 35 show Pine Bar survey data for 1998 and 2000. These figures show changes at Transects A through D, respectively (labeled from upstream to downstream) between 1998 and 2000.

As seen in Transect B in 1998, there was not a well-defined channel between the bar and the bank on the upstream end. In 2000, survey data show a much more defined channel. The survey data at Transect C indicate that the bank and bar in this section were stable through 1998, 1999, and 2000. Data at Transects C and D show some variation in bar shape, but no distinct trend. Visual observations of the bar material on the high point of the bar (around Transect D) indicate some coarsening on the surface of the bar between 1998 and 2000.

### ***Salt Creek Bar***

Salt Creek Bar is located at RM 222.4 on the Oregon side of the Snake River. Figure 36 shows a plan view of the bar. Debris fans bound the bar at the upstream and downstream sides. A high, sandy terrace forms the bank and the western boundary, and the river forms the east boundary. Based on visual observation, surface particle sizes range from fine sand to gravel. Vegetation, consisting of grasses and groupings of mature hackberry trees, covers the terrace around the bar, as seen in Figure 37. Grasses and other vegetation are also located on some sections of the bar.

Our survey data for Salt Creek Bar are available for the following dates: November 19, 1997; November 5, 1998; and December 5, 2000. The 1997 survey data did not coincide with the long-term monitoring transects. Therefore, we did not use them in this analysis. Three transects are located at Salt Creek Bar: Transect A (Figure 38) represents the upstream end, Transect B (Figure 39) represents the upper third of the bar, and Transect C (Figure 40) represents the middle and lower sections of the bar. All transect data demonstrate that most of the bar did not change noticeably between the 1998 and 2000 surveys. There were minor areas of erosion near the 12,000-cfs water surface elevation and near the top of the cutbank (above the 30,000-cfs water surface elevation).

### ***Fish Trap***

Fish Trap Bar is located at RM 216.4 on the Oregon side of the Snake River. Figures 41 through 45 show a plan view of the bar, transect locations, and areas of change (deposition or erosion). Debris fans bound Fish Trap Bar both upstream and downstream, forming the north and south boundaries. The west and east boundaries are, respectively, a high, sandy terrace and the Snake River.

Our survey data for Fish Trap Bar are available for the following dates: November 20, 1997; November 4, 1998; November 11, 1999; and December 4, 2000. Between 1997 and 2000, Fish Trap Bar experienced substantial change, both in deposition and erosion. The changes in the bar are illustrated in Figures 42 through 45, which show Transects A through D, respectively (labeled from upstream to downstream) between 1997 and 2000.

The 1997 and 1998 surveys indicate that, in general, the bar had more deposition than erosion. The majority of the bank and bar had not experienced noticeable deposition. However, there was considerable deposition along the bar's crest, as illustrated by Figure 41. There had been some local erosion on the river side of the bar.

Between the 1998 and 1999 surveys, the bar's crest decreased in elevation, and the width of the bar increased. The decrease in elevation appears to be somewhat offset by the increase in the width of the bar. As a result of this erosion, the elevation of the crest in 1999 is near the water surface elevation resulting from 30,000-cfs discharge out of HCD. The area of erosion and deposition between the 1998 and 1999 surveys is illustrated in Figure 41.

Results of the 1999 and 2000 surveys demonstrate that erosion occurred on the front of the bar. The rest of the bar and bank did not appear to experience substantial changes between 1999 and 2000. In addition to the analysis done of the cross section profiles and GIS grid layers, we analyzed the cutbank stability using 1999 and 2000 data and EagleImage™ (high-resolution

digital georeferenced and orthorectified) images. The 1999 and 2000 images demonstrate that the position of the top of the cutbank had not changed substantially (in plan view) between the 1999 and 2000 surveys.

### ***China Bar***

China Bar is located at RM 192.3 on the Oregon side of the Snake River. Figure 46 shows a plan view of the bar, transect locations and areas of change (deposition or erosion). The upstream boundary is composed of a debris fan, while the downstream boundary is a bedrock outcrop. Like Fish Trap Bar, China Bar is adjacent to a high terrace that delineates the southeast boundary of the study area, while the river forms the northwest boundary. The bar is composed of fine to coarse sand and relatively free of gravels.

Our transect surveys for China Bar are available for the following dates: November 18, 1997; November 5, 1998; and December 5, 2000. Between the 1997 and 2000 surveys, China Bar experienced deposition in the spring of 1998 and erosion and deposition between the 1998 and 2000 surveys. Transects A (Figure 47), B (Figure 48), and C (Figure 49) show changes to the crest elevation that occurred between the 1997 and 2000 surveys. Deposition and erosion at China Bar appear to be equivalent in quantity but occurred at different locations on the bar. The survey data demonstrate that, between 1997 and 1998, materials were deposited in the center of the bar. The toe of the bank increased in elevation, but the top remained unchanged. Transect data also illustrate that the bar decreased in elevation and increased in width between the 1998 and 2000 surveys. The areas over the crest of the bar at the downstream end have experienced the greatest amount of erosion, while the front of the bar at the downstream end has experienced the greatest amount of deposition. Figure 46 shows the areas of erosion and deposition for the 1998 and 2000 comparison. Overall, China Bar did not appear to change in volume, as depicted by the three transects. However, sediment was repositioned on the bar, decreasing its elevation but increasing its width. For the rest of the bar and bank, there was no indication of substantial deposition or erosion.

Some bank erosion is seen in Transect B, which lies adjacent to a trail commonly used to access cultural sites on the terrace. In addition to accessing the cultural sites, boaters and hikers often use the terrace for their tent locations and portable restroom facilities. Figure 46 shows the location of the trail. As seen in the 2000 data, the crest of the bar is near the water surface elevation equivalent of 30,000 cfs, the hydraulic capacity of HCD.

### ***General Discussion***

In general, the survey data indicate that the bars and banks experienced both deposition and erosion between 1997 and 2000. The exception is Salt Creek Bar, for which 1997 data were not used. These data show only erosion occurring between 1998 and 2000 at Salt Creek Bar. Although each bar experienced erosion, the banks remained stable. The exception, as illustrated in Figures 50 and 51, is a localized area of the bank that is popular for boat landing at Pine Bar, which experienced erosion. Fish Trap Bar (Figure 52) and China Bar seem to be the most active of the four bars in terms of raising or lowering crest elevations. At the bars with a distinct crest (all except Salt Creek Bar), the crest elevation seems to stabilize near the 30,000-cfs water surface elevation. A series of historical aerial photographs from 1946, 1949, and 1964 of

Pine Bar (Figure 53) show that the bars have been a dynamic feature since well before the HCC was constructed.

In addition to river hydraulics, recreational influences at Pine Bar are affecting the bar and the bank. Erosion has occurred on the upstream end of the bar and bank (from the large hackberry tree to the upstream boundary, a bedrock outcrop), as shown by Figure 32 (Transect A). Transect A is located at a heavily used campsite area for boaters and hikers. As the survey data indicate, erosion occurs where high recreational use exists. The 1994 site inventory photographs from the USFS, 1999 inventory photographs from IPC, and 1993 aerial photographs from IPC document the location of the bar that is commonly used for boat landings.

Boats and rafts commonly land at all of the bars because they are popular recreational sites, as illustrated in Figures 50 and 51. Two common effects associated with landing boats and rafts result from the boats on the bank and the foot traffic. One effect associated with jet boats at sandbars is the effect of their jet pumps, creating local turbulence and high velocities. This turbulence can mobilize local sand particles and cause them to be redistributed in the immediate area. Although jet boat pumps can displace material as the boats pull into or out of a location with a shallow sand bottom, this effect has not been quantified and it is not known whether the practice significantly affects sandbars.

The second effect is from foot traffic associated with the landing of the boats. This traffic includes dragging and carrying camping equipment up onto the high terrace and using restroom facilities. Each of the four sites had pit toilets located near the center of the bar on the sand terrace. In addition, Salt Creek Bar and China Bar each has a picnic table located on the terrace above the bar. For more information on recreational use and campsite conditions in Hells Canyon, see Brown (2002) and Hall and Bird (2002). For a historical perspective of the land-use practices, see Chatters et al. (2001).

### **10.1.3. Bar Counts**

Sandbar counts from aerial photographic surveys from 1955, 1964, 1973, 1977, 1982, and 1997 were performed according to the methodology discussed in Section 9. The photographic series for these years covered the entire reach from HCD to the Salmon River. Sandbar counts for sections of this reach are included for 1946 and 1955. The section analyzed for the 1946 and 1955 comparison is governed by the coverage of the 1946 series.

Figure 54 shows how sandbars in three reaches in Hells Canyon have changed since 1955 (before the HCC was constructed). All sandbar counts in this figure have been adjusted to 12,000 cfs flow by the methodology discussed in Section 9. As the figure shows, overall the number of sandbars in Hells Canyon has decreased from about 215 to about 142 or 34% between 1955 and 1997. Between the pre-HCC series (1955) and the 1964 series, (the time period that includes construction of Brownlee Dam and Oxbow Dam) the total number of sandbars actually increased from 215 to 238, or 11%. The largest decline in terms of both total numbers and percentages is between 1964 and 1973 when sandbars declined from 238 to 150, or 37%. The other period of decline was between 1977 and 1982 (20%). Overall, there have been two periods of substantial decline bracketed by two periods of increase for a net decline of 34% (the fifth period 1973 to 1977 was essentially flat). However, note that the first two full series available

show an increase so it is not clear what a true baseline should be to determine impacts to sandbars in Hells Canyon. This is discussed further at the end of this section.

Sandbars have not responded uniformly throughout the length of Hells Canyon. The reach of the canyon from HCD to Pine Bar has the steepest gradient within the study reach. This reach had the lowest number of bars per mile in the canyon and was the only reach that shows a decline throughout the study period (1955-1997). The sharpest reduction in this reach occurred between 1964 and 1973 with a reduction from 70 to 23 bars or 67%.

The Pine Bar to Pittsburg Landing reach is the next steepest reach and it shows a pattern similar to the upstream reach but with a less severe overall decline from 34 to 16 bars or 53%. This reach also shows an increase in the start of the study period from 1955 to 1964 from 34 to 40 bars or 18% and another increase between 1977 and 1982 from five to 17 bars or 240%. This last percentage increase should perhaps be viewed with some skepticism both because it starts with a very small base (five bars) and because the 1977 series was taken with a low flow (5,310 cfs) and therefore has been adjusted substantially down from the actual count to estimate the count at 12,000 cfs.

The most downstream reach from Pittsburg Landing to the Salmon River has the lowest gradient in the study area. This reach has the highest number of sandbars per mile (in all years evaluated), and is the longest reach within the study area. It shows a significantly different pattern in sandbar change than the rest of the river. Over the full study period there has been an increase from 105 bars to 109 bars or 4%. This analysis shows that there is the capacity to lose bars (1982 series) and then regain them under current sediment supply, river processes, and operations of the HCC.

In order to give a frame of reference to evaluate the changes in sandbar counts, this section presents percentage of change from 1955. Normally, changes should be measured from a baseline condition with baseline representing some equilibrium natural or pre-project condition. In this case, the earliest complete data available is from immediately pre-project and the first two data points (1955 and 1964) show a clear increase in sandbar counts. We also evaluated limited aerial photographs available from 1946 (presented later in this section) but the results are not conclusive. It is not apparent from available data what the pre-HCC level of sandbar frequency was in Hells Canyon. However, using 1955 as a baseline yields an overall change of 34%, which is far less than what other researchers have reported (Grams and Schmidt 1991). Using 1964 as the baseline as other researchers have done (Grams and Schmidt 1991) clearly overstates the change because there are more sandbars in the 1964 series even though there is no reason to believe that the 1964 count is more representative than the 1955 count.

It is quite likely that construction upstream (including two major earth fill dams, Brownlee and Oxbow dams) had an effect on the number and size of sandbars in the 1964 series of photos. Sandbar counts in 1955 were also probably affected by anthropogenic impacts within Hells Canyon and upstream, although these effects would be somewhat diminished by distance because they occurred farther upstream than the construction of Brownlee and Oxbow dams. Given the lack of any better alternative, we have used 1955 as the comparison year but recognize that using this year may overstate reductions in sandbar counts to some unknown degree.

The greatest overall change occurs in the steepest section of the river (upstream of Pine Bar), which is to be expected because features composed of fine-grained sediments would likely be the least persistent in high-gradient areas. Perhaps even more important than gradient, this reach is the most upstream, and would be the first to respond to a change in sediment supply (increase or decrease) resulting from upstream anthropogenic disturbance. Since approximately 1973, the overall number of sandbars has remained relatively constant with the upper canyon (above Pittsburg Landing) seeing a small decrease in the number of sandbars and the lower canyon (below Pittsburg Landing) seeing the number of sandbars remaining constant.

In an effort to extend our understanding of sandbar frequencies prior to the construction of the HCC, aerial photographs from an incomplete 1946 series (relative to the river) were compared to 1955. The first segment analyzed was the reach from RM 190.6 to 199.0. The 1946 photographs showed 30 sandbars on the Idaho side of the Snake River and 24 on the Oregon side. The 1955 photographs showed 29 sandbars on the Idaho side and 22 on the Oregon side. Within these results, there were two bars (Bar #9-Idaho and Bar #18-Oregon) that were present in 1955 but not in 1946. This change may be attributed to the higher flows during the time of the aerial photography in 1946, or it could be from the formation of new bars during the nine-year period. For example, Bar #21-Idaho was a single bar in 1955; however, in the 1946 photographs, it occurred as two distinct bars. Once again, this difference may be attributable to the higher flows that occurred in 1946. Another example is Bar #11-Oregon, which may have been caused by access that was developed into Hells Canyon at this site between 1946 and 1955. In the 1946 photographs, there is no bar at this site, while the 1955 photographs appear to show quite a bit of sand along the Snake River. Figure 55 clearly shows that the river has remained stable between 1946 and 1955 in this area, and that the primary cause of this newly formed sandbar is from disturbed soil and vegetation associated with the development of the upland area. Development of the upland area includes roads into the area that extend to the banks of the river, buildings on the upper terrace overlooking the river, and a parking lot or turn out area above the river as well. This analysis indicates that a few of the bars may have shifted slightly, but overall they appear to have remained stable in this area from 1946 to 1955.

The second segment analyzed was from RM 201.5 to 205.6. The 1946 photograph showed 24 sandbars on the Idaho side of the Snake River and 18 on the Oregon side. The 1955 photograph contained 24 bars on the Idaho side and 20 on the Oregon side. The two bars that seem to be missing in the 1946 photographs (Oregon side) may be a result of the higher flows during that year that prevented identifying the sandbars in the photograph. In some cases, we can observe the tip of the bar in 1946, while in 1955 the entire bar is visible. This analysis indicates that the number of bars also appear to have remained stable in this area from 1946 to 1955.

#### **10.1.4. Area and Distance Measurements**

Ten sandbars were selected and analyzed for surface area, as described in Section 9. The ten sandbars also included sandbars where survey measurements were performed, as discussed in Section 10.1.2. Because of issues presented in Section 9 including determining the bar boundaries (terrace, cut bank, vegetation, sand vs. gravel) with quantifying areas of sandbars, these methods are only used to validate some findings from the sandbar count.

In the 1964 aerial photos, four of the 10 bars increased in size compared with 1955 photos, while the other sandbars either slightly increased in surface area or remain the same as 1955 photos. Johnson Bar and Pine Bar increased the most (~ 35%) in new sand surface area as illustrated by Figure 56.

### **10.1.5. Sandbar Summary**

The analysis of sandbars in Hells Canyon yields or confirms several important points:

- The majority of the sediments found in the sandbars fall within the sand-size range (0.062 to 2 mm [0.002 to 0.07 inch]), with less than 7% of the material falling into the silt- and clay-size range (< 0.074 mm [0.003 inch]). Therefore, maintenance of the sandbars requires supplies of material of this same size range.
- Of the sediments trapped in Brownlee Reservoir, less than 4% are larger than fine sand (0.25 mm [0.01 inch]) and therefore would contribute little to maintaining sandbars in the Hells Canyon reach.
- Sandbars have been and continue to be dynamic features of the river system, features that are growing, shrinking, and changing shape in response to varying flows and sediment loads in the river.
- The provenance of the sediments sampled in the sandbars and terraces indicates that 50 to 85% of these fine-grained materials originated from the Idaho Batholith. Sediment supplies from the Idaho Batholith were largely cut off by projects upstream of the HCC prior to construction of the HCC.
- Based on sandbar counts, there has been an overall decrease of 34% of sandbars from 1955 to 1997.
- Both sandbar counts and sandbar area increased from 1955 to 1964. This increase indicates that sandbars in Hells Canyon were not in a state of equilibrium in 1964, and that 1964 is not an appropriate year to use as a baseline to measure change in sandbars.
- The number of sandbars in the Hells Canyon Reach has been relatively stable from 1973 to 1997.
- Photographs from the 1940s show that sandbar and terrace areas showed signs of erosion, which indicates that erosion of these features is not solely a response to the construction and operation of the HCC (Miller et al. [2003]).
- During cultural surveys, archaeologists noted a distinct lack of soil horizons at Salt Creek Bar. The lack of these horizons strongly indicates that the entire area has been reworked in historical times, likely through hydraulic mining activities. Archaeologists also noted evidence of placer mining activities throughout the Hells Canyon reach of the Snake River.

In summary, there is no direct evidence that the size and number of sandbars found in historical accounts (oral, written, and photographic) existed within a regime of dynamic equilibrium in the overall system. Or, whether the size and frequency of sandbars was affected by anthropogenic factors within Hells Canyon and upstream (from the mid-1800s through mid-1900s) (Miller et al. 2003). While it is likely that construction and operation of the HCC has had some effect on sandbars in Hells Canyon, and the reduction since pre-HCC in sandbar counts is 34%, there is no direct evidence of what proportion of this decline is related to the HCC. This same evidence shows that over the last 30 years the sandbar counts have decrease by about 5% and over the last 20 years the sandbar counts have actually increased (20%). Given the inaccuracies inherent in the methodology, the most reasonable conclusion is that sandbar counts are now relatively stable.

## 10.2. Bed Stability

We used two methods to evaluate bed stability. The first method was through measured data using cross section measurements conducted by the USGS at flow measurement sites below the HCC. The second method was using calculations of incipient motion at numerous locations below the HCC. This section shows that, based on these methods, the riverbed is predominantly stable below the HCC. This conclusion is also supported by the channel classification information provided in Miller et al. (2003).

### 10.2.1. USGS Gauge—Snake River Downstream of Hells Canyon Dam

Figure 57 shows a plot of cross sections measured by the USGS at the flow measurement gauge in the Snake River at HCD (ID-OR 13290450). Only part of the total data available was plotted for clarity. As the plot shows, this section of river is very stable, with no apparent trends in either the vertical or horizontal directions. Differences between cross sections are generally limited to 61 or 91 cm (2 or 3 ft), and the highest and lowest cross sections are the first two sections measured, so no trend is apparent. It is possible that a series of cross section measurements could show no vertical or horizontal trends but still have significant bed movement if bed material was being eroded and deposited in relatively equal amounts through normal river processes. However, given that the only appreciable sediment source, Deep Creek, Idaho, is located between Hells Canyon Dam and the USGS gauge site, it is not reasonable that if there were significant erosion, Deep Creek, Idaho, alone would be sufficient to provide enough supply to prevent a lowering in bed level. Therefore, the most reasonable explanation is that the bed is not mobile and was not before the HCC was constructed.

Since the first measurement shown at the USGS gauge site is in 1968 and Brownlee Dam was completed in 1958, it could be argued that the river below HCD had already degraded and armored as a result of Brownlee and Oxbow dams and therefore the construction of the HCC as a whole impacted the riverbed. However, for this speculation to be plausible, the riverbed from Brownlee Dam downstream would have fully armored over a period of 10 years. Furthermore, the construction of HCD could not have had any further influence on the armoring process. This is not a reasonable explanation so again, the simplest explanation that fits all available data are that the riverbed was armored before the HCC was constructed and continues to be armored in a similar state.

### **10.2.2. USGS Gauge—Snake River Near Joseph, Oregon**

A USGS gauging station (13209500) was established on the Snake River near China Bar in 1955 at RM 192.36 but discontinued in 1971. The USGS office located discharge measurements for three cross sections. These measurements show no trend in channel changes. However, information with these measurements was insufficient to indicate when they were taken. Therefore, they are of little use in evaluating changes in the channel over time.

The description of the gauging station notes: “Bottom is solid rock with some boulders and cobble” (undated notes from the USGS). Two rating tables were provided by the USGS, the first prepared in 1963 and the second in 1965. A note on the bottom of the second table indicates that the rating curve below 2.6 m (8.6 ft) is the same as in the previous table. Also, a rating curve prepared by IPC in 2001 only adjusted flows from the old rating table by 100 cfs.

All of this evidence indicates that the Snake River near the confluence with the Imnaha River is very stable and has been since the HCC was built (at a minimum).

### **10.2.3. Incipient Motion Calculations**

Section 9 includes the procedures and criteria we followed for calculating incipient motion of the mainstem river and specific salmon spawning sites. The mainstem incipient motion results are presented graphically in Figures 58 through 60 (each with nine panels) and in tabular form in Table 12. Tables 13 and 14 show the results of the spawning site computations. These results are for mobilizing the existing armor layer and should not be confused with the ability of the river to transport material.

Figures 58 through 60 display the locations of bed mobility at flows of 30,000 cfs, 39,670 cfs, and 100,000 cfs for a dimensionless critical shear stress of 0.047. These results for the mainstem indicate isolated pockets of bed-material movement for flows currently experienced in the Snake River reach of Hells Canyon. However, the majority of the bed appears to be stable. The channel stability can be attributed to the armored surface that may have been established by historical, high-flow events. The magnitude and occurrence of these large flows is discussed in Miller et al. (2003). During these high-flow events, large material was deposited along the river channel, and current flow conditions do not have sufficient energy to move this established layer of surface armor. Therefore, most of the sediment located under the surface layer is not available for sediment processes in Hells Canyon. However, the incipient motion results do indicate some mobile bed material, and these mobile areas are typically located downstream of a tributary. This finding indicates that local tributaries supplied these isolated pockets of mobile material after the historical, high-flow events and that this material has deposited in areas downstream of the parent tributary. Typically, this material is smaller in diameter than material in other areas of the river. For example, Panel 1 of Figure 58 shows a  $d_{84}$  of 100 to 130 mm (3.93 to 5 inches) downstream of Three Creek. Panel 4 of Figure 58 shows material sizes of 100 to 180 mm (3.93 to 7 inches) below Getta Creek and materials ranging from 100 to 150 mm (3.93 to 6 inches) below Wolf Creek. These reaches are mobile at high flows. However, long reaches between tributaries, which usually have larger bed material (200 mm [7.87 inches] or greater), are shown as stable. This small material may move along the river, over the top of a stable bed,

until it is deposited in some of the deeper pools downstream or retained by some of the large downstream bars. This finding also indicates that the tributaries are supplying sediment to the mainstem Snake River.

Table 12 displays the estimated percentage of the mainstem bed that would mobilize at flows of 30,000 cfs, 39,670 cfs, and 100,000 cfs for critical dimensionless shear stress values of 0.03 and 0.047. Table 12 shows that a critical dimensionless shear stress value of 0.047 appears to provide the most reasonable incipient motion results and that 0.030 overpredicts the amount of armor that mobilizes at higher flows. For example, at 100,000 cfs the amount of armor that mobilizes is 33% and 63% for critical dimensionless shear stress values of 0.047 and 0.030, respectively. Based on aerial photographs of the river channel, the cobble bars and bed have changed very little over the past 40 years due to the heavy armoring that developed on the river bed as a result of the historical high flow events previously discussed. Therefore, a dimensionless shear stress value of 0.047 appears to provide the most reasonable results for this reach of river, and is also consistent with research discussed in Section 9. Other features of Hells Canyon that contribute to the stability of the river channel are the presence of bedrock and rapids created by debris flows. When debris flows occur, both large and small material is washed into the river channel. The river transports the small material downstream, but material too large to be transported remains, creating a stable armored channel. This armoring occurred at Wild Sheep, Granite, and Rush Creek rapids, as well as at numerous small rapids along the river. As a result of the large material armoring the channel, the rapids shown in the panels of Figures 58 through 60 are considered to be stable. In addition, bedrock constrictions force flow convergences that consistently keep the channel scoured. Therefore, since the bedrock is not mobile, it also creates consistent flow conditions that maintain stable channels.

Tables 13 and 14 include the results of the incipient motion computations for the spawning sites. Sizes of spawning gravels typically range from 25 to 150 mm (1 to 6 inches) (Groves and Chandler 1999); however, these computations were completed using gravel sizes of 25 and 50 mm (1 and 2 inches), which are the smallest median ( $d_{50}$ ) sizes typically found in the spawning sites. Of the 112 sites Groves and Chandler (1999) evaluated, approximately 95% have a median size of at least 50 mm (2 inches). However, for our incipient motion analysis, the smallest median sizes were used for the computations because, if these sizes were stable, then the larger gravels in the spawning bed would also be stable. To determine the bed stability, the dimensionless shear stress at each site was calculated following the procedures described in Section 9, and these values were compared with the critical dimensionless shear stress values of 0.03 and 0.047. The site was considered to be stable if the calculated dimensionless shear stress was less than critical dimensionless shear stress. If it was greater than critical dimensionless shear stress, then movement could occur for gravels equal to or smaller than the size used in the computations. Table 13 displays the results of the 25-mm (1-inch) gravel, and Table 14 displays the results of the 50-mm (2-inch) gravel. Information used to complete these calculations was obtained from the MIKE 11 model. This model is calibrated to peak flows of approximately 100,000 cfs, the largest flow of record. Therefore, slopes and depths obtained from the model for flows above 100,000 cfs have not been verified.

Using a critical dimensionless shear stress of 0.047 and comparing to the results shown in Table 13 indicate that the smallest spawning gravel size of 25 mm (1 inch) is stable in all of the spawning sites for flows up to 100,000 cfs except the site at Rocky Bar/Wild Sheep. At this site,

flows greater than 100,000 cfs appear to move 25-mm (1-inch) material. To determine the flows necessary to mobilize spawning gravels at other sites, dimensionless shear stress values were computed for a flow of 150,000 cfs, which is approximately 1.5 times larger than the flow of record in the study area. Again only one site, the Rocky Bar/Wild Sheep site was the only spawning location that would indicate mobility. However, results in Table 14 indicate that 50-mm (2-inch) gravels would not move at any of the spawning sites, even at flows up to 150,000 cfs, since the calculated dimensionless shear stress is less than the critical dimensionless shear stress of 0.047. Therefore, gravels larger than 50 mm (2 inches) would not move at any of these sites either. If the values in Tables 13 and 14 were compared to a lower dimensionless shear stress value of 0.03, only five of the 17 sites would indicate mobility at the highest flow of record (100,000 cfs) for 25-mm (1-inch) material and none of the sites would mobilize if their median particle size was 50 mm (2 inches) or greater. Since 95% of the sites in Hells Canyon have median particle sizes of at least 50 mm (2 inches), the majority of spawning sites within the canyon are stable.

In summary, only one spawning site shows gravel movement at flows experienced in the study area, and this movement occurs only for the smallest material. For the remaining sites, the computations indicate that gravels of all sizes are stable. Since the larger gravel sizes do not move, they may shield the smaller material and prevent it from moving, which in turn enhances the stability of the spawning sites.

Results for incipient motion at spawning sites should not be compared with results for incipient motion in the mainstem because the shear stress computations for the spawning gravels are site specific. Also, the mainstem computations use an average shear stress across the river channel. Therefore, the mainstem calculations might indicate general movement of the bed, but stability at particular locations in the channel could occur. An example can be shown for two spawning sites, Copper Creek (RM 205.2) and Eureka Bar (RM 190.7). For these two sites, results for incipient motion at the spawning site indicate that the gravels are stable, but results for mainstem incipient motion indicate channel movement. For these sites, the spawning gravel calculations represent the stability of a specific site, since the shear stress computation is site specific, whereas the mainstem computation is an average of the shear stress across the channel. This approach indicates that general movement of the bed material could occur. However, the spawning sites would remain stable.

#### **10.2.4. Bed Stability Summary**

Both empirical data and computational analysis indicate that the mainstem riverbed upstream and downstream of the HCC is generally stable. The analytical evaluations indicate that there are localized areas where the bed materials could be mobilized within historical flow conditions.

The USGS gauges (Snake River at HCD and Snake River near Joseph) that we reviewed all indicate that the riverbed has been generally stable (no appreciable trends of downcutting or aggradation) over the historical record for each gauge. Note that this indication of stability does not preclude sediment transport through the reach.

The apparent stability of the riverbed, particularly above the HCC, is supported by the size of material that is deposited in Brownlee Reservoir. There is no evidence of riverbed materials (in the larger sand and gravel size ranges) found in the reservoir sediment deposits.

The implication of the riverbed stability upstream of the HCC is that bed materials are not a source of sediment supply to Brownlee Reservoir. Likewise, the implication of the riverbed stability downstream of the HCC is that bed materials are not a source of sediment supply to the Hells Canyon reach. The conclusion is that the riverbed materials are not a source of sediment supply, independent from the presence and operation of the HCC. The stability of the riverbed in both the upstream and downstream reaches is supported by results presented in Miller et al. (2003).

In addition, incipient motion calculations for mobility assessments in the mainstem indicate that the majority of the bed is stable. This channel stability can be attributed to the armored bed surface, which was likely established under flow regimes of much higher discharges. The magnitude and occurrence of these large flow events is also discussed in Miller et al. (2003).

We also analyzed local mobility of spawning size gravels at known salmon spawning sites. These results indicate that the spawning sites within even the potentially “mobile” reaches are stable.

Again, the results of all of these analyses apply to the existing armor layer mobility and should not be confused with the ability of the river to transport material if it is available.

### **10.3. Bank Stability**

There are three elements to the bank stability analysis. First, the assessment of general bank stability is based on visual observation and field mapping of areas of riverbank erosion. Second, geotechnical analysis of sandbar stability is conducted for fluctuating flows, where sandbars are the flatter sloped sand deposits adjacent to the river. Third, terraces stability was evaluated under fluctuating flow conditions, where terraces are considered the upland areas adjacent to the river, but not regularly inundated.

#### **10.3.1. General Bank Stability**

Riverbanks in Hells Canyon are very stable except at a few locations. A study of shoreline erosion (Holmstead 2001) indicates that the Hells Canyon reach is one of the most stable of the reaches studied (from Weiser upstream of the HCC to the Salmon River). Erosion occurred at 60 sites, or in 3.9 km (2.44 mi) out of 201 km (125 mi) (on both sides of the river), an area that accounts for about 2% of the reach. Most sites were above the range of typical flow fluctuation (Holmstead 2001).

### **10.3.2. Sandbar Stability**

Three (3) specific sandbar sites were considered in the geotechnical analysis discussed in this section, Fish Trap Bar, Pine Bar, and Tin Shed. Complete discussion of the results summarized in the section can be found in Appendix H.

The stability analysis was completed using a combination of a modified infinite slope method, termed the Equilibrium Seepage Slope (ESS) method (Budhu and Gobin 1994) and limit equilibrium solution completed using the computer program PCSTABL.

The analyses used cross sections or transects of the sandbars that were developed from actual surveys of the site. Transects were generally located at distance intervals of approximately 14 m (45 ft) along the length (as measured along the river) of the sandbar. Surface water elevations at the sandbars were derived from hydrographs based on flows from HCD and routed downstream using the MIKE 11 model. The analyses indicate that daily load following flows from proposed operations are unlikely to cause geotechnical instability or mass wasting of the sandbar. The flood recession case has a greater potential to cause instability of the sandbar slopes; however, the portion of the slope that shows instability is above the sandbar and could be classified as a terrace face. Also, the ESS analysis uses very conservative drainage assumptions. That is, the method assumes that very little drainage of the slope will occur during recession of the flood flows. Because the bars are composed of sand, which should be well draining, this assumption is probably overly conservative. Therefore, it is likely that many of the slopes will be stable during flood recession.

### **10.3.3. Terrace Stability**

IPC obtained the services of Engineering and Hydrosystems, Inc. to complete a bank stability analysis at the Tin Shed site at RM 215.6. The evaluation of the site was completed by analyzing three potential failure modes; [1) geotechnical slope failure, 2) erosion, and 3) groundwater piping.] A summary of the results is presented below:

**Geotechnical Slope Failure:** A critical condition for bank failure usually occurs during rapid drawdown of the water surface elevation on the riverside of the bank. The reason for this is that the riverbank might become saturated during high-flow conditions and that the phreatic surface of the infiltrated water in the bank does not recede at the same rate as the water level in the river. This leads to excess pore water pressures within the soil of the bank, weakening the soil and providing cause for bank failure.

This analysis considered deep-seated failure, surface raveling and sloughing and the effect of seepage from the bank on its stability. The geotechnical bank stability analysis was conducted at RM 215.7 and RM 215.6 using the SLIDE software. Two discharge conditions were analyzed, each representing an extreme flood recession affecting different areas of the bank: [1) the first analyses evaluated the maximum change in water surface elevation during a 24-hour period. This occurred on May 26 to May 27, 1999, when the discharge fell from 59,215 cfs to 19,880 cfs and 2) the second event analyzed a change in discharge during the recession of an extreme flood event. This event occurred from January 4 to January 5, 1997, when the discharge fell from 91,311 cfs to 55,790 cfs.]

This geotechnical evaluation indicated that the terraces are generally stable for the large majority of flows. However, an instantaneous drawdown in the river flow from 91,311 cfs to 55,790 cfs, resulted in potential riverbank instability at RM 215.6 while the same flow is not expected to induce instability at RM 215.7.

**Erosion:** Bank erosion can only occur when the water along the bank is deep enough to expose the bank surface to the erosive power of the water and the erosive power of the water concurrently exceeds the erosion threshold of the bank material. A streampower-based erosion analysis utilizing the MIKE 21C hydrodynamic model results indicates that the threshold for erosion at the toe of the bank at RM 215.6 is exceeded at a discharge of 30,000 cfs, which approximates the power plant capacity at HCD. At RM 215.7, the threshold of erosion of the toe of the bank occurs at flows of 50,000 cfs and higher. In addition, geotechnical analyses indicate that scour of approximately 60 cm (2 ft) at the toe of the bank does not lead to bank failure, although it decreases the factor of safety of bank stability. Given that erosion of the bank does not start until the power plant capacity of HCD is exceeded, it is unlikely that the riverbanks will fail due to the variation in water surface elevation resulting from load following.

**Groundwater Piping:** The site investigation revealed the presence of groundwater piping. However, the lack of measured water levels in the piezometers prevented full assessment of the magnitude of the relative contribution of this mechanism to bank failure. The available information indicates that groundwater piping most probably plays a minor role in determining bank instability.

#### **10.3.4. Bank Stability Summary:**

In summary, the bank stability analyses show:

- Erosion occurs along approximately 2% of the Hells Canyon reach and most of these sites are above the range of typical flow fluctuations.
- Both sandbars and terraces are stable under conditions associated with load following.
- Portions of the terraces may become unstable when subjected to rapid drawdown of water surface elevations following major flood events.

### **10.4. Sediment Supply to the Mainstem**

This section discusses sources of sediment currently available to supply the Snake River downstream of the HCC and sources that were available to the river before the HCC was constructed. These sources include the Snake River itself and tributaries to the Snake River that enter the reservoirs directly within the Hells Canyon reach.

Sources of sediment supply to the Snake River in Hells Canyon can be divided into four areas or categories: upstream of and to the HCC, tributaries downstream of the HCC, riverbed material, and hills sloping directly into the river. The dams in the HCC have largely cut off sources upstream of HCD. For these sources, the question is this: was there a significant sediment supply

reaching the Hells Canyon area before the HCC was constructed and did that sediment contribute to sediment-related features in Hells Canyon? Supplies from the tributaries downstream of the HCC have been estimated, and the estimate is presented in this section. As discussed in Section 10.2., the riverbed is largely stable. Therefore, sediments in the riverbed are largely unavailable and have been for hundreds of years. Hillslopes along the river likely contribute some quantity of sediment directly to the river, but this contribution is difficult to quantify.

#### **10.4.1. Sediment Supply Upstream of Hells Canyon Complex**

There is little question that the HCC would prevent essentially all of the sediments in the Snake River upstream of the HCC sand size and larger from traveling to the Hells Canyon reach of the Snake River. So are there significant supplies of sand-size and larger sediments that would be available to the Hells Canyon reach of the Snake River if the HCC were not in place? Direct and indirect evidence indicates that the answer is no. That is, even if the HCC were not in place, the supply of sand-size and larger sediment to Hells Canyon would not change significantly. This section includes evidence indicating that the HCC has blocked only minor quantities of sediments that would contribute to the features downstream.

Brownlee Dam was the first of three dams constructed as part of the HCC. At the time Brownlee Dam was completed (1958), the vast majority of the drainage basin above the HCC was already cut off from supplying sediment to the study area. Figure 3 shows major dams upstream of the HCC and when they were constructed.

Prior to the completion of the Brownlee Reservoir, more than 155,917 km<sup>2</sup> (60,200 mi<sup>2</sup>) of drainage area that could have potentially contributed sediment to Hells Canyon had already been blocked by numerous dams on the mainstem and tributaries. This area represents 87% of the total Snake River drainage area of 179,277 km<sup>2</sup> (69,200 mi<sup>2</sup>) at Weiser. In other words, most of the drainage area of the Snake River that would otherwise contribute sediment to the system, is located upstream of dams that were constructed before 1958. By 2000, an additional 1,554 km<sup>2</sup> (600 mi<sup>2</sup>) had been cut off. Furthermore, most of the areas cut off from supplying sediment were in the higher yield areas in the upper parts of watersheds and particularly in the Idaho Batholith area (Boise River and Payette River watersheds). Provenance of materials in sandbars in Hells Canyon indicates that 50 to 85% of the sands originated upstream in the Idaho Batholith. This suggests that sandbars were deposited prior to the other upstream regulation projects.

Additional information on development upstream of the HCC as it affects sediment supply to the Hells Canyon area is available in Miller et al. (2003).

##### **10.4.1.1. Snake River above Brownlee Reservoir**

The Weiser River is the only major tributary to the Snake River downstream of Swan Falls Dam and upstream of the HCC that is not blocked by a major dam. The USGS gauge on the Snake River at Weiser (13269000) is downstream of all major tributaries to the Snake River before it enters Brownlee Reservoir. Analysis of the USGS data indicates that, on average, about 81% of the suspended sediment in the Snake River near Weiser is smaller than 0.062 mm (0.002 inch), meaning that this sediment is predominantly silts and clays (smaller than very fine sand).

Based on the data from samples taken in Brownlee Reservoir (Appendix B), almost no sediment trapped in the reservoir is larger than fine sand (4%). This finding is consistent with the suspended sediment data collected by the USGS at the gauge near Weiser. We estimated that Brownlee Reservoir has trapped about 62,000 acre-feet of sediment; an average of 1,550 acre-feet per year during the 40-year period between when Brownlee Dam was closed in 1958 and the bathymetric survey was completed in 1998. Because of its small size, most of this sediment would have been passed downstream if the HCC had not been constructed.

Since larger sediment sizes have not been located in Brownlee Reservoir, a reasonable question could be asked—have they been deposited in the river above Brownlee Reservoir due to the backwater effect from Brownlee Reservoir? Section 10.4.1.4. uses information at the USGS gauge near Weiser to address this question. If material has been deposited in the river above Brownlee Reservoir, the bed elevation in this reach should show a general aggradation trend. The data collected by USGS do not show such a trend.

There are three fairly obvious ways of estimating sediment supplies above Brownlee Reservoir (the uppermost dam in the HCC). The first uses direct measurement of Brownlee Reservoir sediments; the second uses measured loads in the streams flowing into the reservoirs; and the third uses sediment yield values from USBR reservoir surveys of the watershed above the dam. IPC estimated supplies using all three of these methods:

1. Direct measurements used pre-impoundment bathymetry and recently collected bathymetry data. IPC used GIS to estimate the volume difference between the surfaces of the two surveys. This procedure is discussed in Butler (2002). PSDs from samples taken in the reservoir were used in conjunction with volumes of sediment from GIS to estimate a volume-weighted PSD for the material found in the reservoir. The volume of sediments measured in Brownlee Reservoir is approximately 62,000 acre-feet. Using a measured bulk density of 82.4 lbs/ft<sup>3</sup> (1.32 g/cm<sup>3</sup>) this estimate equates to 2.78 million tons per year with approximately 387,000 tons per year sand size or larger.
2. Measurement of loads brought in by inflows is necessarily less inclusive because sediment loads have been measured only in the Snake River near Weiser to represent the load to Brownlee Reservoir by the Snake River. Therefore, loads brought in by tributaries local to Brownlee Reservoir are not included. Also, the measurements at Weiser have not been continuous and have only included suspended load, not bedload. However, using an annual average flow of 18,533 cfs (1959–2000), an average concentration of sand of 13 mg/L (average of USGS measurements that include size class information), and assuming that bedload should be approximately 15% of the total (on the high side of the literature range of 5–15% [Collins and Dunne 1990]), an average annual load supplied to Brownlee Reservoir is calculated to be approximately 1.47 million tons per year with approximately 279,000 tons per year sand size or larger. This estimate is reasonably close to the load calculated in (1) above, particularly given that it does not include loads from minor tributaries feeding directly into Brownlee Reservoir. Including load from the tributaries would increase this estimate of inflow loads and bring it closer to the estimate presented in (1) above.
3. Yield estimates using an average value of 0.15 acre-feet/mi<sup>2</sup>/year from several reservoirs as discussed in Miller et al. (2003) and the same assumptions as used in the estimate shown in

(1) above for bulk density etc. gives an estimate of 2.49 million tons per year (55,500 acre-foot total), which falls in between the other two estimates. With this method, no information is available regarding the proportion of sand size or larger.

This analysis shows that three independent estimates of supply upstream of Brownlee Dam provide reasonably close agreement.

The only direct information available (sampling sediment directly in Brownlee Reservoir) indicates that no significant sediments in the size range of spawning gravels (25 to 150 mm [1 to 6 inches]) have been captured from sources above Brownlee Dam. This is true in spite of the fact that in its sampling, IPC intentionally went looking for larger materials. Because of large drawdowns, especially in the spring for flood control, the question of where large material might be found is not a simple one. Classically, large size class materials from upstream would be deposited at the point where the Snake River enters Brownlee Reservoir and finer materials would tend to be deposited progressively downstream. However, when the reservoir is drawn down in anticipation of a high flow event and that flow event occurs (as happened in 1996/1997 and other years) the deposition delta can be relocated farther downstream into the reservoir. In addition, the sampling program was set up after the bathymetry data were available; therefore, we were able to concentrate the deep-core sampling in areas of deep deposition. The deep cores were located at the upper end of the deposition delta where larger sediments would be expected.

When only a limited quantity of coarse material was found in Brownlee Reservoir, the obvious question became, if it is not in the reservoir, where is it? One potential answer is that the presence of the pool in Brownlee Reservoir could create a backwater effect and cause the coarse material to deposit in the Snake River above Brownlee Reservoir. A record of bathymetry over time is not available in the Snake River above Brownlee Reservoir except at the USGS gauge site at Weiser. If significant deposits have occurred in the Snake River because of Brownlee Reservoir it is likely that there would be some long-term trend of rising bed level and/or change in the rating curve of the gauge at Weiser. We found no such evidence. It should be noted that this does not make any statement about whether there is transport of material past the Weiser gauge or not.

This information is reinforced by the analysis completed by Osterkamp (1997) that shows that even if spawning size gravels were available upstream of Brownlee Reservoir, the Snake River (at least in the reach studied by Osterkamp) would be unable to mobilize any but the very small end of the range (30 mm [1.18 inches]).

Osterkamp (1997) also states that movement of material in the 20–30 mm (0.79–1.18 inch) range is restricted by limited transport capacity resulting from the other upstream regulation projects. Specifically, the USGS modeling results predict that 20-mm (0.79-inch) gravel would only move under peak flows (in the 25–35,000 cfs range) in isolated pockets as specific stream hydraulic conditions allow. Larger gravels (30 mm [1.18 inches]) would only be mobilized at high peak flow conditions (35,000 cfs; Osterkamp 1997). Based on observation by IPC, it appears that although this material might be able to be mobilized if it were available, in fact the channel bed in this reach is armored in many places by baseball- and softball-sized materials.

#### 10.4.1.2. Transport Capability of the Snake River above Brownlee Reservoir

For the Snake River upstream of the HCC to be a contributor of bed-size materials in the river downstream of the HCC, these sizes would have to be transported through the upstream reach. Miller et al. (2003) discuss the findings of Osterkamp (1997), who studied sediment movement near the Deer Flats Wildlife Refuge (located upstream of the HCC). This study indicates that bedload during the last 70 years or more has been restricted to sand and gravel sizes with a  $d_{50}$  size of 30 mm (1.18 inches) or smaller, as stated above and discussed in greater detail in Miller et al. (2003).

As mentioned earlier, the armor layer in a channel is formed from particles in the bed material. This layer can develop when the stream is incapable of moving the largest sizes of the bed material but does move some of the smaller size classes. Therefore, we selected a size smaller than the largest sizes in the armor layer (the  $d_{50}$  size) to evaluate whether the bed material in the Snake River below the HCC could have been transported through the Snake River above the HCC under current hydrologic conditions. Using data from the underwater photography, we determined that the average  $d_{50}$  of the surface layer in Hells Canyon is 144 mm (5.66 inches). To move material of this size through the reach of the Snake River between the Weiser River and Brownlee Reservoir, the Snake River would have to flow at a depth of over 200 feet. A rough estimation based on cross section and slope data (IPC, unpubl. data) indicates that the flows required to produce depths in this range are on the order of at least 9 million cfs. Alternatively, for a flow of about 100,000 cfs (in the range of current 100-year peak flow), the slope would have to approximate 36 ft per mi (or about five times the current slope of the Snake River between Weiser and HCD) to mobilize the  $d_{50}$  material. Taken together, these data indicate that the Snake River upstream of the HCC is incapable (under current hydrological conditions) of transporting the sizes of material that dominate the river downstream of the HCC. Therefore, the Snake River above the HCC has not been and would not be a source of surface bed materials to the Hells Canyon with or without the HCC in place.

#### 10.4.1.3. Sediments Trapped in Brownlee Reservoir

In December 1998, samples were collected from the bed of Brownlee Reservoir to evaluate sediments that have been trapped since the reservoir's construction. The results of this sampling indicate that less than 4% of the sediments consist of fine sand-size and larger particles (CH2M HILL 2000). Table 15 shows a more complete breakdown of materials sampled in Brownlee Reservoir including estimated quantities in terms of volume and weight. Therefore, there is no indication that the reservoir has trapped material that could significantly affect the stability of features in Hells Canyon.

#### 10.4.1.4. River Cross Section Stability

Active alluvial rivers are regularly eroding and depositing material from the riverbanks and bed. This process leads to the formation and destruction of features within the river that change flow patterns and cause the river channel to change shape and location over time. At its flow measurement gauges, the USGS regularly measures the shape of the channel cross section and velocity to update the stage discharge curve used to estimate flow. Cross sections surveyed during these measurements for different years were plotted on a single plot to show changes in the riverbed over time. Some of the differences shown in these plots may be attributable to

difficulties in accurately measuring depth under adverse conditions. However, in general, these measurements show that the Snake River near Weiser is very stable, i.e., it is not meandering, down cutting, or aggrading.

Figure 61 shows a plot of cross sections measured by the USGS in the Snake River near Weiser. Additional data are available, but for clarity, data were plotted only about every 10 years. The plot shows that, while there is some lateral shift, there has been no major movement in the last 88 years. The deepest area of the channel has also been very stable, both in location and depth. Vertical changes are less than about 60 cm (2 ft). The channel on the left side of the thalweg does show some change. Sometime between 1936 and 1955, a considerable amount of material was deposited, especially close to the bank. The bridge across the Snake River at the gauge was constructed in 1951. The construction of this bridge may have contributed to the appearance of this material. Since 1955, this area of deposition has flattened out somewhat and then been fairly stable since sometime before 1977. Overall, the indication is that the base level of the river through this reach has not changed significantly since Brownlee was constructed.

This same conclusion can be reached by looking at the rating curves prepared and used by the USGS for the gauges at Weiser and below the HCD. Figure 62 shows the rating curves used for the gauge at Weiser since it was installed in 1910. There have been only seven rating curves used since the gauge was installed. Since these rating curves plot essentially on top of each other with little change, we know that the river has neither degraded nor aggraded since the gauge was installed. Figure 63 shows rating curves for the gauge below HCD where data are available since 1965. A similar conclusion can be reached based on the rating curves at this gauging station.

Note that in neither case does the relative stability of the river mean that no sediment can be transported through the reach. The stability is only used to illustrate the fact that there is no sign of significant aggradation or degradation of the river at these locations.

#### **10.4.2. Sediment Supply from Wildhorse River and Pine Creek**

Wildhorse River and Pine Creek are the two largest tributaries entering the HCC that are not blocked by water storage dams. The Wildhorse River enters Oxbow Reservoir about 1.6 km (1 mi) downstream of Brownlee Dam. Pine Creek enters Hells Canyon Reservoir just downstream of Oxbow Dam.

The Burnt and Powder rivers also flow directly into Brownlee Reservoir, but both of these tributaries are dammed. Therefore, some portion of the total sediment supply is blocked upstream of the HCC.

The Wildhorse River has a drainage basin of about 458 km<sup>2</sup> (177 mi<sup>2</sup>). Parameter information (such as drainage basin area and slope) on the Wildhorse River drainage was included in tabular form in a USGS report (Hortness and Berenbrock 2001). IPC data generated by the same method used for other tributaries downstream of the HCC comported well with data shown in the USGS report, verifying that the techniques and base data used by IPC in developing tributary flows matched those used by the USGS in developing the methodology.

Contour maps were prepared for the areas inundated by HCC reservoirs before they were filled. In addition, some bathymetry data were collected in 1999 in the upper 7.2 km (4.5 mi) of Oxbow Reservoir. We attempted to check the recent bathymetry data against this preimpoundment data to calculate an average deposition rate from the Wildhorse River. Initial data appeared to indicate a sedimentation yield from the watershed of about 0.22 acre-feet/mi<sup>2</sup> per year (479 tons/mi<sup>2</sup> per year). This preliminary estimate did not consider that the early contour maps stopped at the river's edge while the bathymetry data continued through the full width of the reservoir. During attempts to refine the estimate and account for the blank area in the early contour mapping, it became obvious that small adjustments in overlaying the recent bathymetry and the early contour data could easily overwhelm the differences between the two surfaces. This inconsistency is partly because of a lack of detail in the early contour map (6-m [20-ft] contours are not sufficiently detailed on the valley floor where most deposition would likely occur) and partly because no common control point allows accurate referencing of the two data sets. As a result, these data cannot be used to calibrate or verify estimates of sediment load from the Wildhorse River.

Using the same methodology as for the tributaries downstream of the HCC (described in Section 9), estimates of sediment supply show that Wildhorse River would supply no sediment.

USGS records for the Pine Creek gauge (13290190) show a drainage basin area of 596 km<sup>2</sup> (230 mi<sup>2</sup>). However, the USGS outline of the watershed gives an area value of 779 km<sup>2</sup> (301 mi<sup>2</sup>). The values shown in this study are based on the 779 km<sup>2</sup> (301 mi<sup>2</sup>) value.

Sediment supply estimates for Pine Creek show that Pine Creek also would supply no sediment. The Schoklitsch equation indicates that the armor in Pine Creek would not be broken up until a flow of about 5,400 cfs is reached. The highest average daily flow for a 1% frequency occurs in April and is about 2,000 cfs. Therefore, under the Schoklitsch equation, and the 1% frequency limit on flow, no sediment supply is available. Similarly for Wildhorse River, the Schoklitsch equation estimates armor breakup at about 1,270 cfs and the maximum flow evaluated was 1,340 cfs (not enough to move significant material) However, the 1997 flow in Wildhorse River was estimated to be about 4,200 cfs, well above armor mobilization.

During the high flows in January 1997, Pine Creek and Wildhorse River clearly moved a lot of material, a situation that at first would seem to contradict the estimate of no sediment supply from these basins. However, sediment transport was estimated only for flows occurring 1% or more of the time. In the case of Pine Creek, only the Smart equation (described in Section 9.6.1.) indicates transport at flows below the 1% frequency. The flow event that occurred in January 1997 had an estimated peak of 11,600 cfs, a discharge that is more than 5 times the 1% frequency daily average flow. At 11,600 cfs, all of the transport equations indicate that sediments would be transported. Similarly, the equations show that Wildhorse River would mobilize the bed under the 1997 flow but this is well above the highest flow evaluated in our methodology. Therefore, the movement of sediment at these high flows does not contradict the validity of the sediment transport equations.

### **10.4.3. Sediment Supply from Tributaries**

Two aspects of sediment supply from tributaries are important in the context of this study. The first is the transport capacity of the streams. Sediment delivered to the mainstem Snake River must be from hillslope processes delivering it to the river or from streams that are tributaries to the river transporting it. Second is the sediment available to the tributaries for transport. Although papers have been presented on the subject of sediment supply, no single parameter can be measured to determine whether a stream is supply limited. The sediment supply values given in this section are the capacity of the tributaries to transport sediment. There are indications that the tributaries have readily available supplies of sediment including sands and gravels. Indications of sediment supply in the tributaries will be discussed in this section and are also discussed in Miller et al. (2003). However, the sediment supplies discussed in this section should probably be regarded as an upper bound of a range of possible sediment supply from local tributaries.

The sediment supply calculated in this section is for the area through the HCC down to the Salmon River. Two of the tributaries for which data were collected and calculations performed are downstream of the Salmon River confluence. These tributaries were included in the analysis to estimate the area-wide average supply. However, the area and supply from these two tributaries are not included directly in the totals discussed.

#### **10.4.3.1. Sediment Supply From Tributaries Below HCD**

Table 16 summarizes the sediment load calculated from the 17 tributaries. The results are also discussed in the sediment budget section of this chapter. The two largest suppliers of sediment (by a factor of 10) are located in the upper part of Hells Canyon (Granite Creek at about RM 239.6 and Sheep Creek at about RM 229.4) upstream of most of the sand beaches and spawning areas identified as areas of particular concern. This finding means that the majority of sediments supplied by the tributaries are supplied upstream of the areas in the canyon that benefit from sediment supply.

The tributaries with calculated sediment supply located between the HCC and the Salmon River (not including the Imnaha River drainage) account for approximately 901 km<sup>2</sup> (348 mi<sup>2</sup>) of a total watershed area of 1,398 km<sup>2</sup> (540 mi<sup>2</sup>). The average sediment yield from these calculated tributaries was applied to the remaining area producing a total sediment supply of 8.60 million tons per year. The same calculations for sand and spawning-size gravels, respectively, are 1.44 and 4.14 million tons per year.

The average sediment yield of 15,900 tons/mi<sup>2</sup> per year is in the upper range of values found in the literature (Table 7). However, given the characteristics of the tributaries in Hells Canyon, including steep slopes, relatively small drainage areas, and limited groundcover (arid conditions), the sediment yields would be expected to be high. Restricting the movement of any sediment until 85% or more of the bed-material sizes are mobile, is a conservative assumption. In several of the drainages, no movement was allowed, even at the 1% exceedance flow in the peak month, because of this restriction when clearly, based on visual evidence, these tributaries have produced sediment supplies in recent years. Barta (2001) notes that several different researchers have correlated the discharge producing the largest cumulative transport to floods that occur

every 1.5 years. This information also indicates that the assumptions used in calculating sediment transport values shown in Table 16 are conservative.

In engineering terms, “conservative” is taken as tending in the direction least likely to cause harm or damage. For example, a conservatively designed structure is stronger than necessary to make sure that, in case of an error, it will still be unlikely to fail. In environmental terms, a conservative approach would generally be to overestimate pollutants or harmful constituents so that, even in case of an error, the reality would probably still be better than estimated. In the particular case of this report, given the concern of reduction in sediment load and supply, conservative means that assumptions used in calculating the estimate of sediment yield skew the results toward lower sediment yield not higher.

#### **10.4.3.2. Sediment Supply From Tributaries Within the HCC**

Sediment supplies from tributaries directly to the HCC have also been estimated using the same methodology as described for the tributaries below HCD. The results of these calculations are shown in Table 17 and summarized in the sediment budget discussed later in this chapter.

Oxbow Reservoir has a very limited number of drainages that appear to supply sediment. Based on visual evidence, Wildhorse River obviously supplied sediment during the January 1997 event and likely does on a fairly regular basis. The only other tributary (Salt Creek) that fit within the parameters of our methodology (i.e., basin size, percent slope, etc.) shows some evidence of sediment movement but nothing like some of the tributaries to Hell Canyon Reservoir, the Snake River in Hells Canyon, or even tributaries to Brownlee Reservoir. These other tributaries show large amounts of obviously recently deposited materials of a wide range of sizes from sands through cobbles and little vegetation growing on them. Sediment deposits at the mouth of Salt Creek on the other hand are more armored and have large trees still growing over most of the alluvial fan area. Calculations show zero sediment transported to Oxbow Reservoir as shown in Table 17. Therefore, in estimating the sediment budget, an average of sediment yield from tributaries to Brownlee Reservoir and tributaries to Hells Canyon Reservoir was applied to the Oxbow Reservoir drainage area to estimate sediment supply to Oxbow Reservoir.

#### **10.4.3.3. Confirmation of Sediment Supply Estimates**

As discussed elsewhere in this report, no empirical data are available to directly confirm the sediment supply estimates presented in this section. However, there are checks that can be used to evaluate the reasonableness of the estimates. Table 7 shows sediment yields from other published reports and areas. Table 10 shows total sediment yields from the various areas within the study reach in various units to allow comparison. The bottom of Table 10 also includes some ranges of yield based on other basins in the area and based on lowering estimates at Oxbow Reservoir.

Clearly the yields from tributaries in Hells Canyon between HCD and Pine Bar are the highest shown. Comparing these to the highest local yield (from Cascade Reservoir) shows that somewhere between one and two orders of magnitude reduction in the supply based on transport calculations might be appropriate.

Comparing the same yields with the estimates of lowering of the general ground surface at Oxbow Reservoir also shows that a decrease in yield of one order of magnitude would bring the supply value for the HCD to Pine Bar reach within the range of lowering rate estimates. However, this same reduction factor would lower the supply estimates from other reaches by too much (except possibly tributaries directly to Hell Canyon Reservoir).

Therefore, until additional data are available, a one order of magnitude decrease in sediment supply estimates from the local tributaries is probably a reasonable correction factor.

#### **10.4.3.4. Indicators of Sediment Availability**

##### ***Visual Field Investigation***

One indication of sediment availability is the appearance of pockets of material of a wide range of sizes, from sands through cobbles, in a stream. The presence of this material indicates that, even if the streambed is armored, material is moving through the system under a range of flows. For most of the tributaries discussed in this report, investigators hiked up the lower reach from the Snake River. At least one engineer or scientist with extensive field experience in the areas of sediment supply and transport performed these investigations, which took place from 1 to 4 years after the major runoff event in the winter of 1996–1997, depending on the tributary. If the tributaries are severely supply limited, we would expect that these pockets of material would have been swept out of the stream, leaving an armored surface layer. In fact, the investigators found numerous places above the base flow but within a bankfull level with well-graded material (material with a wide distribution of sizes).

##### ***Hillside Slopes in Hells Canyon***

The angle of repose for most natural sediments is near 28 degrees. Slopes flatter than this angle would depend primarily on surface runoff to transport sediments to streams. Slopes greater than 28 degrees are probably composed of material that is somewhat durable or cohesive and not very available to transport by streams. Slopes in the range of the natural angle of repose are likely composed of material that is loose and regularly available to streams for transport. These areas are probably composed primarily of talus slopes, slides, and areas where any disturbance that moves material (such as animal movement and freeze-thaw cycles) will cause some material to move down the slope to the adjacent streambed.

Miller et al. (2003) show the percentage of area in Hells Canyon in several slope classes. Approximately 55% of the slopes are in the 10 to 40% slope class.

#### **10.4.4. Bed-Material Mineralogy**

Over the last several years, sediment samples from bed materials (including spawning gravels) have been collected for various purposes. Although these samples were collected during numerous field efforts for a variety of purposes, they have been used to aid in the understanding of potential effects of the HCC on sediments in Hells Canyon. A subset of these samples was visually analyzed for lithology, mineralogy and degree of rounding. It is important to reiterate that all of the bed materials represent subsurface materials collected from beneath an extensive

armor layer. To provide a better understanding of the provenance and characteristics of sediments above and below the HCC, IPC submitted a representative subset of the fine-grained samples (including bed materials, reservoir samples, and sandbar samples) for semi-quantitative XRD analysis.

The visual analysis of coarse-grained bed materials (coarse gravels to large cobbles ranging between 25.4 and 200 mm [1 and 7.87 inches]) suggests that most of the coarse surface bed sediments at the 23 mainstem and three tributary sites below the HCC are locally derived from the Columbia River Basalts, Seven Devils Group of meta-sediments, and the diorite intrusives exposed in local tributaries to Hells Canyon. Two of the mainstem sites included in this analysis represent spawning gravel sites. As discussed previously in the draft and final E.1-1 and Miller et al. (2003) technical reports, these materials reflect pre-impoundment conditions because they are locked beneath a well-armored layer that appears to have been armored since well before the construction of the HCC. Visual analysis of fine-grained subsurface bed sediments (less than 4.76 mm [18.74 inches] in diameter) initially suggested that these sediments were also locally derived (as reported in the draft Miller et al. [2003]). However, additional XRD analyses described below have changed this conclusion.

XRD data were used above the HCC to determine the relative contribution of upstream tributaries (i.e., Owyhee, Boise, Payette, Malheur, and Weiser rivers) to the mainstem sediment load coming into Brownlee Reservoir. These data were compared to XRD data collected on core samples from Brownlee Reservoir to help characterize the nature and sources of upstream sediment being trapped within the HCC.

The XRD data indicate that three major minerals (quartz, plagioclase and potassium feldspar [k-spar]) have sufficient bedrock associations, distribution, and variability to be useful in estimating the provenance of materials throughout the study area. From a mineralogical perspective, sediments from the upstream Snake River Basin are distinct from local sediments within Hells Canyon on their respective quartz, plagioclase, and k-spar composition. In general, sediments upstream from the HCC have high quartz and k-spar levels, but relatively low plagioclase. K-spar is essentially limited to the rocks of the Idaho Batholith and provides a unique chemical signature in the fine-grained bed sediments in the Boise and Payette rivers (the two tributaries with the largest input of discharge to the mainstem upstream from Brownlee Reservoir). In contrast, sediments derived from below the HCC generally have high plagioclase, but relatively low quartz and particularly low k-spar.

Based on their mineralogical signatures, the sediments found in Brownlee Reservoir appear to be mainly from the upper mainstem channel (70%), with a relatively smaller contribution of upper tributary sediments (e.g., from the Boise, Payette, and Weiser rivers; 30%). These results are consistent with the observation that more than 87% of the sediment-producing upper watershed, including the upper tributary basins, was cut off from the mainstem Snake River above Brownlee Reservoir prior to the construction of the HCC.

Below the HCC, fine-grained subsurface bed sediments have an upstream mainstem mineralogical signature. However, the signature from local sediments (from the local tributaries or hillslopes below the HCC) indicates an increasing contribution in the downstream direction from local sources (that is, the mineralogical signature confirms that the relative contribution of

local sediments increases as one moves downstream through Hells Canyon). Quartz and plagioclase decrease at a rate of about 1% per river mile below the HCC, while k-spar remains relatively constant with a much smaller decrease in the downstream direction (that is, the rate of k-spar decrease is considerably lower than the rate of quartz decrease).

The very small rate of k-spar decrease is an important piece of information that suggests that the local tributary and hillslope sediments dilute the upstream signature in the downriver direction (that is, as one moves downstream from the HCC, local sources have an increasing influence on bed sediments). If the entrapment of sediments within HCC was primarily responsible for diluting the upstream signature, the rate of k-spar decrease would be similar to the rate of quartz decrease.

The provenance results indicating that gravels and larger material are primarily of local origin does not contradict the provenance results that sand size materials (sandbars) are 50 to 85% Idaho Batholith. These sand size materials were transported over a generally stable bed of larger substrate.

#### **10.4.5. Bed-Material Size Distribution**

An additional indication of the source of sediments in the reach of the Snake River below the HCC is the size distribution of the bed-material particles. Bulk samples were collected from the bed material in the mainstem Snake River both above and below the HCC, as well as in the tributaries below the HCC. The armor layer was removed (where present) before extracting these bed-material samples, as described in Section 6.1.2. Therefore, data described in this section are independent of any armoring processes. Figure 64 shows the PSD of the bed material above and below the HCC. This figure clearly identifies that data from above the HCC is generally grouped separately from data from below the HCC. Although there is some overlap, the distinction is clear.

Figure 65 shows PSD data from the tributaries below the HCC plotted over the PSD from the mainstem (both above and below the HCC). Once again, there is some overlap, with data from the tributaries falling in between the group of data from below the HCC and the group of data from above the HCC. Figure 66 shows just the average  $d_{16}$ ,  $d_{50}$ , and  $d_{84}$  with plus and minus one standard deviation error bars. This figure indicates that although the smaller sizes are fairly comparable between the three areas of samples, the bed material below the HCC and the tributaries below the HCC clearly have more larger size classes. In fact, the  $d_{84}$  of the river below the HCC and the tributaries below the HCC are extremely close and clearly distinct from the  $d_{84}$  of the river above the HCC.

#### **10.4.6. Sediment Supply Summary**

In summary, the analysis of sediment supply to the Snake River in Hells Canyon yields or confirms several important points:

- When the HCC was constructed, the majority (87%) of the watershed available to supply sediment to the mainstem Snake River at Weiser was upstream of one or more dams.

Therefore, this area was unavailable to supply sediment to the downstream reaches. Moreover, the higher yield areas of the watershed, particularly those draining the Idaho Batholith, were cut off.

- There is no evidence that Brownlee Reservoir (the uppermost reservoir in the HCC) has trapped significant quantities of sediment in sizes that could affect any of the important sediment features in Hells Canyon. More than 96% of the material trapped in Brownlee Reservoir is fine sand and therefore smaller than the majority of material found in the sandbars in Hells Canyon. No sediments of spawning gravel size were found in Brownlee Reservoir sampling.
- The transport competency of the river upstream of the HCC is insufficient to mobilize and transport material such as that found in the riverbed of the Hells Canyon reach. Therefore, no supply of bed materials would be available from sources upstream of the HCC under historical hydrologic conditions.
- There are tributaries in Hells Canyon not affected by the HCC that supply sediment in the size range useful for maintaining sediment-related features such as sandbars and spawning sites in Hells Canyon.
- There is clear visual evidence that many of these tributaries have supplied sediment to the Snake River in Hells Canyon in recent years under current hydrologic conditions.
- Mineralogical composition of coarse bed-material sediments and spawning gravels suggests that these sediments are of local Hells Canyon origin. The lack of minerals characteristic of the upper regions of the Snake River Basin suggests that riverbed materials in the Hells Canyon reach were not transported from upper parts of the basin (Miller et al. 2003).
- There are data from the early 1900s (well before the HCC was built) through the present time indicating that the Snake River upstream of the HCC is highly stable. More recent data from downstream of the HCC indicate similar findings.

## 10.5. Description of Operating Scenarios

Two operating scenarios, proposed and full pool run-of-river (Parkinson 2002), are considered in this section. Because the proposed scenario has operations following the current rules, flows and fluctuations would be similar to those experienced in the recent past, subject to changes in inflow hydrology. The full pool run-of-river scenario removes essentially all regulation and runs the reservoirs at a full level. In this scenario, the amount of water flowing into Brownlee Reservoir, plus inflows from tributaries entering the HCC, is the amount released at HCD. Figure 67 shows flow-duration curves for the proposed and the full pool run-of-river operational scenarios. Table 11 shows flows and exceedance values to help us see how common flow ranges may change.

## 10.6. Impacts from Changes in Operation

Table 11 and Figure 67 together show that changing to a full pool run-of-river operational scenario would essentially have no effect on sediment features influenced by flow levels. Changing to full pool run-of-river operations would slightly increase flows in the lower and in the middle to upper ranges (less than 12,000 cfs and greater than 30,000 cfs) but slightly decrease flows in the middle range (12,000 to 30,000 cfs). None of the changes are significant given that they are near or less than errors commonly associated with measuring flow in a natural system.

Monitoring of the sandbars indicates that, after a large event builds up the sandbars, they tend to work back to an equilibrium condition where the top of the bar is near the upper end of the operational capacity of HCD (30,000 cfs). Table 11 shows that a flow of 30,000 cfs has an exceedance value of about 15% under proposed operational conditions. Under full pool run-of-river operations, the 15% exceedance flow would increase by less than 1% to 30,273 cfs. This difference is within even the inaccuracies inherent in measuring flow in a natural channel such as the Snake River. Therefore, results from sandbar monitoring suggest that no changes would be expected from changes in flow.

The sediment studies were developed to evaluate if sediment features would be affected by flows typically experienced in the Hells Canyon Reach. To evaluate the harshest conditions the flows could have on the sediment features, IPC used the most extreme flow scenarios observed. In most cases the study results concluded that sediment features would not be affected by IPC daily operations, but discharges scenarios higher than power plant capacity could affect some sediment features. The sediment features evaluated and the general conclusions are as follows:

- Sandbars: Three sandbars were evaluated for geotechnical stability during load following and for flows exceeding the power plant capacity. The analysis concluded that load following would not have any affect on sandbars stability, but the area where the sandbars transition to terraces could become unstable during recession of flood flows (higher than power plant capacity).
- Terraces: One terrace was evaluated (Tin Shed) for geotechnical stability during load following and for flows exceeding the power plant capacity. The analysis concluded that load following would not affect the stability of the terrace, but the terrace could become unstable during recession from extreme flood conditions.
- General bed stability: River bed material were evaluated to determine the percentage of channel that may be stable for flows typically experienced in Hells Canyon. The results show that the bed is generally stable with movement of bed material in some areas.
- Spawning Gravel Stability: Seventeen fall Chinook spawning sites were evaluated to determine if the substrate would move at the range of flows experienced in Hells Canyon. The analysis indicated that the beds were generally stable, but some movement may occur at only the sites composed of the smallest spawning substrate.

## 10.7. Sediment Budget by Size Class

A sediment budget can be a useful tool for assessing the relative effects from the HCC on downstream features. However, as noted by Grams and Schmidt (1999a), “Calculation of a sediment budget for the Hells Canyon reach of the Snake River is severely hindered by the scarcity of sediment transport data.” They further comment that to develop a sediment budget, “More sediment transport data are needed to calculate a sediment budget for the Hells Canyon reach. In particular, measurements or estimates of gauged and ungauged tributary contributions are essential.”

Because of this lack of data, this sediment budget is not comprehensive, and some information is based in part on assumptions and analyses, which introduces potential for substantial error.

Very simply, a sediment budget accounts for all sediment entering, leaving, and being stored in a river system (Collier et al. 1996). The budget is typically formulated as:

$$S_i + S_t - S_o = \Delta S_r$$

where:  $S_i$  = rate of sediment entering the reach from upstream  
 $S_t$  = rate of tributary additions  
 $S_o$  = rate of sediment leaving the reach  
 $\Delta S_r$  = rate of change in storage along river’s banks and bed

According to Reid and Dunne (1996), there are two general sources of sediments; those available in the bed and banks, and those transported into the system. The heavily armored bed (both above and below the HCC) demonstrates that the sediments stored in the bed are generally not available for transport or geomorphic processes. The river banks in Hells Canyon are very stable, with only 2% showing evidence of erosion. Therefore, in this case, the last term, rate of change in storage along the river’s banks, and bed is likely to be quite small.

Typically, sediment budgets are prepared for much smaller watersheds and include processes of hillslope erosion into channels (Dietrich et al. 1982). Reid and Dunne (1996) state that a complete sediment budget “accounts for rates and processes of erosion and sediment transport on hills and in channels, for temporary storage of sediment in bars, alluvial fans, and other sites, and for weathering and breakdown of sediments while in transport or storage.” To address resource management issues such as those faced within Hells Canyon, this level of detail is unnecessary and the primary components of a sediment budget include the type and location of major sources of sediment, as well as the approximate amount and grain-size distribution of sediment contributed by each source (Reid and Dunne 1996).

In larger watersheds sediment budgets are typically difficult to define. For example, even in the Grand Canyon where extensive research has been conducted for more than 20 years, “one elusive goal of Grand Canyon researchers has been to provide managers an accurate budget of inflows, outflows, and changes in storage of sand” (Schmidt 1999). Thus, even in situations where data are relatively comprehensive, sediment budgets may only be able to provide a conceptual framework.

It is important to note that this sediment budget reflects post-impoundment conditions. At this time, there are no estimates for how much sediment originally reached and passed through the reservoir reach downstream into Hells Canyon prior to other upstream impoundment projects or prior to the HCC. However, available information suggest that prior to other water regulation projects that cut off sediment supplies from tributaries and along the mainstem Snake River upstream of the project area, a substantial amount of upstream sediment passed through to Hells Canyon to build sandbars and contribute to finer-grained channel bed materials. This information is discussed in Miller et al. (2003).

Table 15 shows the sediment budget. Where multiple estimates have been developed for loads based on information from different sources, each estimate is shown. For example, loads to Brownlee Reservoir are estimated three different ways and all three values are shown to allow comparison. The bases for the values shown in Table 15 are discussed previously. IPC believes that percentages sometimes give readers a better picture of the importance of some items relative to the total as opposed to a volume or weight, so the table includes percentages as well as volumes and weights in certain cases.

For sediments sampled at Weiser, the only size class breakdown available is between sand sizes and silt/clay sizes, and this break was only available in a portion of the samples collected. However, the samples were collected with a suspended sediment sampler so at least in the suspended load, no sediment would be larger than sand sizes. Bedload is shown to not include silt/clay sizes because these sizes are transported as suspended load. Empirical sampling in Brownlee Reservoir showed almost no sediment larger than sand.

Note that the estimates for supplies from local tributaries are based on transport calculations. As such, these estimates are likely an upper bound on the range of potential supplies from the tributaries.

General notes to be kept in mind when evaluating the data shown in Table 15 include the following:

- Conversion between volume and mass are based on a typical bulk density of 100 lbs/ft<sup>3</sup> (1.6 g/cm<sup>3</sup>) except where empirical information is available. Sediment samples in Brownlee Reservoir provided empirical data that showed an average of 82.4 lbs/ft<sup>3</sup> (1.32 g/cm<sup>3</sup>) so this value was used in converting units for measured deposits in Brownlee Reservoir.
- The ratio of sand to total suspended sediment load at Weiser does not show any significant correlation to flow. Also, the concentration of total suspended sediment shows no significant correlation to flow. Therefore, in evaluating sediment load measured at Weiser, IPC used an arithmetic average for flow and sand concentration based on USGS data.
- Literature shows a range of values from 5% to 15% (Collins and Dunne 1990) for bedload as a percentage of total. IPC analyzed sediment transport data collected by the USGS on the Snake River at Anatone and the Clearwater River near Spaulding. Data from these studies indicated that sand sized bedload as a percentage of suspended sand

load was about 13% for both stations. Therefore IPC chose to use the upper end of the range (15%) as a reasonable estimate.

- Suspended load at Weiser is shown to include particles up to very coarse sand. This is because the data provide no breakdown beyond the separation of silt/clay size particles. The likely size was cut off at sand sizes because the equipment used in suspended sampling would not have collected gravel sizes. It is likely that the true upper end of sizes samples is much lower, probably either fine sand or medium sand based on the sampling in Brownlee Reservoir.
- By similar reasoning, the bedload at Weiser is shown to include no sediments finer than very fine sand. Typically it would be assumed that the majority of bedload is coarser sands and gravels but the only empirical data available to address this question (sediment sampling in Brownlee Reservoir) indicate that very little sediment is in these size classes. Therefore in the sediment budget, bedload sizes are shown to include all sand and gravel size classes.
- Sediment load estimates to Brownlee Reservoir based on watershed yield values use the area between Brownlee Dam (RM284.6) and the next dam upstream on any tributary. This estimate also uses 40 years to maintain consistency with the reservoir sedimentation data collected in Brownlee Reservoir.
- As noted in Section 10.4.3.2, transport calculations for Salt Creek, Idaho and Wildhorse River show no transport. There is visual evidence of sediment transported into Oxbow reservoir however so supply directly to Oxbow Reservoir was estimated using an area weighted average between transport to Brownlee Reservoir and transport to Hells Canyon Reservoir.
- For a discussion of how sediment transport values from tributaries below HCD were used to estimate total supply to the Hells Canyon reach, see Section 10.4.3.1.
- The PSD of material sampled in sandbars in Hells Canyon was included to allow an easy comparison with the PSD of material trapped in Brownlee Reservoir. PSD of material found in the sandbars includes samples from deep in the sandbar and there is relatively little variation in sizes within the sandbars. Therefore, it is clear that this PSD represents material that would be required to maintain the bars in either their present state or in the state they were prior to construction of the HCC.

## 11. ACKNOWLEDGMENTS

The listed authors of this report fully recognize that it took the work of many people to complete the work presented here. In particular, we wish to thank Steve Zanelli, Nathan Black, and Toby Wilson for their extraordinary efforts in acquiring data for this report. Their dedication to working in conditions that ranged from blistering heat to freezing cold, their on-the-spot ingenuity in making sure that accurate data were collected, and their ability to pack 80-pound

sacks of material samples were vital to the project's success. Steve Zanelli deserves special thanks for his boat-piloting skills, which ensured that all trips into this remote area were completed safely and efficiently. We also would like to recognize the employees of the USGS and the USFS who provided some of the data, photographs, and other materials used in describing the existing and historical condition of the study area.

## 12. LITERATURE CITED

- Ackers P, White WR. 1973. Sediment transport: new approach and analysis. *Journal of the Hydraulics Division, ASCE*, Vol. 99, No. HY11, pp. 2041–2060.
- Allen PB. 1986. Drainage density versus runoff and sediment yield. *Proceedings of the 4th Federal Interagency Sedimentation Conference, March 24–27, 1986, Las Vegas, NV.*
- Alpha TR, Vallier TL. 1994. Physiography of the Seven Devils Mountains and adjacent Hells Canyon of the Snake River, Idaho and Oregon. In: TL Vallier and HC Brooks, editors. *Geology of the Blue Mountains region of Oregon, Idaho, and Washington: stratigraphy, physiography, and mineral resources of the Blue Mountains region.* Professional Paper No. 1439, U.S. Geological Survey, Washington, D.C.
- American Society of Civil Engineers (ASCE). 1963. Friction factors in open channels. Progress report of the Task Force on Friction Factors in Open Channels of the Committee of Hydromechanics of the Hydraulics Division, E Silberman, Chairman. *Journal of the Hydraulics Division, ASCE*, Vol. 89, No. HY2, pp. 97–143.
- Andrews ED. 1983. Entrainment of gravel from naturally sorted riverbed material. *Geological Society of America Bulletin*, Vol. 94, pp. 1225–1231.
- Andrews ED, Parker G. 1987. Formation of a coarse surface layer as the response to gravel mobility. In: CR Thorne, JC Bathurst, RD Hey, editors. *Sediment transport in gravel-bed rivers.* John Wiley and Sons, Chichester, United Kingdom. pp. 269–325.
- Andrews ED. 2000. Bed Material Transport in the Virgin River, Utah. *Water Resources Research*, Vol. 36, No. 2, Pages 585-596, February 2000. Paper number 1999WR900257.
- Ashworth PJ, Ferguson RI. April 1989. Size-selective entrainment of bedload in gravel bed streams. *Water Resources Research*, Vol. 25, No. 4, pp. 627–634.
- Barta AF. 2001. Gravel entrainment and scour in steep headwater channels. *Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25–29, 2001, Reno, NV.*
- Bathurst JC. 1978. Flow resistance of large-scale roughness. *Journal of the Hydraulics Division, ASCE*, Vol. 104, No. HY12, pp. 1587–1603.
- Bathurst JC. 1985. Flow resistance estimation in mountain rivers. *Journal of the Hydraulics Division, ASCE*, Vol. 111, No. 4, pp. 625–643.

- Bathurst JC, Li RM, Simons DB. 1981. Resistance equation for large-scale roughness. *Journal of the Hydraulics Division, ASCE*, Vol. 97, No. HY12, pp. 1593–1613.
- Bathurst JC, Thorne CR, Hey RD. 1979. Secondary flow and shear stress at river bends. *Journal of the Hydraulics Division, ASCE*, Vol. 105, No. HY10, pp. 1277–1295.
- Bathurst JC, Graf WH, Cao HH. 1987. Bedload discharge equations for steep mountain rivers. In: CR Thorne, JC Bathurst, RD Hey, editors. *Sediment transport in gravel-bed rivers*. John Wiley and Sons, Chichester, United Kingdom. pp. 453–491.
- Blair C, Braatne J, Simons R, Rood S, Wilson B. 2001. Effects of constructing and operating the Hells Canyon Complex on wildlife habitat. In: *Technical appendices for new license application: Hells Canyon Hydroelectric Project*. Technical Report E.3.2-44, IPC, Boise, Idaho. 200 pp.
- Braatne J, Simons R, Rood S, Gom LA, Canali G. 2002. Riparian vegetation ecology of the Hells Canyon corridor: field data, analysis and predictive modeling of plant responses to inundation and regulated flows. In: *Technical appendices for new license application: Hells Canyon Hydroelectric Project*. Technical Report E.3.3-3, IPC, Boise, Idaho.
- Bray DI. 1979. Estimating average velocity in gravel-bed rivers, *Journal of the Hydraulics Division, ASCE*, Vol. 105, No. HY9, pp. 1103–1122.
- Bray DI. 1982. Flow resistance in gravel-bed rivers. In: RD Hey, JC Bathurst, CR Thorne, editors. *Gravel-bed rivers*. John Wiley and Sons, Chichester, United Kingdom.
- Brown M. 2002. Recreational use associated with the Snake River in the Hells Canyon National Recreation Area. In: *Technical appendices for new license application: Hells Canyon Hydroelectric Project*. Technical Report E.5-3, IPC, Boise, Idaho.
- Budhu M, Gobin R. 1994. *“Instability of Sandbars in Grand Canyon.”* *Journal of Hydraulic Engineering*, Vol. 120, No. 8, ASCE, pp. 919–933.
- Buffington JM, Montgomery DR. August 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research*, Vol. 33, No. 8, pp. 1993–2029.
- Buffington JM, Dietrich WE, Kirchner JW. February 1992. Friction angle measurements on a naturally formed gravel streambed: Implications for critical boundary shear stress. *Water Resources Research*, Vol. 28, No. 2, pp. 411–425.
- Butler M, editor. 2002. Topographic integration for the Hells Canyon studies. In: *Technical appendices for new license application: Hells Canyon Hydroelectric Project*. Technical Report E.1-3, IPC, Boise, Idaho.
- CH2M HILL. 1987. Hells Canyon Dam and powerhouse: Safety Report (FERC Project No. 1971). Prepared for IPC, Boise, Idaho.

- CH2M HILL. 1990. Hells Canyon Dam and powerhouse: stability study (FERC Project No. 1971). Prepared for IPC, Boise, Idaho.
- CH2M HILL. 2000. Estimate of total “pass through” fine sediment quantity in Brownlee Reservoir. Technical memorandum.
- Chandler JA, Brink S, Butler M, Parkinson SK. 2001. Hells Canyon instream flow assessment. In: Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.2.3-2, IPC, Boise, Idaho.
- Charleton FG, Brown PM, Benson RW. 1978. The hydraulic geometry of some gravel rivers in Britain. Report No. IT180, Hydraulics Research Station, Wallingford, United Kingdom.
- Chatters JC, Root MJ, Reid KC, Ferguson DE, Harder DA, Langdon JL, Leo MD, Nakonechny L, Harder DA, McKnight RM. 2001. From Hells Canyon Dam to the Salmon River: archaeological survey of Hells Canyon. In: Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.4-1, IPC, Boise, Idaho.
- Church M, Wolcott JF. November 1991. A test of equal mobility in fluvial sediment transport: behavior of the sand fraction. *Water Resources Research*, Vol. 27, No. 11, pp. 2941–2951.
- Clark LR, Sampson RN. 1995. Forest ecosystem health in the Inland West: A science and policy reader. Forest Policy Center, American Forests, Washington, D.C.
- Collier M, Webb RH, Schmidt JC. 1996. Dams and rivers: a primer on the downstream effects of dams. Circular 1126, U.S. Geological Survey, Tucson, AZ.
- Collins B, Dunne T. 1990. Fluvial geomorphology and river gravel mining: A guide for planners, case studies included. California Division of Mines and Geology Special Publication 98. Sacramento. In Kondolf GM, 1997. Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management*. Volume 21, No. 4.
- Dickerson BP. 1975. Stormflows and erosion after tree-length skidding on Coastal Plain soils. *Transactions of the American Society of Agricultural Engineers*, Vol. 18, No. 5, pp. 867–868, 872.
- Dietrich WE, Dunne T, Humphrey N, Reid LM. 1982. Construction of a sediment budgets for drainage basins. In: *Sediment Budgets and Routing in Forested Drainage Basins*, USFS Technical Report PNW-141, pp. 5–23.
- Engelund F, Hansen E. 1967. A monograph on sediment transport in alluvial streams, Teknisk Forlag, Copenhagen, Denmark.
- Garland RD, Rondorf DW, Tiffan KF, Clark LO. 2001. Subyearling fall chinook salmon use of shoreline riprap habitats in a reservoir of the Columbia River. In: KF Tiffan, DW Rondorf, WP Connor, HL Burge, editors. Post-release attributes and survival of

- hatchery and natural fall chinook salmon in the Snake River. Annual Report 1999. Prepared for the U.S. Department of Energy, Bonneville Power Administration.
- Gee DM, Thomas WA. 1991. HEC-6 User's manual supplement. U.S. Army Corps of Engineers, Hydrologic Engineering Center.
- Gessler J. 1971. Beginning and ceasing of sediment motion. In: HW Shen, editor. River mechanics. Fort Collins, CO. pp. 7:1–22.
- Glancy PA. 1973. A reconnaissance of stream flow and fluvial sediment transport. Incline Village Area, Lake Tahoe, Nevada. Water Resources Information Series, 2nd Progress Report, 1971, Nevada Division of Water Resources, Carson City, NV.
- Golder Associates, Inc. 1996. Photographic fragmentation assessment. In: GoldSize user guide. Redmond, WA.
- Grams PE, Schmidt JC. 1991. Degradation of alluvial sandbars along the Snake River below Hells Canyon Dam, Hells Canyon National Recreation Area, Idaho. Senior Thesis, Department of Geology, Middlebury College, Middlebury, VT. 98 p.
- Grams PE, Schmidt JC. 1999a. Sandbar erosion and deposition on the Snake River in Hells Canyon between 1990 and 1998. Final Report, Department of Geography and Earth Resources, Utah State University, Logan, UT. 54 p.
- Grams PE, Schmidt JC. 1999b. Sandbar and terrace erosion between 1964 and 1996 at the Tin Shed and Camp Creek cultural resource sites on the Snake River in Hells Canyon. Department of Geography and Earth Resources, Utah State University, Logan, UT.
- Griffiths GA. 1981. Flow resistance in gravel-bed rivers. Journal of the Hydraulics Division, ASCE, Vol. 107, No. HY7, pp. 899–918.
- Gross G. 2000. Prehistoric and historic archaeological inventory in the Oxbow and Hells Canyon reservoirs, Hell Canyon Complex (FERC No. 1971), southern Idaho. Prepared for IPC, Boise, Idaho.
- Groves PA. 2001a. The timing and distribution of fall chinook salmon spawning downstream of the Hells Canyon Complex. In: PA Groves, editor. Chapter 1. Evaluation of anadromous fish potential within the mainstem Snake River, downstream of the Hells Canyon Complex of reservoirs. Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.3.1-3, IPC, Boise, Idaho.
- Groves PA. 2001b. The quality and availability of fall chinook salmon spawning and incubation habitat downstream of the Hells Canyon Complex. In: PA Groves, editor. Chapter 3. Evaluation of anadromous fish potential within the mainstem Snake River, downstream of the Hells Canyon Complex of reservoirs. Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.3.1-3, IPC, Boise, Idaho.

- Groves PA, Chandler JA. 1999. Spawning habitat used by fall chinook salmon in the Snake River. *North American Journal of Fisheries Management*, Vol. 19, pp. 912–922.
- Groves PA, Chandler JA. 2001. Physical habitat and water quality criteria for chinook salmon associated with the Hells Canyon Complex. In: PA Groves, editor. Chapter 2. Evaluation of anadromous fish potential within the mainstem Snake River, downstream of the Hells Canyon Complex of reservoirs. Technical appendices for Hells Canyon Hydroelectric Project. Technical Report E.3.1-3, IPC, Boise, Idaho.
- Hall TE, Bird ER. 2002. Description of existing recreation sites in the Hells Canyon Complex and Hells Canyon National Recreation Area. In: Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.5-9, IPC, Boise, Idaho.
- Hayward JA. 1980. Hydrology and stream sediment from Torlesse Stream catchment. Special Publication 1, Tussock Grasslands and Mountain Lands Institute, Lincoln College Canterbury, New Zealand. 236 pp.
- Heady HF, Child RD. 1994. Rangeland ecology and management. Westview Press, Boulder, CO.
- Hey RD. 1979. Flow resistance in gravel-bed rivers. *Journal of the Hydraulics Division, ASCE*, Vol. 105, No. HY4, pp. 365–379.
- Holmstead GL. 2001. Shoreline soil erosion in Hells Canyon. In: Technical appendices for Hells Canyon Complex Hydroelectric Project. Technical Report E.3.2-42, IPC, Boise, Idaho.
- Hortness JE, Berenbrock C. 2001. Estimating monthly and annual streamflow statistics at ungaged sites in Idaho. WRI Report 01-4093, U.S. Geographical Survey, Boise, Idaho.
- Interior Columbia Basin Ecosystem Management Project (ICBEMP). 2001. Precipitation data for Hells Canyon. Available at <<http://www.icbemp.gov>>.
- Idaho Department of Environmental Quality (IDEQ). August 1993. Idaho agricultural pollution abatement plan. IDEQ and Idaho Department of Lands Soil Conservation Commission, Boise, Idaho.
- Jarrett RD. 1984. Hydraulics of high-gradient streams. *Journal of the Hydraulics Division, ASCE*, Vol. 110, No. 11, pp. 1519–1539.
- Karim MF, Holly FM. 1986. Armoring and sorting simulation in alluvial rivers. *Journal of Hydraulic Engineering, ASCE*, Vol. 112, No. 8, pp. 705–715.
- Karim MF, Holly FM, Kennedy JF. 1982. IALLUVIAL: A computer based flow and sediment routing model for alluvial streams and its application to the Missouri River. Report No. 250, Institute of Hydraulic Research, University of Iowa, Iowa City.

- Kellerhals R, Bray DL. 1971. Sampling procedures for coarse fluvial sediments. *Journal of the Hydraulics Division, ASCE*, Vol. 97, No. HY8, pp. 1165–1180.
- Kjelstrom LC, Stone MAJ, and Harenberg WA. 1996. Statistical summaries of streamflow data for selected gaging stations in Idaho and adjacent states through September 1990. In: Vol. 1, Gaging stations with 10 or more years of record. *Water-Resources Investigations Report 94-4069*, U.S. Geological Survey, Boise, Idaho.
- Kuhnle RA. 1993. Incipient motion of sand-gravel sediment mixtures. *Journal of Hydraulic Engineering, ASCE*, Vol. 119, No. 12, pp. 1400–1415.
- Lagasse PF, Schall JD, Johnson F, Richardson EV, Richardson JR, Chang JM. 1991. Stream stability at highway structures. *Hydraulic Engineering Circular No. 20*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.
- Lamberti A, Paris E. 1992. Analysis of armoring processes through laboratory experiments. In: P Billi, RD Hey, CR Thorne, P Tacconi, editors. *Dynamics of gravel-bed rivers*. John Wiley and Sons, Chichester, United Kingdom. pp. 227–250.
- Limerinos JT. 1970. Determination of the Manning coefficient for measured bed roughness in natural channels. *Water Supply Paper 1898-B*, U.S. Geological Survey, Washington, D.C.
- Little WC, Mayer PG. 1972. The role of sediment gradation on channel armoring. Publication No. ERC-0672, School of Civil Engineering in cooperation with Environmental Research Center, Georgia Institute of Technology, Atlanta, GA.
- Lopes VL, Osterkamp WR, Bravo-Espinosa M. 2001. Evaluation of selected bedload equations under transport- and supply-limited conditions. *Proceedings of the 7th Federal Interagency Sedimentation Conference*, March 25–29, 2001, Reno, NV.
- Marcus MD, Young MK, Noel LE, Mullan BA. 1990. Salmonid–habitat relationships in the western United States: a review and indexed bibliography. *General Technical Report RM-GTR-188*, U.S. Department of Agriculture, Forest Service, Rocky Mountain forest and Range Experiment Station, Fort Collins, CO.
- Mauser L, Nelson MA, Miss CJ. 2001. Cultural resources survey of the Brownlee Reservoir drawdown zone and reservoir margin, Washington and Adams counties, Idaho; Baker and Malheur counties, Oregon. Prepared for IPC, Boise, Idaho.
- Megahan WF. 1975. Sedimentation in relation to logging activities in the mountains of central Idaho. In: *Present and prospective technology for predicting sediment yields and sources*. ARS-S-40, U.S. Department of Agriculture, Sedimentation Laboratory, Oxford, MS. pp. 74–82.
- Meyer-Peter E, Muller R. 1948. Formula for bedload transport. Vol. 6. *Proceedings of the 2nd Congress, International Association for Hydraulic Research*, Stockholm, Sweden. pp. 39–64.

- Milhous RT. 1973. Sediment transport in a gravel-bottomed stream. Ph.D. Dissertation, Kyoto University, Kyoto, Japan.
- Milhous RT, Klingeman PC. 1973. Sediment transport systems in a gravel-bottomed stream. In: Hydraulic engineering and the environment. Proceedings of the ASCE 21st Annual Hydraulics Division Specialty Conference, Bozeman, MT. pp. 293–303.
- Milhous RT, Updike MA, Schneider DM. 1989. Physical habitat simulation system reference manual, version II. Instream Flow Information Paper 26, National Ecology Research Center, Fort Collins, CO.
- Miller S, Glanzman R, Doran S, Parkinson SK, Buffington J, Milligan J. 2003. Geomorphology of the Hells Canyon Reach of the Snake River. In: Technical appendices for Hells Canyon Hydroelectric Project. Technical Report E.1-2, IPC, Boise, Idaho.
- Molinas A. 1998. Effect of size gradation on transport of sediment mixtures. Journal of Hydraulic Engineering, ASCE, Vol. 124, No. 8, pp. 786–793.
- Morris GL, Fan J. 1997. Reservoir sedimentation handbook: Design and management of dams, reservoirs, and watersheds for sustainable use. McGraw-Hill.
- Mussetter RA. 1989. Dynamics of mountain streams. Ph.D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, CO.
- Naiman RJ, Johnson CA, Kelley JC. 1988. Alteration of North American streams by beaver. BioScience, Vol. 38. pp. 753–762.
- National Park Service (NPS). 2001. Snake River: Idaho and Oregon. Available at <<http://www.nps.gov/rivers/wsr-snake.html>>.
- National Council for Air and Stream Improvement (NCASI). December 1999. Silviculture and water quality: a quarter century of Clean Water Act progress. Special Report No. 99–06, National Council for Air and Stream Improvement, Corvallis, OR.
- Northwest Power Planning Council (NPPC). 2000. Return to the river. Publication 2000-12, Northwest Council, Northwest Power Planning Council, Portland, OR.
- O'Connor JE. 1993. Hydrology, hydraulics, and geomorphology of the Bonneville Flood. Special Paper 274, Geological Society of America, Boulder, CO.
- Osterkamp W. 1997. Expert witness report in SRBA Case No. 39576. Twin Falls (ID): Prepared for the U.S. Fish and Wildlife Service.
- Othberg KL. 1994. Geology and geomorphology of the Boise Valley and adjoining areas, western Snake River Plain, Idaho. Bulletin 29, Idaho Geological Survey, Moscow, Idaho.
- Pacific Northwest River Basins Commission. 1973. Anatomy of a River...An Instream Controlled Flow Investigation of the Middle Snake River; Hell's Canyon Reach:

- March 20–26, 1973; Some Findings and Recommendations. Pacific Northwest River Basins Commission, 1 Columbia River, PO Box 908, Vancouver, Washington, 98660.
- Parker G. 1990. Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*, Vol. 28, No. 4, pp. 417–436.
- Parkinson SK, editor. 2002. Project hydrology and hydraulic models applied to the Hells Canyon reach of the Snake River. In: Technical appendices for Hells Canyon Hydroelectric Project. Technical Report E.1-4, IPC, Boise, Idaho.
- Pierce KL, Scott WE. 1982. Pleistocene episodes of alluvial-gravel deposition, southeastern Idaho. In: B Bonnicksen RM Breckenridge, editors. *Cenozoic geology of Idaho*. Bulletin 26, Idaho Bureau of Mines and Geology, Moscow, Idaho. pp. 685–702.
- Platts WS. 1991. Livestock grazing. Influences of forest and rangeland management on salmonid fishes and their habitat. Special Publication 19, American Fisheries Society. pp. 389–423.
- Proffitt GT. 1980. Selective transport and armoring of nonuniform alluvial sediments. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand.
- Raudkivi AJ. 1990. *Loose boundary hydraulics*. 3rd edition. Pergamon Press, Oxford, United Kingdom.
- Raudkivi AJ. 1998. *Loose boundary hydraulics*. AA Balkema Publishers, Rotterdam, The Netherlands.
- Reid LM, Dunne T. 1996. *Rapid Evaluation of Sediment Budgets, GeoEcology*, ISBN 3-923381-26-3.
- Rocklage AM, Edelmann FB. 2001. Effects of water-level fluctuations on riparian habitat fragmentation. In: Technical appendices for new license application: Hells Canyon Hydroelectric Project. Technical Report E.3.2-41, IPC, Boise, Idaho.
- Rosgen D, Silvey HL. 1996. *Applied river morphology*. Wildland Hydrology, Pagosa Springs, CO.
- Sargent RJ. 1979. Variation of Manning's  $n$  roughness coefficient with flow in open river channels. *Journal of the Institution of Water Engineers and Scientists*, Vol. 33, No. 3, pp. 290–294.
- Schmidt JC Rubin DM. 1995. Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. In J.E. Costa, A.J. Miller, K.W. Potter, and P.R. Wilcock (eds.) *Natural and Anthropogenic Influences in Fluvial Geomorphology*. Washington (DC): American Geophysical Union, Monograph 89, pp. 177–196.
- Schoklitsch A. 1962. *Handbuch des wasserbaues*. 3rd edition. Springer-Verlag, Vienna, Austria.

- Shields A. 1936. Application of similarity principles and turbulence research to bedload movement. Translated from German. California Institute of Technology, Pasadena.
- Simons DB, Senturk F. 1992. Sediment transport technology: water and sediment dynamics. Water Resources Publications, Littleton, CO.
- Simons, Li & Associates, Inc. 1989. Technical report for national forest stream studies. Prepared for the State of Colorado, Office of the Attorney General.
- Slaughter CW, Cooley KR, Hanson CL, Pierson FB, Hartzmann RL, Huber AL, Awang JB. 1996. Baseline sediment yield from dissimilar headwaters research watersheds. Proceedings of the 6th Federal Interagency Sedimentation Conference, March 10–14, 1996, Las Vegas, NV.
- Smart GM. 1984. Sediment transport formula for steep channels. *Journal of Hydraulic Engineering, ASCE*, Vol. 110, No. HY3, pp. 267–276.
- Smart GM, Jaeggi MNR. 1983. Sediment transport on steep slopes. *Mitteil 64, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH-Zurich, Switzerland*. 191 pp.
- Spaulding WM, Ogden RD. 1968. Effects of surface mining on the fish and wildlife resources of the United States. Publication 68, U. S. Fish and Wildlife Service, Bureau of Sport Fisheries and Wildlife Resources.
- Spence BC, Lomnický GA, Hughes RM, Novitzki RP. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057, ManTech Environmental Research Services Corporation, Corvallis, OR.
- Stelczer K. 1981. Bedload transport: theory and practice. Water Resources Publications, Littleton, CO. 295 pp.
- Strand RI, Pemberton EL. 1982. Reservoir sedimentation. Technical guideline for Bureau of Reclamation. Sedimentation and River Hydrology Section, Hydrology Branch, Division of Planning Technical Services, Engineering and Research Center, Bureau of Reclamation, Denver, CO.
- Thorne CR. 1997. Channel types and morphological classification. In: C. R. Thorne, R. D. Hey, and M. D. Newson. *Applied fluvial geomorphology for river engineering and management*. John Wiley and Sons, Chichester, United Kingdom. pp. 175–222.
- Tiffan KF, Garland RD, Rondorf DW. 2002. Submitted to *North American Journal of Fisheries Management*. Modeling flow-dependent changes in juvenile fall chinook salmon rearing habitat and entrapment areas in the Hanford reach of the Columbia River.
- Tisdale EW. 1986. Canyon grasslands and associated shrublands of west central Idaho and adjacent areas. Bulletin 40, Forest, Wildlife, and Range Experiment Station, University of Idaho, Moscow. 42 pp.

- U.S. Bureau of Reclamation (USBR). April 1998. Biological assessment: Bureau of Reclamation operations and maintenance in the Snake River Basin above Lower Granite Reservoir, Boise, Idaho. U.S. Bureau of Reclamation, Pacific Northwest Region.
- U.S. Department of Agriculture (USDA). October 16, 1995. A comparison of stream materials moved by mining suction dredge operations to the natural sediment yield rates. Letter to the record prepared by Michael Cooley, U.S. Department of Agriculture, Siskiyou National Forest, Grants Pass, OR.
- U.S. Department of Agriculture (USDA). November 1996. Status of Interior Columbia Basin: Summary of scientific findings. U.S. Forest Service, Pacific Northwest Research Station, Interior Columbia Basin Ecosystem Management Project, Portland, OR.
- U.S. Department of Agriculture (USDA). October 1997. South fork Clearwater subbasin. Preliminary Report, Landscape Assessment, U.S. Forest Service, Nez Perce National Forest, Grangeville, Idaho.
- U.S. Forest Service (USFS). 1985. The wild and scenic Snake River Hells Canyon National Recreation Area. Publication 1985-595-832 (revised in 1994), U.S. Government Printing Office, Washington, D.C.
- U.S. Forest Service (USFS). November 6, 1998. Information needs assessment. Draft providing IPC with a detailed description of Forest Service study requirements displaying Forest Plan direction and scope of required analysis, U.S. Department of Agriculture, Forest Service.
- U.S. Geological Survey (USGS). 2001. Magnitude and frequency of instantaneous peak flow at gaging stations in Idaho. Retrieved from <http://idaho.usgs.gov/swdata/floodfreq.html> on January 11, 2001.
- Vallier TL. 1998. Islands and rapids: A geologic story of Hells Canyon. Confluence Press, Lewiston, Idaho.
- Vanoni VA, editor. 1975. Sedimentation engineering. Reprinted in 1977, ASCE Task Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Subcommittee of the Hydraulics Division, ASCE.
- Vanoni VA, editor. 1977. Sedimentation engineering. Task Committee for the Preparation of the Manual on Sedimentation of the Sedimentation Committee of the Hydraulics Division, ASCE, New York, NY. 388 pp.
- Webb RH, Griffiths PG, Hartley DR. 2001. Techniques for estimating sediment yield of ungaged tributaries on the southern Colorado plateau. Proceedings of the 7th Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, NV. pp. I-24-I-31.
- White WR, Day TJ. 1982. Transport of graded gravel bed material. In: RD Hey, JC Bathurst, CR Thorne, editors. Gravel-bed rivers. John Wiley and Sons, Chichester, United Kingdom. pp. 181-213.

- Whittaker JG. 1987. Sediment transport in step-pool streams. In: CR Thorne, JC Bathurst, RD Hey, editors. Sediment transport in gravel-bed rivers. John Wiley and Sons, Chichester, United Kingdom. pp. 545–579.
- Wiberg PL, Smith JD. August 1987. Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. *Water Resources Research*, Vol. 23, No. 8, pp. 1471–1480.
- Wohl E. 2000. Mountain rivers. Water Resources Monograph 14, American Geophysical Union, Washington, D.C.
- Wolman MG. 1954. A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union*, Vol. 35, No. 6, pp. 951–956.
- Worman A. 1992. Incipient motion during static armor. *Journal of Hydraulic Engineering*, ASCE, Vol. 118, No. 3, pp. 496–501.
- Wright K, Sendek KH, Rice RH, Thomas RB. 1990. Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California, *Water Resour. Res.*, 26, 1657, 1990.
- Yang CT. 1996. Sediment transport: theory and practice. McGraw-Hill, New York.
- Ziemer RR. 1981. Storm flow response to road building and partial cutting in small streams of northern California, *Water Resour. Res.*, 17, 907, 1981.

### 13. ADDITIONAL RESOURCES

- Afzalimehr H, Anctil F. 1998. Estimation of gravel-bed river flow resistance. *Journal of Hydraulic Engineering*, Vol. 124, No. 10, pp. 1054–1058.
- Ashida K, Bayazit M. 1973. Initiation of motion and roughness of flows in steep channels. *Proceedings of the 15th Congress, International Association of Hydraulic Engineering and Research, Istanbul, Turkey*, Vol. 1, pp. 475–484.
- Ashida K, Takahashi T, Sawada T. 1976. Sediment yield and transport on a mountainous small watershed. Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan, *Bulletin DPRI*, Vol. 26, No. 240, pp. 119–144.
- Ashida K, Takahashi T, Sawada T. 1981. Processes of sediment transport in mountain stream channels. In: TRH Davies, AJ Pearce, editors. *Erosion and sediment transport in Pacific Rim steeplands*, International Association of Hydrology, Science Publication No. 132, pp. 166–178.
- Barnes HH. 1967. Roughness characteristics of natural channels. *Water Supply Paper 1849*, United States Geological Survey, Washington, D.C. 213 pp.

- Bathurst JC. 1986. Slope-area discharge gaging in mountain rivers. *Journal of Hydraulics Division, ASCE*, Vol. 112, No. 5, pp. 376–391.
- Bettess R. 1984. Initiation of sediment transport in gravel streams. *Proceedings of the Institution of Civil Engineers*, Vol. 77, Part 2, Tech. Note 407, pp. 79–88.
- Brice JC. 1983. Planform properties of meandering rivers. In: C. M. Elliott, editor. *River meandering. Proceedings of the Conference on Rivers '83*, New Orleans, LA, Oct. 24–26, 1983, ASCE Special Publication, pp. 1–15.
- Brink M, Grant G. August 1999. Literature review of geomorphic, hydrologic, and sediment transport literature pertaining to Hells Canyon and the Snake River. U.S. Forest Service, Pacific Northwest Research Station, Corvallis, OR.
- Carling PA. 1983. Threshold of coarse sediment transport in broad and narrow natural streams. *Earth surface processes and landforms*, Vol. 8, pp. 1–18.
- Carling PA. 1983. Threshold of coarse sediment transport in broad and narrow natural streams. *Earth surface processes and landforms*, Vol. 8, pp. 493–500.
- Chang HH. 1980. Geometry of gravel streams. *Journal of Hydraulics Division, ASCE*, Vol. 106, No. HY9, pp. 1443–1456.
- Chow VT. 1959. *Open-channel hydraulics*. McGraw-Hill, New York.
- Dey S, Debnath K. 2000. Influence of stream-wise bed slope on sediment threshold under stream flow. *Journal of Irrigation and Drainage Engineering, ASCE*, Vol. 126, No. 4, pp. 255–264.
- Egiazaroff IV. 1965. Calculation of non-uniform sediment concentrations. *Journal of Hydraulics Division, ASCE*, Vol. 91, No. HY4, pp. 225–247.
- Einstein HA, Chien N. 1953. Transport of sediment mixtures with large ranges of grain sizes. MRD Sediment Series No. 2, U.S. Army Engineering Division, Missouri River, U.S. Army Corps of Engineers, Omaha, NE.
- Emmett WW. 1975. The channels and waters of the upper Salmon River area. Idaho Professional Paper 870-A, U.S. Geological Survey. Washington, D.C. 116 pp.
- Emmett WW, Thomas WA. 1978. Scour and deposition in Lower Granite Reservoir, Snake and Clearwater rivers near Lewiston, Idaho, USA. *Journal of Hydraulic Research*, Vol. 16, No. 4, pp. 327–345.
- Ferro V, Giordano G. 1991. Experimental study of flow resistance in gravel-bed rivers. *Journal of Hydraulics Division, ASCE*, Vol. 117, No. 10, pp. 1239–1246.
- Jackson WL. 1981. Bed material routing and streambed composition in alluvial channels. Ph.D. Dissertation, Oregon State University, Corvallis, OR. 164 pp.

- Jackson WL, Beschta RL. 1982. A model of two-phase bedload transport in an Oregon coast range stream. In: Earth surface processes and landforms, Vol. 7, No. 6, pp. 517–527.
- Kellerhals R. 1967. Stable channels with gravel paved beds. Journal of the Waterways and Harbors Division, ASCE, Vol. 93, No. WW1, 63 pp.
- Kjelstrom LC, Stone MAJ, Harenburg WA. 1996. Statistical summaries of streamflow data for selected gaging stations in Idaho and adjacent states through September 1990—volume 1: gaging stations with 10 or more years of record. U.S. Geological Survey Water-Resources Investigations Report 94-4069.
- Klingeman PC, Emmett WW. 1982 Gravel bedload transport processes. *In*: RD Hey, JC Bathurst, CR Throne, editors. Gravel-bed rivers. John Wiley and Sons. Chichester, United Kingdom, pp. 141–169.
- Komar PD. 1987. Selective grain entrainment by a current from a bed of mixed sizes. Jour. Sediment. Petrol. Vol. 57, pp. 203–211.
- Lane EW. 1953. Design of stable channels. Transactions, ASCE, Vol. 120, No. 280, pp. 1243–1260.
- Laronne JB, Carson MA. 1976. Interrelationships between bed morphology and bed-material transport for a small, gravel-bed channel. Sedimentology, Vol. 23, No. 1, pp. 67–85.
- Miller MC, McCave IN, Komar PD. 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, Vol. 24, pp. 507–527.
- Neill CR. 1987. Sediment balance considerations linking long-term transport and channel processes,” In: C. R. Thorne, J. C. Bathurst, and R. D. Hey, editors. Sediment transport in gravel-bed rivers. John Wiley and Sons, Chichester, United Kingdom, pp. 225–240.
- Parker G. 1979. Hydraulic geometry of active gravel rivers. Jour. Hydr. Div., ASCE, Vol. 105, No. HY9, pp. 1185–1201.
- Parker G, Klingeman PC, McLean DG. 1982. Bedload and size distribution in paved gravel-bed streams. Jour. Hydraul. Div. ASCE, Vol. 108, No. HY4, pp. 544–571.
- Proffitt GT, Sutherland AJ. 1983. Transport of non-uniform sediments. Journal of Hydraulic Research, Vol. 21, No. 1, pp. 33–43.
- Raudkivi AJ, Ettema R. 1982. Stability of armor layers in rivers. Jour. Hydraulics Division, ASCE, Vol. 108, No. HY9, pp. 1047–1057.
- Reid I, Frostick LE. 1984. Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channels. In: EH Koster RJ Steel, editors. Sedimentology of gravels and conglomerates. Canadian Society of Petroleum Geologists, Memoir 10, pp. 61–68.

- Reid LM, Dunne T. 1996. Rapid Evaluation of Sediment Budgets, GeoEcology, ISBN 3-923381-26-3.
- Ryan S. 2001. The influence of sediment supply on rates of bedload transport: a case study of three streams on the San Juan National Forest. Proceedings of the Seventh Federal Interagency Sedimentation Conference, March, 2001, Reno, NV. pp. III-48–III-54.
- Samanaga BR, Ranga Raju KG, Garde RJ. 1986. Bedload transport of sediment mixtures. Jour. Hydraulic Engineering, ASCE, Vol. 112, No. 11, pp. 1003–1018.
- Schmidt JC. 1999. Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon. In RH Webb, JC Schmidt, GR Marzolf, and RA Valdez (eds.) The Controlled Flood in Grand Canyon. Washington (DC): American Geophysical Union, Monograph 110, pp. 329–341.
- Shih S, Komar P. 1990. Differential bedload transport rates in a gravel-bed stream: a grain size distribution approach. Earth surface processes and landforms, Vol. 15, pp. 539–552.
- Simons & Associates, Inc. In association with Hydrau-Tech Engineering. 1989. Computer analysis of highway encroachments on mobile boundary streams. Quarterly Progress Report to the National Cooperative Highway Research Program on Project NCHRP 15-11.
- Simons RK, Mussetter RA, Julien PY, Simons DB. 1989. Modeling resistance to flow in open channels. Proc. 1989 National Conference on Hydraulic Engineering.
- Wilcock PR. 1993. Critical shear stress of natural sediments. Jour. of Hydraulic Engineering, ASCE, Vol. 119, No. 4, pp. 491–505.
- Wilcock PR. 1998. Sediment maintenance flows: feasibility and basis for prescription. *In*: PC Klingeman, RL Beschta, PD Komar JB Bradley, editors. Gravel-bed rivers in the environment. Water Resources Publications. Littleton, CO. pp. 608–638.

Table 1. Upstream reservoirs and sediment trapping efficiency.

Reservoir	Storage Capacity <sup>1</sup> (acre-feet)	Upstream Gauge	Average Annual Inflow (cfs)	Outlet Works Capacity (cfs)	Reservoir Length (mi)	Churchill Methodology				Brune's Methodology	
						(average inflow)		(outlet capacity)		Capacity/ Inflow	Sediment Trapped (%)
						K	Sediment Trapped (%)	K	Sediment Trapped (%)		
American Falls	1,672,590	695	4,912	19,400	24.0	5.59E+10	100.0	3.58E+09	92.4	0.470	95.0
Anderson Ranch	493,200	1860	779	10,000	13.6	3.41E+11	100.0	2.07E+09	90.1	0.875	97.0
Arrowrock	286,600	1905/1850	2,202	10,230	17.0	1.15E+10	96.4	5.34E+08	83.3	0.180	91.0
Beulah/Agency Valley Dam	59,900	2175 <sup>1</sup>	144	600	2.6	7.70E+11	100.0	4.44E+10	100.0	0.575	
Black Canyon	44,650	2475	3,253	1,203	9.0	2.42E+08	78.3	1.77E+09	89.4	0.019	58.0
Bully Creek	31,650	2265	55	580	3.0	1.29E+12	100.0	1.15E+10	96.4	0.798	
Cascade	703,200	2390	364	2,530	15.0	2.88E+12	100.0	5.96E+10	100.0	2.668	97.0
Deadwood	162,000	2365 <sup>1</sup>	233	2,600	3.5	1.60E+12	100.0	1.28E+10	96.8	0.960	97.0
Lucky Peak	306,000	1905/1850	2,202	5,500	12.0	1.86E+10	97.9	2.98E+09	91.6	0.192	92.0
Mann Creek	12,950			300	1.8			1.20E+10	96.6		
Owyhee	1,122,000	1810	975	2,530	52.0	2.95E+11	100.0	4.38E+10	100.0	1.590	97.0
Thief Valley	26,000	2850 <sup>1</sup>	122	2,150	2.4	2.18E+11	100.0	7.05E+08	84.8	0.294	94.0
Unity	27,000	2725 <sup>1</sup>	122	620	1.97	2.86E+11	100.0	1.11E+10	96.3	0.305	94.0
Warm Springs	192,400	2150 <sup>1</sup>	191	2,000	6.5	1.81E+12	100.0	1.65E+10	97.5	1.391	97.0
						Maximum	100.0		100.0		97.0
						Minimum	78.3		83.3		58.0
						Average	97.9		93.9		91.7

<sup>1</sup> Total storage capacity where available, active capacity otherwise.

Table 2. Sources, years, scale, and approximate coverage of aerial photographs used in the study (RM 247.6 downstream to RM 188.28).

<b>Source</b>	<b>Year</b>	<b>Scale</b>	<b>River Mile Coverage</b>
Wallowa–Whitman National Forest (Enterprise, OR)	1946	1/20,000	RM 233.3 to RM 190.6
Nez Perce National Forest (Grangeville, Idaho)	1948	1/20,000	RM 223.7 to RM 206.1
	1949	1/20,000	RM 232.5 to RM 215.9
USDA APFO (Salt Lake City, UT)	1955	1/20,000	RM 247.6 to RM 188.28
	1964	1/12,000	RM 247.6 to RM 188.28
US Army Corp of Engineers (Walla Walla District)	1973	1/12,000	RM 247.6 to RM 188.28
	1977	1/12,000	RM 247.6 to RM 188.28
	1982	1/12,000	RM 247.6 to RM 188.28
Idaho Power Company (Boise, ID)	1961	1/20,000	RM 211.5 to RM 187.0
	1968	1/20,000	RM 205.6 to RM 187.0
	1997	1/8,400	RM 247.6 to RM 188.28

Table 3. Sandbars surveyed by location, date, and daily average flow (cfs) at time of survey.

<b>Location</b>	<b>Date</b>	<b>Daily Average Flow (cfs)</b>
Pine Bar	11/17/1997	12,144
Fish Trap Bar	11/20/1997	12,147
China Bar	11/18/1997	12,141
Salt Creek	11/19/1997	12,129
Pine Bar	11/3/1998	9,557
Fish Trap Bar	11/4/1998	9,555
China Bar	11/5/1998	9,575
Salt Creek	11/4/1998	9,555
Pine Bar	11/9/1999	12,997
Fish Trap Bar	11/11/1999	12,988
China Bar	Not surveyed	
Salt Creek	Not surveyed	
Pine Bar	12/3/2000	9,972
Fish Trap Bar	12/4/2000	12,044
China Bar	12/5/2000	15,337
Salt Creek	12/4/2000	12,044

Table 4. Coefficients and exponents for power form flow resistance equations.

Stream Gradient (%)	Intermediate-Scale Roughness			Large-Scale Roughness		
	A	B	C	a	b	c
< 1.5	2.24	0.60	-0.30	*	*	*
1.5-4.0	1.68	0.44	-0.40	1.29	0.75	-0.60
4.0-10.0	0.86	0.56	-0.50	0.36	0.50	-1.40
> 10.0	*	*	*	0.35	0.35	-1.60

\* No relationship developed because of inadequate data.

Table 5. Bed shear stress values ( $\tau_b$ ) from MIKE 11 model in  $N/m^2$ .

		River Mile	247.4	247.3	247.2	247.1	247
		Chainage	400.40	521.30	886.00	945.50	1025.70
CFS	CMS	$\tau_b-N/m^2$	$\tau_b-N/m^2$	$\tau_b-N/m^2$	$\tau_b-N/m^2$	$\tau_b-N/m^2$	$\tau_b-N/m^2$
30,000	850	74.42	82.62	161.32	43.81	40.68	
39,670	1,124	82.16	93.8	176.34	60.47	49.67	
100,000	2,832	132.18	147.14	246.36	179.62	88.72	

Table 6. Calculated dimensionless shear stress values ( $\theta_*$ ) using equation 31.

		River Mile	247.4	247.3	247.2 (Rapid)	247.1	247
		Chainage	400.40	521.30	886.00	945.50	1025.70
		$d_{84}$ mm	230	170	150	230	160
CFS	CMS						
30,000	850	0.018	0.028	0.061	0.011	0.014	
39,670	1,124	0.020	0.031	0.067	0.015	0.018	
100,000	2,832	0.033	0.049	0.093	0.044	0.031	

Table 7. Sediment yield values from published sources.

Reference	Value	Units	Watershed Area	Description
Glancy (1973)	351	ton/mi <sup>2</sup> /yr		Mined areas, Lake Tahoe area
	6,899	ton/mi <sup>2</sup> /yr		
Glancy (1973)	55	ton/mi <sup>2</sup> /yr		Undisturbed areas, Lake Tahoe area
	843	ton/mi <sup>2</sup> /yr		
Spaulding and Ogden (1968)	77,380	ton/yr		Hydraulic mining in the Boise River Basin
J. Barry (pers. comm., 2001)	4,015	ton/mi <sup>2</sup> /yr		Rapid River
	730	ton/mi <sup>2</sup> /yr		South Fork Salmon River
	12,775	ton/mi <sup>2</sup> /yr		
	3,285	ton/mi <sup>2</sup> /yr		Red River
Morris and Fan (1997)	2,851	ton/mi <sup>2</sup> /yr		Extremely high value
	142,350	ton/mi <sup>2</sup> /yr		
Megahan (1975)	193	ton/mi <sup>2</sup> /yr		Undisturbed watershed in Idaho
	29,784	ton/mi <sup>2</sup> /yr		Disturbed watershed in Idaho
Vanoni (1977)	10,731	ton/mi <sup>2</sup> /yr		Briar Creek Basin, 14.6mi <sup>2</sup>
	500	ton/mi <sup>2</sup> /yr		From reservoir measurements
	4,891	ton/mi <sup>2</sup> /yr		From reservoir measurements
	6,497	ton/mi <sup>2</sup> /yr		Upper end of range
ICBEMP (1993)	241	ton/mi <sup>2</sup> /yr		Arrowrock—measured October 1947
	329	ton/mi <sup>2</sup> /yr		Arrowrock—measured June 1997
	369	ton/mi <sup>2</sup> /yr		Black Canyon—measured August 1936
	329	ton/mi <sup>2</sup> /yr		Black Canyon—measured June 1971
	329	ton/mi <sup>2</sup> /yr		Bully Creek
	1,132	ton/mi <sup>2</sup> /yr		Cascade
	285	ton/mi <sup>2</sup> /yr		Mann Creek
	850	ton/mi <sup>2</sup> /yr		Mann Creek—measured June 1992
285	ton/mi <sup>2</sup> /yr		Unity	
6 <sup>th</sup> FISC (Slaughter et al. 1996).	540	ton/mi <sup>2</sup> /yr		Reynolds Creek watershed
7 <sup>th</sup> FISC (Webb et al. 2001)	2,340	ton/mi <sup>2</sup> /yr		Southern Colorado plateau
4 <sup>th</sup> FISC (Allen 1986)	1,657	ton/mi <sup>2</sup> /yr		Unnamed drainage in Oklahoma
	2,486	ton/mi <sup>2</sup> /yr		Unnamed drainage in Oklahoma
	956	ton/mi <sup>2</sup> /yr		Winter Creek
	1,365	ton/mi <sup>2</sup> /yr		East Bitter Creek
7 <sup>th</sup> FISC (Webb et al. 2001)	163	ton/mi <sup>2</sup> /yr	11.3 mi <sup>2</sup>	Moenkopi Wash #1 (Colorado Plateau)
	338	ton/mi <sup>2</sup> /yr	52.2 mi <sup>2</sup>	Yellow Water Wash #1 (Colorado Plateau)
	483	ton/mi <sup>2</sup> /yr	3650 mi <sup>2</sup>	Paria River at Lees Ferry (Colorado Plateau)
<b>Hells Canyon Calculated Values</b>	51,800	ton/mi <sup>2</sup> /yr	33.4 mi <sup>2</sup>	<b>Granite Creek</b>

Table 8. PSD of Sand Data Collected During Provenance Sampling at Fish Trap Bar.

Location	Test Hole	Depth		Sediment Sizes (% in Class)												
		top ft	bottom ft	d <sub>84</sub> mm	d <sub>50</sub> mm	d <sub>16</sub> mm	σ <sub>g</sub>	Silt/Clay	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand	Very Fine Gravel	Medium and Fine Gravel	Coarse and Larger Gravel
								<0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1 mm	1-2 mm	2-4 mm	4-16 mm	>16 mm
Fish Trap	F1	0	1	0.69	0.40	0.27	2.57	0.8	1.0	10.0	63.1	24.3	0.7	0.0	0	0
Fish Trap	F1	1	2	0.70	0.40	0.26	2.75	1.5	1.2	11.9	59.0	25.6	0.8	0.0	0	0
Fish Trap	F1	2	3	0.71	0.39	0.23	3.10	1.2	2.1	15.3	55.3	24.1	1.5	0.3	0.1	0
	<b>Average</b>			<b>0.70</b>	<b>0.40</b>	<b>0.25</b>	<b>2.79</b>	<b>1.2</b>	<b>1.4</b>	<b>12.4</b>	<b>59.1</b>	<b>24.7</b>	<b>1.0</b>	<b>0.1</b>	<b>0.0</b>	<b>0.0</b>
	<b>Median</b>			<b>0.70</b>	<b>0.40</b>	<b>0.26</b>	<b>2.75</b>	<b>1.2</b>	<b>1.2</b>	<b>11.9</b>	<b>59.0</b>	<b>24.3</b>	<b>0.8</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>
Fish Trap	F2	0	0.5	0.43	0.26	0.15	2.91	4.4	4.5	38.9	50.2	1.8	0.1	0.0	0	0
Fish Trap	F2	0.5	1	0.43	0.26	0.15	2.93	3.6	5.9	39.1	50.1	1.2	0.0	0.0	0	0
Fish Trap	F2	1	1.5	0.42	0.23	0.13	3.32	5.1	10.5	40.0	41.8	2.4	0.1	0.0	0	0
Fish Trap	F2	1.5	2	0.45	0.30	0.15	3.03	3.0	7.0	29.8	53.9	6.1	0.1	0.0	0	0
Fish Trap	F2	2	2.5	0.47	0.34	0.19	2.43	1.5	3.2	20.8	66.7	7.9	0.0	0.0	0	0
Fish Trap	F2	2.5	3	0.45	0.30	0.16	2.78	1.7	5.8	30.4	59.1	2.9	0.1	0.0	0	0
Fish Trap	F2	3	3.5	0.47	0.34	0.20	2.35	0.8	2.9	20.9	68.6	6.7	0.1	0.0	0	0
Fish Trap	F2	3.5	4	0.45	0.32	0.17	2.66	1.6	4.3	27.6	61.6	4.8	0.0	0.0	0	0
Fish Trap	F2	4	4.5	0.46	0.33	0.17	2.62	2.1	4.7	23.2	65.0	4.9	0.2	0.0	0	0
Fish Trap	F2	4.5	5	0.47	0.34	0.19	2.50	1.9	4.6	19.1	66.7	7.6	0.2	0.0	0	0
Fish Trap	F2	5	5.5	4.33	0.34	0.15	29.45	4.6	7.3	23.4	41.9	4.5	0.5	1.7	16.2	0
	<b>Average</b>			<b>0.80</b>	<b>0.31</b>	<b>0.16</b>	<b>4.90</b>	<b>2.8</b>	<b>5.5</b>	<b>28.5</b>	<b>56.9</b>	<b>4.6</b>	<b>0.1</b>	<b>0.2</b>	<b>1.5</b>	<b>0.0</b>
	<b>Median</b>			<b>0.45</b>	<b>0.32</b>	<b>0.16</b>	<b>2.84</b>	<b>2.1</b>	<b>4.7</b>	<b>27.6</b>	<b>59.1</b>	<b>4.8</b>	<b>0.1</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>
Fish Trap	F3	0	1	0.61	0.40	0.28	2.18	0.5	0.8	6.4	72.0	19.8	0.5	0.0	0	0
Fish Trap	F3	1	2	0.45	0.24	0.16	2.84	0.9	0.9	50.8	38.4	8.9	0.1	0.0	0.0	0
Fish Trap	F3	2	3	0.53	0.38	0.26	2.01	0.9	1.4	10.7	70.2	16.3	0.3	0.0	0.3	0
Fish Trap	F3	3	4	0.70	0.39	0.21	3.34	1.1	3.9	16.4	52.3	26.2	0.1	0.0	0	0
	<b>Average</b>			<b>0.57</b>	<b>0.35</b>	<b>0.23</b>	<b>2.52</b>	<b>0.9</b>	<b>1.8</b>	<b>21.0</b>	<b>58.2</b>	<b>17.8</b>	<b>0.3</b>	<b>0.0</b>	<b>0.1</b>	<b>0.0</b>
	<b>Median</b>			<b>0.57</b>	<b>0.38</b>	<b>0.23</b>	<b>2.41</b>	<b>0.9</b>	<b>1.2</b>	<b>13.5</b>	<b>61.2</b>	<b>18.0</b>	<b>0.2</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>
Fish Trap	F4	0	1	0.49	0.38	0.26	1.90	0.4	0.9	12.1	72.7	13.4	0.4	0.0	0	0
Fish Trap	F4	1	2	0.47	0.36	0.24	2.00	0.7	1.3	15.8	74.5	7.7	0.1	0.0	0	0
Fish Trap	F4	2	3	0.47	0.34	0.20	2.39	0.7	1.0	24.9	65.3	8.0	0.1	0.0	0	0
	<b>Average</b>			<b>0.48</b>	<b>0.36</b>	<b>0.23</b>	<b>2.07</b>	<b>0.6</b>	<b>1.1</b>	<b>17.6</b>	<b>70.8</b>	<b>9.7</b>	<b>0.2</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>
	<b>Median</b>			<b>0.47</b>	<b>0.36</b>	<b>0.24</b>	<b>2.00</b>	<b>0.7</b>	<b>1.0</b>	<b>15.8</b>	<b>72.7</b>	<b>8.0</b>	<b>0.1</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>

Table 9. PSD of Sand Data Collected During Provenance Sampling at Pine Bar.

Location	Test Hole	Depth		Sediment Sizes (% in Class)												
		top ft	bottom ft	d <sub>84</sub> mm	d <sub>50</sub> mm	d <sub>16</sub> mm	σ <sub>g</sub>	Silt/Clay	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand	Very Fine Gravel	Medium and Fine Gravel	Coarse and Larger Gravel
								<0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1 mm	1-2 mm	2-4 mm	4-16 mm	>16 mm
Pine Bar	P1	0	0.5	0.40	0.21	0.10	3.81	5.2	16.3	44.4	31.2	1.4	1.0	0.3	0.3	0
Pine Bar	P1	0.5	1	0.42	0.22	0.11	3.90	5.4	15.1	38.4	38.1	2.0	0.4	0.3	0.4	0
Pine Bar	P1	1	1.5	0.41	0.22	0.10	3.97	5.2	16.3	37.7	38.3	2.5	0.0	0.0	0	0
Pine Bar	P1	1.5	2	0.41	0.21	0.09	4.53	8.0	17.9	34.8	36.6	2.7	0.0	0.0	0	0
Pine Bar	P1	2	2.5	0.43	0.24	0.11	3.86	3.8	16.0	34.3	42.6	3.3	0.0	0.0	0	0
Pine Bar	P1	2.5	3	0.42	0.22	0.10	4.08	2.9	20.4	34.1	39.5	3.0	0.1	0.0	0	0
Pine Bar	P1	3	3.5	0.41	0.22	0.13	3.13	2.6	11.5	45.7	38.4	1.7	0.0	0.0	0	0
Pine Bar	P1	3.5	4	0.36	0.17	0.08	4.74	10.1	27.1	35.8	25.2	1.8	0.0	0.0	0	0
Pine Bar	P1	4	4.5	0.44	0.26	0.14	3.09	2.8	8.6	37.2	47.9	3.5	0.0	0.0	0	0
Pine Bar	P1	4.5	5	0.41	0.23	0.14	2.88	2.0	6.9	47.8	42.0	1.3	0.0	0.0	0	0
Pine Bar	P1	5	5.5	0.24	0.14	0.06	4.27	17.9	28.2	42.2	11.3	0.3	0.0	0.0	0	0
Pine Bar	P1	5.5	6	0.19	0.10	0.04	4.21	22.1	52.9	17.5	1.2	0.8	2.4	3.0	0	0
Pine Bar	P1	6	6.5	3.19	0.17	0.06	57.54	17.9	24.1	24.3	4.7	0.6	2.2	17.0	9.1	0
Pine Bar	P1	6.5	7	0.23	0.13	0.07	3.23	10.6	37.9	42.4	5.8	0.9	1.8	0.6	0	0
Pine Bar	P1	7	7.5	0.19	0.10	0.07	2.81	10.4	58.3	28.7	2.1	0.3	0.1	0.0	0	0
Pine Bar	P1	7.5	8	0.21	0.12	0.07	3.01	9.7	47.7	38.4	3.2	0.2	0.8	0.0	0	0
	<b>Average</b>			<b>0.52</b>	<b>0.18</b>	<b>0.09</b>	<b>5.66</b>	<b>8.5</b>	<b>25.3</b>	<b>36.5</b>	<b>25.5</b>	<b>1.6</b>	<b>0.6</b>	<b>1.3</b>	<b>0.6</b>	<b>0.0</b>
	<b>Median</b>			<b>0.41</b>	<b>0.21</b>	<b>0.10</b>	<b>4.23</b>	<b>6.7</b>	<b>19.1</b>	<b>37.4</b>	<b>33.9</b>	<b>1.6</b>	<b>0.1</b>	<b>0.0</b>	<b>0.0</b>	<b>0.0</b>
Pine Bar	P2	0	1	1.75	0.65	0.33	5.27	0.6	0.7	3.5	33.8	37.3	10.7	6.7	6.7	0
Pine Bar	P2	1	2	0.99	0.61	0.33	3.01	0.6	0.6	3.8	35.2	45.1	8.3	1.6	4.8	0
Pine Bar	P2	2	3	0.92	0.58	0.33	2.77	0.6	0.5	2.6	38.2	50.5	5.9	1.0	0.7	0
Pine Bar	P2	3	4.5	0.93	0.64	0.35	2.63	0.3	0.4	3.0	29.8	58.6	6.6	1.2	0.3	0
	<b>Average</b>			<b>1.15</b>	<b>0.62</b>	<b>0.34</b>	<b>3.41</b>	<b>0.5</b>	<b>0.6</b>	<b>3.2</b>	<b>34.2</b>	<b>47.9</b>	<b>7.9</b>	<b>2.6</b>	<b>3.1</b>	<b>0.0</b>
	<b>Median</b>			<b>0.96</b>	<b>0.63</b>	<b>0.33</b>	<b>2.89</b>	<b>0.6</b>	<b>0.6</b>	<b>3.2</b>	<b>34.5</b>	<b>47.8</b>	<b>7.4</b>	<b>1.4</b>	<b>2.8</b>	<b>0.0</b>
Pine Bar	P3	0	1	0.47	0.30	0.16	2.88	1.1	5.5	31.9	52.7	7.4	0.4	0.3	0.5	0
Pine Bar	P3	1	2	0.47	0.32	0.18	2.67	0.8	3.7	28.2	58.1	7.6	0.6	0.4	0.6	0
Pine Bar	P3	2	3	0.47	0.32	0.17	2.73	1.0	4.1	27.9	56.9	6.9	1.1	1.1	1.0	0
	<b>Average</b>			<b>0.47</b>	<b>0.32</b>	<b>0.17</b>	<b>2.76</b>	<b>0.9</b>	<b>4.5</b>	<b>29.3</b>	<b>55.9</b>	<b>7.3</b>	<b>0.7</b>	<b>0.6</b>	<b>0.7</b>	<b>0.0</b>
	<b>Median</b>			<b>0.47</b>	<b>0.32</b>	<b>0.17</b>	<b>2.71</b>	<b>1.0</b>	<b>4.1</b>	<b>28.2</b>	<b>56.9</b>	<b>7.4</b>	<b>0.6</b>	<b>0.4</b>	<b>0.6</b>	<b>0.0</b>

Table 10. Total sediment yields based on various methods/data.

Location/Area	Load tons/year	Area mi <sup>2</sup>	Yield tons/mi <sup>2</sup> /year	Bulk Density lbs/ft <sup>3</sup>	Volume ac-ft/year	Yield ac-ft/mi <sup>2</sup> /year	Lowering mm/year
Weiser Gage based on USGS data	1,290,000	9,260	139	82.4	719	0.078	0.037
Brownlee Reservoir based on bathymetry	2,780,000	11,500	242	82.4	1,549	0.135	0.064
Brownlee Reservoir based on transport (not including Weiser)	5,990,000	2,230	2,690	82.4	3,338	1.50	0.71
Oxbow Reservoir based on transport	1,247,900	218	5,724	100	573	2.63	1.25
Hells Canyon Reservoir based on transport	4,140,000	447	9,260	100	1,901	4.25	2.03
HCD to Pine Bar based on transport	6,330,000	207	30,500	100	2,906	14.0	6.67
Pine Bar to Tin Shed based on transport	750,000	91	8,240	100	344	3.78	1.80
Tin Shed to Salmon River excluding Imnaha based on transport	1,520,000	242	6,280	100	698	2.88	1.37
HCD to Salmon River (excluding Imnaha) based on transport	8,605,099	540	15,900	100	3,951	7.31	3.48
17 Tributaries below HCD based on transport	6,688,835	348	19,200	100	3,071	8.83	4.21
					<b>High</b>	14.01	6.674
					<b>Average</b>	4.54	2.163
					<b>Low</b>	0.078	0.037
Ranges for Comparison	<b>Yields</b>						
	<b>High</b>	0.52	<b>ac-ft/mi<sup>2</sup>/year</b>	Cascade Reservoir (from Miller et al. [2003])			
	<b>Average</b>	0.15	<b>ac-ft/mi<sup>2</sup>/year</b>				
	<b>Low</b>	0.13	<b>ac-ft/mi<sup>2</sup>/year</b>	Arrowrock & Unity (from Miller et al. [2003])			
	<b>Lowering Rates</b>						
	<b>High</b>	1.22	<b>mm/year</b>	Assuming HC 2 million years old (Vallier)			
	<b>Average</b>	0.396	<b>mm/year</b>	Assuming HC 6 million years old (Vallier)			
	<b>Low</b>	0.24	<b>mm/year</b>	USFS Review Comments Appendix D (Wilcock et al. 2002 page D-23)			

Table 11. Selected flows and return periods for the current/proposed and full pool run-of-river operating scenarios.

<b>Current/Proposed Operations</b>		<b>Full Pool Run-of-River Operations</b>		
<b>% Exceedance</b>	<b>Flow (cfs)</b>	<b>% Exceedance</b>	<b>Flow (cfs)</b>	<b>% Change</b>
100%	5,000	100%	5,000	0
85%	10,555	85%	11,122	5.4%
75%	12,000	75%	12,175	1.5%
50%	15,789	50%	15,612	-1.1%
25%	24,199	25%	23,180	-4.2%
15%	30,000	15%	30,273	0.9%
10%	36,132	10%	36,632	1.4%
5%	45,323	5%	46,480	2.6%
1%	63,477	1%	62,911	-0.9%

Table 12. Percent of mainstem river bed that mobilizes—Snake River, Hells Canyon.

$d_{84}$ used to calculate			
Dimensionless Shear Stress:	<b>30,000 cfs</b>	<b>39,670 cfs</b>	<b>100,000 cfs</b>
$\Theta = \tau_b / (\gamma_s - \gamma_w) d_{84}$	<b>850 cms</b>	<b>1124 cms</b>	<b>2832 cms</b>
<hr/>			
Critical Dimensionless Shear Stress	<b>0.047</b>	<b>0.047</b>	<b>0.047</b>
Total River Length Mobilized: (meters)	19578	22514	54553
Percent of Bed that Mobilizes	12%	14%	33%
<hr/>			
HCD to Salmon River Length Mobilized: (meters)	10826	13360	32285
Percent of River Mobilized HCD to Salmon River:	11%	14%	34%
<hr/>			
Below Salmon River Length Mobilized: (meters)	8751	9153	22268
Percent of River Mobilized Below Salmon River:	13%	13%	32%
<hr/>			
Critical Dimensionless Shear Stress	<b>0.03</b>	<b>0.03</b>	<b>0.03</b>
Total River Length Mobilized: (meters)	45243	52567	105131
Percent of Bed that Mobilizes	27%	32%	63%
<hr/>			
HCD to Salmon River Length Mobilized: (meters)	29161	34079	67497
Percent of River Mobilized HCD to Salmon River:	30%	36%	71%
<hr/>			
Below Salmon River Length Mobilized: (meters)	16082	18488	37633
Percent of River Mobilized Below Salmon River:	23%	26%	54%

Table 13. Evaluation of fall chinook spawning sites for 25-mm (1-inch) gravels—Snake River, Hells Canyon.

Site	R. Mile	Dimensionless						
		Shear Stress						
		30,000 cfs	39,670 cfs	100,000 cfs	150,000 cfs	200,000 cfs	250,000 cfs	300,000 cfs
Rocky Bar/Wild Sheep	240.6	0.03116	0.03472	0.04815	0.05507	0.06100	0.06581	0.07025
Below Granite Rapids	238.6	0.00653	0.00913	0.01717	0.02062	0.02244	0.02274	0.02209
Little Bar	225.1	0.00711	0.00909	0.01938	0.02791	0.03724	0.04808	0.06033
Upper Kirby Creek	219.2	0.02550	0.02453	0.03103	0.03558	0.03922	0.04211	0.04437
Coral Creek	217.3	0.00429	0.00455	0.00658	0.00864	0.01086	0.01301	0.01512
Lower Pleasant Valley	213.7	0.00882	0.01520	0.04523	0.04301	0.04652	0.04964	0.05201
Lookout Creek	207.9	0.02244	0.02720	0.03005	0.03099	0.03223	0.03388	0.03536
High Range	206.4	0.00639	0.01034	0.01839	0.02354	0.02853	0.03307	0.03732
Copper Creek	205.2	0.00635	0.00989	0.02699	0.03443	0.04003	0.04455	0.04814
Robinson Gulch	198.8	0.00116	0.00112	0.00203	0.00280	0.00433	0.00930	0.01287
Lower Dug Bar	196	0.01400	0.02060	0.03306	0.04092	0.04680	0.05170	0.05559
Above Divide Creek	193.7	0.00222	0.00345	0.01180	0.01509	0.01795	0.01999	0.02158

  

Site	R. Mile	Dimensionless						
		Shear Stress						
		31,684 cfs	42,000 cfs	106,490 cfs	155,000 cfs	205,000 cfs	255,000 cfs	305,000 cfs
<b>Below RM-191.6 Imnaha River</b>								
Eureka Bar	190.7	0.01337	0.01920	0.03605	0.03747	0.04098	0.04410	0.04733

  

Site	R. Mile	Dimensionless						
		Shear Stress						
		75,370 cfs	103,194 cfs	166,290 cfs	200,000 cfs	250,000 cfs	300,000 cfs	350,000 cfs
<b>Below RM 168.7 Grande Ronde</b>								
Above Billy Creek (2)	166.5	0.00560	0.00618	0.01101	0.01912	0.02105	0.02240	0.02355
Above Billy Creek	166.2	0.00911	0.01140	0.01948	0.02351	0.02713	0.03035	0.03354
Captain John Creek	162.3	0.01109	0.01406	0.02246	0.02336	0.02503	0.02683	0.02847
Tenmile Canyon	152.2	0.00716	0.00870	0.00978	0.00992	0.01110	0.01225	0.01345

Table 14. Evaluation of fall chinook spawning sites for 50-mm (2-inch) gravels—Snake River, Hells Canyon.

Site	R. Mile	Dimensionless						
		Shear Stress						
		30,000 cfs	39,670 cfs	100,000 cfs	150,000 cfs	200,000 cfs	250,000 cfs	300,000 cfs
Rocky Bar/Wild Sheep	240.6	0.01558	0.01736	0.02408	0.02753	0.03050	0.03290	0.03513
Below Granite Rapids	238.6	0.00327	0.00456	0.00859	0.01031	0.01122	0.01137	0.01105
Little Bar	225.1	0.00355	0.00454	0.00969	0.01395	0.01862	0.02404	0.03016
Upper Kirby Creek	219.2	0.01275	0.01227	0.01552	0.01779	0.01961	0.02105	0.02219
Coral Creek	217.3	0.00215	0.00227	0.00329	0.00432	0.00543	0.00651	0.00756
Lower Pleasant Valley	213.7	0.00441	0.00760	0.02261	0.02150	0.02326	0.02482	0.02600
Lookout Creek	207.9	0.01122	0.01360	0.01503	0.01549	0.01612	0.01694	0.01768
High Range	206.4	0.00319	0.00517	0.00920	0.01177	0.01426	0.01653	0.01866
Copper Creek	205.2	0.00317	0.00495	0.01349	0.01721	0.02001	0.02228	0.02407
Robinson Gulch	198.8	0.00058	0.00056	0.00101	0.00140	0.00216	0.00465	0.00643
Lower Dug Bar	196	0.00700	0.01030	0.01653	0.02046	0.02340	0.02585	0.02780
Above Divide Creek	193.7	0.00111	0.00173	0.00590	0.00754	0.00898	0.00999	0.01079

  

Site	R. Mile	Dimensionless						
		Shear Stress						
		31,684 cfs	42,000 cfs	106,490 cfs	155,000 cfs	205,000 cfs	255,000 cfs	305,000 cfs
<b>Below RM–191.6 Imnaha River</b>								
Eureka Bar	190.7	0.00669	0.00960	0.01803	0.01874	0.02049	0.02205	0.02366

  

Site	R. Mile	Dimensionless						
		Shear Stress						
		75,370 cfs	103,194 cfs	166,290 cfs	200,000 cfs	250,000 cfs	300,000 cfs	350,000 cfs
<b>Below RM 168.7 Grande Ronde</b>								
Above Billy Creek (2)	166.5	0.00280	0.00309	0.00550	0.00956	0.01052	0.01120	0.01177
Above Billy Creek	166.2	0.00456	0.00570	0.00974	0.01176	0.01357	0.01518	0.01677
Captain John Creek	162.3	0.00555	0.00703	0.01123	0.01168	0.01251	0.01342	0.01424
Tenmile Canyon	152.2	0.00358	0.00435	0.00489	0.00496	0.00555	0.00612	0.00672

Table 15. Particle size distribution of sediment loads and resources.

Location	Units	Total	Sediment Sizes (in mm)									
			Silt/Clay <0.063	Very Fine Sand 0.063–0.125	Fine Sand 0.125–0.25	Medium Sand 0.25–0.5	Coarse Sand 0.5–1	Very Coarse Sand 1–2	Very Fine Gravel 2–4	Medium and Fine Gravel 4–25.4	Spawning Gravel 25.4–152.4	Cobble and Larger
Trapped in Brownlee	ac-ft	62,046	53,400	2,330	3,870	1,490	710	230	55.9	0	0	0
	%	100%	86%	3.8%	6.2%	2.4%	1.1%	0.4%	0.1%	0.0%	0.0%	0.0%
	tons/year <sup>a</sup>	2,780,000	2,390,000	105,000	173,000	66,700	31,800	10,000	0.00	0	0	0
	tons/year <sup>a</sup>					387,000						
Suspended Load at Weiser <sup>g</sup>	%	100%	81%			19%						
	tons/year	1,250,000	1,010,000			237,000						
Bed Load at Weiser <sup>b</sup>	tons/year	41,900	0					41,900				
Total Load at Weiser	ac-ft <sup>d</sup>	23,700	18,600					5,120				
	tons/year	1,290,000	1,010,000					279,000				
Yield to Brownlee <sup>c</sup>	ac-ft	55,500										
	tons/year <sup>a</sup>	2,490,000										
Transport Calcs to Brownlee <sup>e</sup>	ac-ft <sup>d</sup>	110,000				34,300					17,200	
	tons/year	5,990,000				1,870,000					935,000	
Transport Calcs to Oxbow <sup>e, h</sup>	ac-ft	21,200				3,170					6,220	
	tons/year <sup>d</sup>	1,247,900				187,000					366,000	
Transport Calcs to Hells Canyon <sup>e</sup>	ac-ft <sup>d</sup>	76,000				13,000					25,500	
	tons/year	4,140,000				710,000					1,390,000	
Supply From Tributaries between HCD and Pine Bar <sup>e</sup>	ac-ft <sup>d</sup>	116,000				17,400					58,000	
	tons/year	6,330,000				948,000					3,160,000	
Supply From Tributaries between Pine Bar and Tin Shed <sup>e</sup>	ac-ft <sup>d</sup>	14,000				2,200					6,800	
	tons/year	750,000				118,000					370,000	
Supply From Tributaries below Tin Shed to Salmon River excluding Imnaha <sup>e</sup>	ac-ft <sup>d</sup>	27,900				7,700					11,500	
	tons/year	1,520,000				418,000					627,000	
Average Sand Bar Sediment <sup>f</sup>	%	100%	2.3%	10%	32%	46%	7.8%	0.7%	0.2%	0.3%	0%	0%

Note: Percentages may not add to 100 due to rounding. Values are limited to 3 significant figures. <sup>e</sup> These supplies are estimated based on transport capacity calculations for individual tributaries; the average for all tributaries is applied to areas outside of the tributary basins.

<sup>a</sup> Based on bulk density of 1.32g/cm<sup>3</sup> or 82.4 lbs/ft<sup>3</sup> for Brownlee deposits (from Appendix B) and Brownlee in place from 1958 to 1998 (40 years).

<sup>b</sup> Estimated based on bed load at 15% of total load.

<sup>c</sup> Estimated based on average yield of 0.15 ac-ft/mi<sup>2</sup>/year; 9,255 ac; and 40 years.

<sup>d</sup> Based on bulk density of 100 lbs/ft<sup>3</sup>.

<sup>f</sup> Average of all core samples in Pine Bar and Fish Trap Bar.

<sup>g</sup> Based on an average annual flow of 18,533 cfs with an average suspended sand concentration of 13 mg/L from 1959–2000.

<sup>h</sup> Estimated based on average yield (from transport calculations) to Brownlee and Hells Canyon reservoirs; 218 mi<sup>2</sup>; and 37 years.

Table 16. Summary of sediment loads from tributaries in Hells Canyon.

Tributary	Area	Total Load		Sand		Spawning Gravel	
	mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>
<b>HCD to Pine Bar</b>							
Deep Creek, Idaho	29.6	960,000	32,432	264,000	8,919	384,000	12,973
Battle Creek	5.1	57,200	11,216	4,570	896	18,100	3,549
Granite Creek	33.4	1,730,000	51,796	222,000	6,647	940,000	28,144
Saddle Creek	18.2	76,900	4,225	15,200	835	43,100	2,368
Bernard Creek	8.1	0	0	0	0	0	0
Sheep Creek	40.4	1,770,000	43,812	179,000	4,431	930,000	23,020
<b>Subtotal</b>	<b>135</b>	<b>4,594,100</b>	<b>n/a</b>	<b>684,770</b>	<b>n/a</b>	<b>2,315,200</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>34,081</b>		<b>5,080</b>		<b>17,175</b>
<b>Average</b>	<b>22</b>	<b>n/a</b>	<b>23,914</b>	<b>n/a</b>	<b>3,621</b>	<b>n/a</b>	<b>11,676</b>
Hillslope area	73	1,736,128	23,914	262,903	3,621	847,649	11,676
<b>Subtotal Area</b>	<b>207</b>	<b>6,330,228</b>	<b>30,522</b>	<b>947,673</b>	<b>4,569</b>	<b>3,162,849</b>	<b>15,250</b>
<b>Pine Bar to Tin Shed</b>							
Temperance Creek	14.5	780	54	65	4	500	34
Salt Creek	6	0	0	0	0	0	0
Kirkwood Creek	15.2	41,900	2,757	4,100	270	21,600	1,421
Corral Creek	10	318,000	31,800	51,700	5,170	156,000	15,600
<b>Subtotal</b>	<b>46</b>	<b>360,680</b>	<b>n/a</b>	<b>55,865</b>	<b>n/a</b>	<b>178,100</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>7,892</b>		<b>1,222</b>		<b>3,897</b>
<b>Average</b>	<b>11</b>	<b>n/a</b>	<b>8,653</b>	<b>n/a</b>	<b>1,361</b>	<b>n/a</b>	<b>4,264</b>
Hillslope area	45	392,136	8,653	61,683	1,361	193,239	4,264
<b>Subtotal Area</b>	<b>91</b>	<b>752,816</b>	<b>8,271</b>	<b>117,548</b>	<b>1,291</b>	<b>371,339</b>	<b>4,080</b>
<b>Tin Shed to Salmon River (not including Imnaha)</b>							
Big Canyon Creek	10.3	0	0	0	0	0	0
Getta Creek	18.9	166,000	8,783	44,800	2,370	84,700	4,481
Wolf Creek	33.2	0	0	0	0	0	0
Deep Creek, OR	26.8	212,000	7,910	59,000	2,201	92,700	3,459
Divide Creek	30.8	455,000	14,773	124,000	4,026	160,000	5,195
Cherry Creek	19.4	30,000	1,546	5,560	287	18,200	938
Cook Creek	27.9	182,000	6,523	56,000	2,007	71,600	2,566
<b>Subtotal (w/o Cherry &amp; Cook Cks)</b>	<b>120</b>	<b>833,000</b>	<b>n/a</b>	<b>227,800</b>	<b>n/a</b>	<b>337,400</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>6,246</b>		<b>1,730</b>		<b>2,553</b>
<b>Average</b>	<b>24</b>	<b>n/a</b>	<b>5,648</b>	<b>n/a</b>	<b>1,556</b>	<b>n/a</b>	<b>2,377</b>
Hillslope area	122	689,055	5,648	189,825	1,556	290,006	2,377
<b>Subtotal Area</b>	<b>242</b>	<b>1,522,055</b>	<b>6,289</b>	<b>417,625</b>	<b>1,726</b>	<b>627,406</b>	<b>2,593</b>
<b>Total Area</b>	<b>540</b>	<b>8,605,099</b>	<b>15,923</b>	<b>1,482,847</b>	<b>2,744</b>	<b>4,161,594</b>	<b>7,701</b>

Table 17. Summary sediment loads from tributaries within Hells Canyon Complex.

Tributary	Area	Total Load		Sand		Spawning Gravel	
	mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>	tons/year	tons/year/mi <sup>2</sup>
<b>Directly into Brownlee Reservoir</b>							
Birch Creek, OR	70.5	51,500	730	9,120	129	12,100	172
Connor Creek, OR	9.3	20,000	2,151	3,220	346	7,180	772
Rock Creek, ID	45.5	0	0	0	0	0	0
Dennett Creek, ID	13.4	141,000	10,522	57,500	4,291	5,330	398
Sturgill Creek, ID	22.7	71,800	3,163	11,400	502	24,700	1,088
Brownlee Creek, ID	62.1	25,800	415	3,860	62	11,400	184
<b>Subtotal</b>	<b>224</b>	<b>310,100</b>	<b>n/a</b>	<b>85,100</b>	<b>n/a</b>	<b>60,710</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>1,387</b>		<b>381</b>		<b>272</b>
<b>Average</b>	<b>37</b>	<b>n/a</b>	<b>2,830</b>	<b>n/a</b>	<b>889</b>	<b>n/a</b>	<b>436</b>
Burnt River, OR	791	2,238,777	2,830	702,804	889	344,496	436
Powder River, OR	800	2,264,250	2,830	710,800	889	348,415	436
Direct Hillslope area	416	1,175,995	2,830	369,172	889	180,958	436
<b>Subtotal Area</b>	<b>2230</b>	<b>5,989,123</b>	<b>2,686</b>	<b>1,867,876</b>	<b>838</b>	<b>934,580</b>	<b>419</b>
<b>Directly into Oxbow Reservoir</b>							
Wildhorse River	177	0	0	0	0	0	0
Salt Creek, ID	5.6	0	0	0	0	0	0
<b>Subtotal</b>	<b>183</b>	<b>0</b>	<b>n/a</b>	<b>0</b>	<b>n/a</b>	<b>0</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>0</b>		<b>0</b>		<b>0</b>
<b>Average</b>	<b>91</b>	<b>n/a</b>	<b>0</b>	<b>n/a</b>	<b>0</b>	<b>n/a</b>	<b>0</b>
Hillslope area	35	0	0	0	0	0	0
<b>Subtotal Area</b>	<b>218</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>
<b>Directly into Hells Canyon Reservoir</b>							
Indian Creek, ID	40.1	2,370,000	59,102	405,000	10,100	797,000	19,875
Pine Creek, OR	301	0		0		0	
Kinney Creek, ID	7.9	0	0	0	0	0	0
McGraw Creek, OR	12.3	26,000	2,114	5,070	412	6,950	565
<b>Subtotal</b>	<b>361</b>	<b>2,396,000</b>	<b>n/a</b>	<b>410,070</b>	<b>n/a</b>	<b>803,950</b>	<b>n/a</b>
<b>Area Weighted Average</b>	<b>n/a</b>		<b>6,632</b>		<b>1,135</b>		<b>2,225</b>
<b>Average</b>	<b>90</b>	<b>n/a</b>	<b>20,405</b>	<b>n/a</b>	<b>3,504</b>	<b>n/a</b>	<b>6,813</b>
Hillslope area	86	1,748,739	20,405	300,291	3,504	583,913	6,813
<b>Subtotal Area</b>	<b>447</b>	<b>4,144,739</b>	<b>9,272</b>	<b>710,361</b>	<b>1,589</b>	<b>1,387,863</b>	<b>3,105</b>
<b>Total Area</b>	<b>2895</b>	<b>10,133,862</b>	<b>3,501</b>	<b>2,578,238</b>	<b>891</b>	<b>2,322,442</b>	<b>802</b>

This page left blank intentionally.