IDAHO POWER
An IDACORP Company

Feasibility of Reintroduction of Anadromous Fish Above or Within the Hells Canyon Complex

James A. Chandler
Editor

Technical Report
Appendix E.3.1-2

Hells Canyon Complex
FERC No. 1971

December 2001

Copyright © 2003 by Idaho Power Company

IDAHO POWER
An IDACORP Company

Existing Habitat Conditions of the Mainstem Snake River Formerly Used by Anadromous Fish

James A. Chandler
Fisheries Biologist

Phillip A. Groves
Fisheries Biologist

Philip A. Bates
Environmental Technician

Technical Report
Appendix E.3.1-2
Feasibility of Reintroduction of Anadromous Fish above or within the Hells Canyon Complex

Chapter 5

Hells Canyon Complex
FERC No. 1971

December 2001
Revised July 2003

Copyright © 2003 by Idaho Power Company

TABLE OF CONTENTS

Table of Contents i

List of Tables iii

List of Figures iv

1. General Description 1

2. Historic Distribution 1

3. Historic versus Present Day Thermal Regimes 5

  3.1. Adult Migration 8

  3.2. Spawn Timing 9

  3.3. Emergence 10

  3.4. Juvenile Rearing/Outmigration 12

4. Water Quality 14

  4.1. Rock Creek 15

    4.1.1. Shoshone Falls to Thousand Springs (RM 614.6–584.2) 15

    4.1.2. Thousand Springs to King Hill (RM 584.2–546.2) 18

  4.2. Mid Snake River—King Hill to C.J. Strike Dam (RM 546.2–494.0) 20

    4.2.1. Water Temperature 20

    4.2.2. Nutrients 20

    4.2.3. Sediment 21

    4.2.4. Tributary Influence 21

  4.3. C.J. Strike Dam to Boise River (RM 494.0–396.4) 21

    4.3.1. Water Temperature 22

    4.3.2. Nutrient and Sediment 22

    4.3.3. Tributary Influence 23

4.4. Lower Snake River—Boise River to Hells Canyon Dam (RM 396.4–247.0)................23

4.4.1. Water Temperature 24

4.4.2. Dissolved Oxygen...24

4.4.3. Nutrients...25

4.4.4. Sediment 26

5. Historic Spawning Habitat...27

5.1. Sediment Permeability..28

5.1.1. Study Sites 28

5.1.2. Sediment Grain Size Distribution 28

5.1.3. Slug Testing 31

5.1.4. Sediment Permeability Conclusions 35

5.2. Hyporheic Water Quality...35

5.2.1. Dissolved Oxygen...36

5.2.2. Water Temperature 37

5.2.3. Hydrogen Sulfide..38

5.3. Incubation Survival...38

6. Acknowledgments...39

7. Literature Cited 39

LIST OF TABLES

Table 1. Comparison of summary statistics for temperature and emergence dates in six reaches of the Snake River and the one reach of the Salmon River................51

Table 2. Estimated julian dates of fall chinook emergence for different years from six reaches of the Snake River and one reach in the Salmon River......................53

Table 3. Summary of mainstem Snake River temperatures, dissolved oxygen levels, conductivity, pH, and turbidity metrics collected April through September 1995 (from Table 4-1 in Harrison et al. [2000]). 54

Table 4. Summary of mainstem Snake River nitrogen, phosphorus, total suspended sediments (TSS), and chlorophyll *a* metrics collected April through September 1995 (from Table 4-2 in Harrison et al. [2000]). 55

Table 5. Relative tributary flow contribution to the lower Snake River Basin segment (from Table 2-1 in Harrison et al. [2000])...56

Table 6. Summary of days for years 1992 to 1998 that dissolved oxygen in the Brownlee Dam tailrace fell below the 3.5 and 6.0 mg/l criteria (from Myers and Pierce 1999). 56

Table 7. Summary of days for years 1992 to 1998 that dissolved oxygen in the Hells Canyon Dam tailrace fell below the 3.5 and 6.0 mg/l criteria (from Myers and Pierce 1999). 57

Table 8. Grain size distributions at the upper and middle sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores. The values d_{16}, d_{25}, d_{50}, d_{75}, and d_{84} represent the grain size in mm at which 16%, 25%, 50%, 75%, and 84%, respectively, of the sampled grains were finer. 57

Table 9. Percentage of fines (< 1 mm) in the bed for individual freeze-core samples...58

Table 10. Geometric mean diameter (d_g) in mm and geometric sorting coefficient (s_g) at the middle and upper sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores. 58

Table 11. Geometric means of hydraulic conductivity estimates at the middle and upper sites. 59

Table 12. Hydraulic head (Δh), vertical hydraulic gradient (*VHG*), and specific discharge (v) at the middle and upper sites...60

Table 13. Other hydraulic conductivity results from riparian environments. 61

Table 14. Year 1 (1999–2000) data collection events. UPS = upstream study site, DNS = downstream study site, WC = water column, Piezo = peizometer. 62

Table 15. Year 2 (2000–2001) data collection events. 63

Table 16. Number of events from year 1 (1999–20000) and year 2 (2000–2001) where H_2S was detected in a redd or piezometer sample from artificial redd locations between Swan Falls Dam and Marsing. 64

LIST OF FIGURES

Figure 1. Snake River study area. 65

Figure 2. Percentages of mainstem habitat loss. 67

Figure 3. Mean daily water temperatures in six reaches of the Snake River from August 1 to November 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set. 69

Figure 4. Mean daily water temperatures in six reaches of the Snake River from November 1 to April 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set. 70

Figure 5. Mean daily water temperatures in six reaches of the Snake River from April 1 to July 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set. 71

Figure 6. Estimated mean emergence dates of juvenile fall chinook salmon representing the correlation between river mile and emergence day during the pre-Hells Canyon Complex era (blue squares and trend line) and the post-Hells Canyon Complex era (red circles). Vertical bars represent the range of emergence estimated for individual year for each of the data sets. 72

Figure 7. Mean thermal unit accumulation of six reaches on the Snake River and one reach on the Salmon River from October 10 and November 15. Arrows above the graph indicate the range of dates of emergence for four of the six reaches of the Snake River depicting the overlap in emergence of the reaches. 73

Figure 8. Four study basins. 75

Figure 9. Rock Creek Study Area. 77

Figure 10. Land uses, land ownership, and elevation ranges as a percentage of basin area for the Rock Creek section of the Snake River, Idaho. 79

Figure 11. Elevation profile of the Snake River depicting the river gradient from Shoshone Falls to approximately the confluence of the Salmon River. Yellow triangles represent locations of mainstem dams. 80

Figure 12. Annual contribution of water to the Snake River from springs along the north bank of the Snake River between Milner Dam and King Hill (from Clark et al. 1998). Numbers above bars represent percentages of annual streamflow. 81

Figure 13. Temperature influence of spring flows on the Snake River between Shoshone Falls and Upper Salmon Falls Dam relative to discharge (measured at Lower Salmon Falls Dam) in 2001. 82

Figure 14. Total phosphorus concentrations (mg/l) within the impounded segment collected at Bliss (RM 559.8), Lower Salmon Falls (RM 572.9), and Upper Salmon Falls (RM 579.6) tailraces. 83

Figure 15. Mid Snake River location map. 85

Figure 16. Land uses, land ownership, and elevation ranges as a percentage of basin area for the middle section of the Snake River, Idaho. 87

Figure 17. Percentage of exceedance curves for total phosphorus and dissolved orthophosphate in the tailwaters of the C.J. Strike Project, the Snake River arm, and the Bruneau Reservoir arm (from Figure 6 in Myers and Pierce [1997]). 88

Figure 18. Percentage of exceedance curves for levels of total suspended solids in the tailwaters of the C.J. Strike Project, the Bruneau arm, and the Snake River arm (from Figure 5 in Myers and Pierce [1997]). 89

Figure 19. Turbidity of water flowing into C.J. Strike Reservoir at Indian Cove Bridge (RM 525.3) and leaving the reservoir (RM 493.7) (from Myers and Pierce 1997). 90

Figure 20. Location map of Swan Falls reach. 91

Figure 21. Land uses, land ownership, and elevation ranges as a percentage of basin area for the Swan Falls section of the Snake River, Idaho. 93

Figure 22. Mean daily temperatures from Swan Falls Reservoir (RM 458.0) and Nyssa (RM 383.2) from March 1996 through May 2001 (IPC, unpubl. data). 94

Figure 23. Map of Lower Snake River. 95

Figure 24. Land uses, land ownership, and elevation ranges as a percentage of basin area for the lower section of the Snake River, Idaho. 97

Figure 25. Plots of dissolved oxygen levels entering Brownlee Reservoir and those leaving Brownlee Dam (from Figure 12 in Myers and Pierce [1999]). 98

Figure 26. Summarized daily average of dissolved oxygen levels in water leaving Brownlee Dam and Hells Canyon Dam from data collected from 1992 through 1998 (from Figure 13 in Myers and Pierce [1999]). 99

Figure 27. Total phosphorus (TP) and ortho-phosphorus (OP) concentrations collected in tributaries within the lower Snake River segment from data collected between 1970 and 1999 (Figure 2.3.6 in IDEQ [2001]). *Snk Mur* represents the Snake River near Murphy, and *Snk Wei* represents the Snake River near Weiser. 100

Figure 28. Frequency of exceedance curves for all total phosphorus levels measured in Brownlee, Oxbow, and Hells Canyon reservoirs from 1991 through 1998 (from Figure 24 in Myers and Pierce [1999]). 101

Figure 29. Average phosphorus (total and ortho) concentrations for Brownlee Reservoir in the lower Snake River segment (from Figure 2.3.16 in IDEQ [2001]). 102

Figure 30. Plots comparing monthly average total phosphorus loads entering Brownlee Reservoir and discharging from Brownlee, Oxbow, and Hells Canyon dams during 1996 and 1997 (from Figure 27 in Myers and Pierce [1999]). 103

Figure 31. Mean total nitrogen loads from Marsing to Porters Flat for April through September 1995 (from Figures 4–10 in Harrison et al. [2000]). 104

Figure 32. Average concentrations of total suspended solids for tributary and mainstem sites within the lower Snake River segment (Figure 2.3.10 in IDEQ [2001]). *Snk Mur* represents the Snake River near Murphy, and *Snk Wei* represents the Snake River near Weiser. 105

Figure 33. Average concentrations for total suspended solids (TSS) for Brownlee Reservoir in the lower Snake River segment (Figure 2.3.22 in IDEQ [2001]). 106

Figure 34. Historic spawning site locations used in sediment permeability and artificial redd evaluations. 107

Figure 35. Upper sediment permeability and artificial redd site, looking upstream. 109

Figure 36. Middle sediment permeability and artificial redd site, looking downstream. 110

Figure 37. Upper and middle study site locations. 110

Figure 38. Middle site sampling locations. 111

Figure 39. Upper site sampling locations. 112

Figure 40. Tri-tube assembly, tripod, and chain hoist used for extracting freeze cores. Liquid nitrogen is poured down into the tubes through the funnels to freeze the bed. 113

Figure 41. Thawing the freeze core over an aluminum sample collection box with a portable propane heater. 114

Figure 42. The surface layer of the sediment core is lost due to thawing. The triangular plate at left was at the riverbed surface.. 115

Figure 43. The sampling template used in the pebble count method. 116

Figure 44. Grain size distributions at the upper and middle sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores. 117

Figure 45. The data logger is inserted into the piezometer through the pressure-regulating device.. 118

Figure 46. The piezometer is outfitted with a pressure-regulating ball valve device and a small electric air compressor. 119

Figure 47. Hydraulic conductivity estimated with the Bouwer and Rice method (*K_BR*) at the middle site. 120

Figure 48. Hydraulic conductivity estimated with the Bouwer and Rice method (*K_BR*) at the upper site. 121

Figure 49. Mean hydraulic conductivity values at the middle and upper sites. (*K_H* represents use of the Hvorslev method and *K_BR* represents use of the Bouwer and Rice method.).. 122

Figure 50. Estimates of vertical hydraulic gradient (VHG) at the middle site. 123

Figure 51. Estimates of vertical hydraulic gradient (VHG) at the upper site. 124

Figure 52. Mean hydraulic conductivity values at the middle and upper sites.................... 125

Figure 53. Surface view of layout of one cluster of artificial redds showing locations of redds and piezometers relative to a central sample collection site. 126

Figure 54. Side profile of layout of artificial redd and intragravel sampling tube and piezometer depths.. 127

Figure 55. Water column dissolved oxygen (DO; mg/l) levels measured in year 1 (1999–2000). 127

Figure 56. Water column dissolved oxygen (DO; mg/l) levels measured in year 2 (2000–2001). 128

Figure 57. Piezometer dissolved oxygen (DO; mg/l) levels measured in year 1 (1999−2000). 129

Figure 58. Piezometer dissolved oxygen (DO; mg/l) levels measured in year 2 (2000−2001). 130

Figure 59. Artificial redd dissolved oxygen (DO; mg/l) levels measured in year 1 (1999−2000). 131

Figure 60. Artificial redd dissolved oxygen (DO; mg/l) levels measured in year 2 (2000–2001). 132

Figure 61. Discharge (Q; cfs) of the Snake River recorded at Murphy gauge during the sampling period of years 1 and 2 artificial redd surveys. Squares on the lines represent individual sampling dates. 133

Figure 62. Surface temperatures in degrees Celsius (ºC) for years 1 and 2 and hyporheic temperature during year 2 for the artificial redd surveys. The solid square represents estimated hatch date (500 cumulative thermal units [ctu]), and the open square represents estimated emergence dates (1,000 ctu +5 days) for year 1. Circles represent year 2 hatch and emergence dates. 134

1. GENERAL DESCRIPTION

This chapter reviews the historic distribution of anadromous fish in the mainstem Snake River above Hells Canyon Dam, as well as the water quality and spawning habitat quality there today.

Migrating anadromous fish face both natural and manmade obstacles. Shoshone Falls, approximately 592 kilometer (km) (368 miles [mi]) above the present-day Hells Canyon Dam site (Figure 1), limited the extent that anadromous fish migrated up the Snake River. The mainstem Snake River above Hells Canyon Dam historically supported fall chinook salmon (*Oncorhynchus tschawytscha*) and Pacific lamprey (*Lampetra tridentata*). These, and possibly white sturgeon (*Acipenser transmontanus*), are the only anadromous fish we know of that spawned and reared in the mainstem Snake River. We have not found evidence that other species, such as steelhead (*O mykiss*), spawned in the mainstem river. Undoubtedly, steelhead and all races of salmon produced above Hells Canyon Dam, including spring and summer chinook salmon and sockeye salmon (*O. nerka*), probably (at least to some degree) reared or overwintered in the mainstem river. (Production areas above Hells Canyon Dam for spring and summer chinook, sockeye, and steelhead are discussed in Chapter 4 [Chandler and Chapman 2001].) For all anadromous fish produced above Hells Canyon Dam, the Snake River was the migration corridor to and from the Columbia River and the ocean.

2. HISTORIC DISTRIBUTION

As with tributaries discussed in Chapter 4 (Chandler and Chapman 2001), dam construction early in Euro-American settlement blocked much of the mainstem Snake River. We know very little about anadromous fish distribution during predevelopment times. Archeological excavations along the middle Snake River (between present-day Twin Falls and the mouth of the Bruneau River) have uncovered anadromous fish bones and fishing gear near areas where native tribes probably fished (Huelsbeck 1981; Plew 1981, 1983; Murphy and Crutchfield n.d.). Some of the earliest records of anadromous fish came from anecdotal accounts that explorers and settlers wrote in their journals (Special Appendix M in Pratt et al. 2001). Most of these early writers related their observations of tribal fisheries distributed all along the Snake River. Many of the accounts refer to Native Americans fishing at some of the large rapids and spawning areas in the middle Snake River, such as Upper Salmon Falls and Lower Salmon Falls (Myers 1998). According to accounts, one popular fishing method involved capturing fish as they ascended the falls. In many of the early explorer journals, Kanaka Rapids was referred to as the “Fishing Falls.” The location of Kanaka Rapids was recorded on John Fremont’s map of the area and subsequently became a landmark (ISHS 1987). On October 3, 1843, Theodore Talbot wrote of a location below the Fishing Falls: “…the river is very full of rapids, thousands of salmon are seen leaping up their farther ascent. The river on this side and all the islands are lined with shanties and black with Indians all occupied in catching or drying salmon” (Carey 1931). Other major fishing areas included the King Hill and Glenns Ferry areas (Evermann 1896, Myers 1998), the Bruneau River (Steward 1970), and near the confluence of the Boise, Owyhee, Payette, and Weiser rivers (Swinney and Wells 1962).

In the late 1800s to early 1900s, nonnative fisheries began operating on the Snake River. For example, the Henoty fishery was near the Washoe Ferry located between the Malheur and Payette rivers (Gregg 1950). These fisheries typically employed large seines set by boat and pulled by horsemen, and they were generally at spawning bed locations. Evermann (1896) described other fisheries between Weiser and Ontario, near Glenns Ferry, and above Lower Salmon Falls at Millet Island. Evermann considered the spawning areas between Huntington and Auger Falls the most important in Idaho. His focus was on the upper Snake River, however, and he did not explore areas downstream of approximately Huntington, Oregon. In years approaching the end of the nineteenth century, declines in salmon fisheries became noticeable. Some years later, the declines were linked to intensive commercial fishing. The declining trend prompted Evermann and others to investigate the natural history of salmon (Evermann 1896).

Also near the end of the nineteenth century, dam construction began to eliminate large mainstem and tributary production areas. The Bruneau River Dam, constructed in the late 1800s for placer mining, was one of the first dams to eliminate large production areas of steelhead and spring and summer chinook (Gilbert and Evermann 1894, Chandler and Chapman 2001). But because this dam was on a tributary, the migration corridor of the Snake River was not impaired. The first dam to block large sections of mainstem Snake River habitat was Swan Falls Dam.

In 1901, the Trade Dollar Mining Company of Silver City constructed the Swan Falls Dam. The dam became the upstream terminus for salmon in the Snake River and, to a large extent, the dam was a barrier to steelhead. Swan Falls Dam blocked approximately 157 mi (253 km) of mainstem Snake River, or approximately 25% of the entire anadromous section of the Snake River (Figure 2). Although a fish ladder was installed during the initial construction, it was not functional—at least for salmon and probably for steelhead (Van Dusen 1903, Irving and Cuplin 1956, Lavier 1976).

In 1922, after Idaho Power Company (IPC) had taken ownership of the dam, the ladder was reconstructed. At the time, it was considered one of the best-constructed fish ladders (IFG 1922). Unfortunately, the ladder was still ineffective at passing salmon around the dam. But apparently some steelhead were able to pass the dam. Irving and Cuplin (1956) reported that a small run of steelhead ascended the river to C.J. Strike Dam (constructed in 1952), which was a complete barrier. Still, very little production potential for steelhead existed between C.J. Strike and Swan Falls dams.

Pacific lamprey apparently could use the fish ladder to pass Swan Falls Dam. Stanford (1942) reported that "Pacific lamprey…were taken in the spring as it made its way with apparent ease, over the fishway or attempted to climb the lower face of the dam." Irving and Cuplin (1956), though, made no mention of Pacific lamprey below C.J. Strike Dam. Considering the dates of Stanford and of Irving and Cuplin's writings, the fishway they referred to would have been the reconstructed fish ladder. It is unclear whether either of these species could use the original fishway to pass the dam. If they could not, then these fish would have been excluded above Swan Falls for approximately 20 years until the new ladder was constructed.

If we assume that some steelhead and Pacific lamprey could pass the original fishway, the first upstream terminus for Pacific lamprey and steelhead was the Lower Salmon Falls Dam (constructed in 1910, built for the Great Shoshone and Twin Falls Water-Power Company; Stacy

1991). In 1947, a new dam and fish ladder were constructed at the Lower Salmon Falls site. However, the upstream terminus soon moved to Bliss Dam (1948), before the Lower Salmon Falls ladder was completed. Bliss Dam had no provision for fish passage. Then in 1952, C.J. Strike Dam was constructed without fishways and became the upstream terminus, at least for steelhead and Pacific lamprey.

Anadromous fish continued to persist in the mainstem below Swan Falls Dam. But spring chinook and steelhead were noticeably declining because of tributary dams and intensive land uses (Chandler and Chapman 2001). The next downstream terminus was Brownlee Dam, constructed in 1958. As described in greater detail in Chapter 2 (Chapman 2001), efforts were made to continue anadromous runs above Brownlee Dam.

In 1956, the diversion tunnel for use during Brownlee Dam construction was completed, along with temporary fish passage facilities to move adults around the construction area. When Brownlee Reservoir filled in May 1958, collection of adult fish was moved downstream to the Oxbow Dam construction site; and then in 1966, to below Hells Canyon Dam. However, shortly after Brownlee Dam construction, it became apparent that downstream collection efforts had failed. In December 1963, the Federal Power Commission ordered IPC to abandon the downstream collection efforts prior to the outmigration of 1964. This order soon led to the development of the hatchery mitigation efforts (Abbott and Stute 2001, Chapman 2001). Because of these events, Hells Canyon Dam became the terminus for wild production of anadromous fish.

The Hells Canyon Complex (HCC) inundated approximately 93 mi (150 km) of Snake River habitat and blocked access to approximately 118 mi (190 km) of free-flowing Snake River up to Swan Falls Dam. A total of 211 mi (340 km), or 34%, of mainstem Snake River habitat was lost. This loss plus the loss above Swan Falls Dam accounted for approximately 59% of Snake River mainstem habitat (Figure 2).

Chapter 6 (Chapman and Chandler 2001) presents estimates of pre-Brownlee Dam run sizes. Richards (1973) estimated run sizes of fall chinook before Celilo Falls was inundated (1954−1956) as 2,695. After Celilo Falls was inundated and before Brownlee Reservoir was filled (1957−1959), escapement to the reach above Brownlee Dam averaged 14,944. Escapement prior to these years is not available because the Brownlee trap offered the first counts in the Snake River. McNary counts began in 1954 and provided counts for Snake River and upper Columbia River fall chinook. Spawning ground counts above Brownlee Dam showed a relatively high redd count in 1947 that corresponded to high counts at the Columbia River dams. Following 1947, numbers continued to decline until the large increase occurred in 1957 (Van Hyning 1968).

The declines in fall chinook abundance observed before Brownlee Dam was built and after Swan Falls Dam was constructed are largely attributable to commercial fishing (Van Hyning 1968). However, the sharp decline in returns to the HCC after Brownlee Dam was constructed through 1971 (when returns to the HCC dropped to less than 10 individuals) is attributable to the lost production area above Brownlee Dam (Chapman 2001). Hatchery efforts to sustain the production were initiated in 1961. Although the efforts were unsuccessful, they continued until 1970 (Abbott and Stute 2001). After that year, the program was discontinued because of insufficient fish returns.

Fall chinook salmon habitat was also being eliminated in the lower Snake River (below Hells Canyon Dam) around the same time Oxbow and Hells Canyon dams were completed. Ice Harbor Dam was constructed in 1962, inundating approximately 32 mi (51.5 km) of the lower mainstem habitat. Construction of Lower Monumental and Little Goose dams followed in 1969 and 1970, respectively. Finally, Lower Granite Dam was constructed in 1975. Combined, these four dams inundated a total of 135 mi (217.3 km; 24%) of mainstem habitat for fall chinook production. By 1975, the total loss in Snake River mainstem habitat was approximately 83% (Figure 2).

Loss of fall chinook habitat may be better expressed in terms of river miles of productive spawning habitat rather than total river miles. Recently, Battelle Pacific Northwest Labs and the U.S. Geological Survey (Battelle and USGS 2000) jointly assessed mainstem fall chinook salmon habitats in the Columbia River basin. For the assessment, they created a fall chinook spawning habitat model. The model developed a geomorphic template of spawning areas based on geomorphic features, such as river gradient (<0.05%), underlying geology (presence of 50% unconsolidated material), and presence of islands and bars—features that are present in known large contiguous spawning areas. They concluded that historically, approximately 58% of high-production potential spawning habitat in the Snake River existed above the present-day Hells Canyon Dam site, and 42% existed below the site. The four lower Snake River dams inundate much of that potential, high-production spawning habitat below Hells Canyon Dam.

Most of the historic high-production habitat that Battelle and the USGS identified in the upper Snake River above Hells Canyon Dam occurs within the reach from Swan Falls Dam (RM 458) to the upper end of Brownlee Reservoir (RM 335). Actual redd counts in the years immediately before construction of Brownlee Dam show that the majority of spawning occurred between Swan Falls Dam and Marsing, Idaho (RM 425), and that very little spawning occurred between Marsing and the upper end of Brownlee Reservoir (Richards 1959). The river downstream of Marsing has a different thermal regime than the river upstream of Marsing. The thermal regime downstream is influenced by several large tributaries that enter the Snake River, including the Boise, Owyhee, Payette, and Weiser rivers. The thermal regime upstream is influenced by the spring discharges into the Snake River near the town of Hagerman, Idaho, discharges that buffer summer maximum and winter minimum temperatures. Historical accounts by Evermann (1896) and early explorers suggest that the areas above Swan Falls provided some of the largest and most important spawning grounds in the Snake River.

According to the Battelle/USGS spawning habitat model, the 100 mi (161 km) of habitat below Hells Canyon Dam (the remaining 17%) is “unsuitable spawning habitat,” which means the area did not conform to the geomorphic template used in the model. The Hells Canyon Reach is relatively high gradient with spawning habitat characterized as consisting of relatively small patches of suitable habitat distributed throughout the 161 km length (Groves and Chandler 2001a). As such these patches would not be represented at the spatial scale of the Battelle/USGS model. There is little question that the historic reaches upstream of Hells Canyon Dam had greater production potential than the present day Hells Canyon Reach. However, that 161 km section currently provides the primary spawning area for Snake River fall chinook. Connor et al. (2001) conservatively estimate that the Hells Canyon Reach is capable of supporting 2,500 redds, or an average of 25 redds per river mile, at full seeding and at a flow near 9,000 cubic feet per second (cfs). Similarly, Groves and Chandler (2001a) predicted that the

Hells Canyon Reach is capable of supporting 3,587 (± 1,222) redds at a flow of 9,500 cfs. According to those estimates, the Hells Canyon Reach is significantly underseeded at present.

In the late 1800s, Gilbert and Evermann (1894) were unable to access the reach from Huntington, Oregon, to Lewiston, Idaho; essentially no information exists on what this reach may have historically supported. We theorize that the Hells Canyon Reach was also influenced by a cold overwinter thermal regime as was the area downstream of Marsing. We further theorize that the construction of Brownlee Dam enhanced the overwinter thermal regime in this reach, increasing the potential for successful incubation of fall chinook salmon. This theory is further explored in Section 3.0 of this chapter.

3. HISTORIC VERSUS PRESENT DAY THERMAL REGIMES

As discussed above, fall chinook habitat and production potential have declined significantly in the Snake River. In addition to changes in the quantity of physical habitat, significant changes have occurred in the thermal regimes available to fall chinook salmon since the predevelopment era. The quantity of physical habitat is different for three periods relating to construction of hydroelectric facilities. The first period is the predevelopment period. Our review of literature accounts found that during this era, some of the most productive habitat in the Snake River was above Swan Falls Dam (Evermann 1896). All indications are that spawning was distributed throughout the entire Snake River, though there is some question about the reach between Huntington and Lewiston. Access to this area was extremely difficult, and no historical accounts are available. Battelle and the USGS (2000) suggested that this area, because of its geomorphology, was largely unsuitable, although present-day observations and study demonstrate that the reach is capable of supporting fall chinook production (Groves and Chandler 2001a). Spawning clearly occurred in the lower Snake River (below the confluence of the Clearwater River) during the predevelopment era. Both Fulton (1968) and Parkhurst (1950) referred to significant spawning areas between the mouth of the Snake River and the confluence of the Clearwater River. We mark the close of the predevelopment period with construction of Swan Falls Dam, which eliminated approximately 25% of the mainstem Snake River habitat and an unknown percentage of the total production potential of Snake River fall chinook.

In the second period, production was reduced to the Snake River below Swan Falls, a reach that still included areas of high production. The spawning areas in the lower Snake River were also still available during this period. It is not known whether the productivity of the Marsing Reach was comparable to the productivity of the area above Swan Falls. Van Hyning (1968) suggested that abundance of fall chinook was declining in the Marsing Reach (Swan Falls Dam to Marsing) and had reached a low in the early 1950s before the inundation of Celilo Falls, an event that resulted in higher returns in the years immediately before construction of the HCC. It is not known whether these higher returns could have been sustained. The decline in fall chinook abundance after Swan Falls Dam construction has been primarily attributed to commercial fishing (Van Hyning 1968); however, the extent to which land uses at that time were impacting the quality of spawning habitat below Swan Falls Dam is unknown.

In the third period, which we call present-day conditions, chinook habitat is limited to the 160-km reach from below Hells Canyon Dam to the upper end of Lower Granite Reservoir. This present-day production area also includes the lower sections of the Clearwater, Grande Ronde, and Imnaha rivers. Our focus will be on the mainstem Snake River production areas. The transition to the third period began in 1958, with closure of Brownlee Dam and the continued construction of the HCC. During this period, dam construction in the lower Snake River was well underway and continued until 1975 when Lower Granite Dam was completed. This 17-year transition marked the greatest decline in habitat and abundance of Snake River fall chinook. With the HCC and lower Snake River dams combined, approximately 58% of the mainstem Snake River was taken out of production, in addition to the 25% lost above Swan Falls, leaving a total of 17% of the mainstem habitat and probably a much lower percentage of the total production capacity.

Not only was physical habitat lost in the second and third periods, but the thermal regime of the Snake River available to fall chinook was altered, a condition that we believe also directly affected the production potential. The thermal regimes of importance for fall chinook include those that affect the pre-spawn, spawn, incubation, and post-emergence life stages. These stages primarily encompass the months September through June. To describe the thermal regimes available during the different periods, we used present-day water temperatures from various reaches of the Snake River. The data available is presented in Table 1 and includes some summary comparisons of the different data sets. We have been unable to locate continuous thermal records for any of the reaches prior to the 1950s. We did locate continuous readings from the Oxbow area for the years 1954 to 1957; we used these to represent the pre-HCC thermal regime for the area below Hells Canyon Dam, at least to the Salmon River.

To represent the production reach above Swan Falls Dam, we used present-day temperature information collected at Indian Cove (RM 522) above C.J. Strike Dam. We used this reach to represent the thermal conditions available in the middle Snake River during the predevelopment period. This reach is and was heavily influenced by spring inflows; however, the contribution of spring flows to base flows in the middle Snake River increased with the initiation of irrigation in the Snake River basin. The predevelopment period had less spring flow contribution than did the 1950s period when spring flow contribution to base flows peaked. Over the last decade, spring flow contribution has begun to decline because of improved irrigation efficiencies. Regardless of these changes in spring-flow contribution, the data set we used represents the warmer thermal regime that was available during the incubation period of fall chinook above Swan Falls Dam rather than post-construction reaches below this dam where larger tributaries and natural cooling begin to reduce the thermal benefit of spring inflows.

We used present-day information from the Marsing Reach to represent the thermal regime in this reach. Although, as discussed above, the present-day thermal regime probably does not represent the predevelopment period within this reach because of changes in spring flows and other anthropogenic effects, today’s thermal regime is probably similar to what was available, at least before completion of Brownlee Dam and at least during the months of interest. Deviation from predevelopment is probably greater during summer months.

To represent inflow conditions to Brownlee Reservoir, we used present-day information collected between the confluence of the Weiser River and the upper end of Brownlee Reservoir at RM 345. For reference, we will refer to this stretch as the Weiser Reach. This data set represents the thermal regime of the inflows into the present-day HCC. In addition, the 1954−1957 data set collected at Oxbow, Oregon, represents potential conditions available before HCC construction or that would be available today if the HCC complex were not in place.

We do not have a data set that would represent the lower Snake River during the three periods to analyze how it may have changed since the predevelopment era. However, our main focus in this discussion is the present-day spawning area in the Snake River below Hells Canyon Dam compared with production areas lost above Hells Canyon Dam. We also included a data set representing the Salmon River, which currently does not support significant spawning of fall chinook salmon.

The primary thermal regime shift from the predevelopment period to the post-Swan Falls Dam period was not a result of a physical change in the thermal regime, but the inability of fish to access the spring-influenced sections in the middle Snake River. Natural cooling during fall and winter months made the Swan Falls Reach cooler than the areas farther upstream that were in the immediate influence of the spring outflows. After 1900, increases in spring flows from increased irrigation probably resulted in slightly warmer winter water conditions immediately below the site of present-day Swan Falls Dam compared with conditions during the predevelopment period. This benefit of increased spring flows likely peaked in the 1950s with the peak in spring discharge. Natural cooling continued downstream in fall and winter. Tributaries entering the Snake River below Swan Falls likely contribute to cooling, so that the Weiser Reach was (and is) cooler during winter than the Marsing Reach, and the area now below Hells Canyon Dam (represented by the pre-HCC Oxbow Reach) was likely cooler than the Weiser Reach. Such cooling is especially apparent when we compare the thermal regime from November through April (Table 1 and Figures 3–5). However, after April, the reaches above Hells Canyon have a more similar thermal regime (Figure 5).

In the third period, construction of the HCC significantly altered the river’s thermal regime below Hells Canyon Dam relative to inflow conditions. Generally, the HCC serves as a buffer on summer maximum and winter minimum temperatures related to inflow temperature, a condition that has shifted the thermal regime that extends both warmer fall temperatures and colder spring temperatures related to inflow (Myers et al. 2002). In addition, construction of the HCC has increased temperatures for overwinter incubation, compared with those before HCC construction, and has shifted the thermal regime closer to that of the Marsing Reach, especially from December through February (Table 1).

To assess the potential benefits or impacts of the altered thermal regime below Hells Canyon Dam, we must compare temperatures experienced during the various life stages with the historic spawning and incubation areas above the HCC. The following sections compare fall chinook adult migration, spawning, incubation and emergence, and post-emergence conditions relative to the thermal regimes.

3.1. Adult Migration

Adult fall chinook currently pass Lower Granite Dam from about mid-August through early November, with the peak migration occurring during the last two weeks of September (data from Fish Passage Center, www.fpc.org). Passage records from the construction period of Brownlee and Oxbow dams indicate that fall chinook salmon passed those areas from early September through early November, with peak migration into the upper river below Swan Falls occurring during the last week of September and the first week of October (Richards 1959). Evermann (1896) observed chinook salmon jumping at Lower Salmon Falls on various visits to the site, including September 16 and October 1, 2, and 7, 1894. The fact that fish were jumping the falls suggests an active migration was underway. In an interview Evermann conducted with William Betz from Glenns Ferry, Betz stated that “the salmon appear about September 15 and the thickest about September 30. We see most dead ones during [the] first half of November.” These accounts suggest that the peak migration of adult fall chinook salmon through the Hells Canyon Reach both currently and historically occurred during mid-September through late October, similar to when it occurred historically above Swan Falls. We conclude that timing of adult migration has not changed from that before either HCC or Swan Falls Dam construction.

The daily mean water temperature (1992−2001) at the Lower Granite Dam forebay currently ranges from 20.5 °C in mid-August to 13.5 °C by late October. During the peak passage of adults (approximately the last two weeks in September), temperatures decline from 20.0 to 18.0 °C. This range is generally comparable to that of all reaches in the Snake River (Figure 3). The mean monthly temperatures for September are generally the same among reaches (Table 1), except for the Salmon River and the reach above C.J. Strike Dam, which have slightly cooler mean temperatures. During October, all monthly mean temperatures in all reaches decline to below 14 °C, except in the reach below Hells Canyon Dam, which has a mean monthly temperature of 16.4 °C (Table 1). However, by the third week in October, temperatures in all reaches, including below Hells Canyon Dam, have declined to below 14.5 °C (Table 1). Adult fall chinook below Hells Canyon Dam currently experience comparable exposure to high temperatures during the early migration period (pre-September 15) as did adult fall chinook before construction of Hells Canyon Dam; however, construction of the HCC resulted in extended exposure to water temperatures above 14.5 °C for approximately two to three weeks longer than in reaches above the HCC (Table 1). Most of the reaches, including the pre-HCC Oxbow Reach, were approximately 10 °C by the end of October, whereas the present-day Hells Canyon Reach averages about 13.5 °C.

There has been no empirical demonstration of the effect of this prolonged exposure of adult chinook salmon to elevated temperature for free-ranging fish. The temperatures of the extended exposure are declining from between 16 to 18 °C to 14.5 °C. These lower temperatures are within the suitability range for migrating adults (Groves and Chandler 2001b, Poole et al. 2001) and for optimal swimming speed (Poole et al. 2001), but they are slightly above the range suitable for gamete viability during holding (> 13−16 °C, Poole et al. 2001). Experiments cited as reference for potential effects of elevated temperatures on gamete viability used adults held in holding ponds, with subsequent incubation temperatures held relatively high throughout the entire period (McCullough 1999). How these findings equate to free-ranging fish is unknown and may be site specific and stock specific. In a free-flowing river, there are thermal refugia associated with hyporheic upwelling, deep pools, and tributary inflows. In addition, temperatures are typically cooler throughout most of the incubation period in a natural setting than in these experiments.

3.2. Spawn Timing

No evidence suggests that the timing of fall chinook spawning has been significantly changed with the altered thermal regimes. The Betz account in Evermann (1896) suggests that spawning was near completion by mid-November. In another account in Evermann, Liberty Millet of Salmon Falls thought the peak of salmon spawning was middle October. If Millet's account was accurate, spawning in the upper Snake River may have occurred slightly earlier than is observed today. However, even if spawning did occur slightly earlier in the upper reach, there is no evidence that spawning in the lower reaches occurred at the same time or slightly later. Spawn time following construction of Swan Falls Dam likely peaked during mid- to late October and was probably complete by the end of the first week of November (Richards 1959). Present-day surveys below Hells Canyon Dam indicate that from 1993 to 2001, approximately 85% of spawning was completed by the end of the first week of November and extended at low numbers even into December (Groves 2001). However, it is important to note that present-day spawning surveys below Hells Canyon Dam are much more intensive than any surveys or casual observations in the pre-Swan Falls Dam period and much more intensive than the redd surveys in the Marsing Reach reported by Richards (1959). It is possible that spawning in all reaches extended into December at low numbers and simply was not observed or reported. While the spawning window below Hells Canyon Dam appears to be longer today, the peak and the majority of spawning do not occur later than that determined for historical timing. We conclude that present-day spawn timing downstream of the Hells Canyon Reach is similar to what occurred historically throughout the Snake River. Connor (2001) also concluded that spawn time between the Marsing Reach and present-day Hells Canyon Dam has not significantly changed.

Despite similarities in spawn time from historical accounts above and below Swan Falls and present-day Hells Canyon Dam, the temperature regimes in these reaches are quite different, suggesting that other environmental cues besides temperature initiate spawning. For example, the most consistent environmental cue among all the reaches is photoperiod. Earliest observed spawning in present-day Hells Canyon Reach was generally after the first week of October. To compare the different reaches, we used October 10 as the initiation date of spawning in all reaches of the Snake River. This date is supported in Groves (2001). With this basis of comparison, mean water temperatures at the initiation of spawning range from approximately 17.5 °C for the upper Hells Canyon Reach to 11.9 °C in the Salmon River (Table 1). The pre-HCC temperature at Oxbow would have been approximately 13.5 °C. Reaches above the HCC would have all been between 14 and 15 °C (Table 1). Temperatures in the upper Hells Canyon Reach do not reach 14 to 15 °C until about the third week in October, suggesting an exposure to temperatures above 14 °C for approximately 2 weeks longer than that experienced historically in reaches above the HCC. This increased exposure affects approximately 8% of the total redd production (Groves 2001). There is no empirical evidence of the effect of this prolonged exposure to elevated temperatures. However, indications from studies in hatchery settings having mean daily temperatures that decline in ranges similar to those observed for these early redds suggest reduced survivals (McCullough 1999). Olson and Foster (1955) found in their study of fall chinook in the Hanford Reach of the Columbia River that if temperatures of initial spawn were less than or equal to 16 °C, survival was greater than or equal to 90%. When initial temperatures were 18.4 °C, survival was 21%. This finding is especially significant to this discussion because the thermal regime immediately before and at initiation of spawning for fall chinook salmon in the Hanford Reach is comparable to that observed below present-day Hells Canyon Dam; hence, any stock-specific adaptations are probably similar to those of Snake River fish (we based this assumption on information from Dauble and Watson [1997]).

In the upper Hells Canyon Reach, temperatures were above 16ºC on average between October 10 and 18. This suggests that redds constructed during this time period may have lower survival than redds constructed after this time period. Redds constructed after this period have equal probability of survival regardless of the temperature at which they were constructed. This suggests that less than 2% of the redds in an average spawning distribution would be affected by elevated temperatures (Groves 2001). Spawning in the lower Hells Canyon Reach initiates at a temperature of approximately 16 °C, and therefore, survival of redds in this reach should not be influenced by elevated temperatures.

3.3. Emergence

The rate of embryonic development in poikilothermic animals is generally related to thermal unit accumulation, which is directly influenced by thermal regime throughout the incubation period. Of all the different life stages, embryonic development leading to the point of emergence and exogenous feeding is likely to be most affected by alterations in the thermal regime. To compare the different thermal regimes with emergence timing, we used the date on which 1,000 thermal units were accumulated from the point of spawning and added 5 days to that date to estimate the time of emergence (Alderdice and Velsen 1978). To define the distribution of emergence dates, we used the average distribution of spawning observed from 1993 to 2001 from Groves (2001). We used an individual-based approach and randomly assigned redd construction on dates relative to the spawn distribution. For example, if 23% of the redds in an average spawn distribution were constructed in week 4 of the spawning period, then out of a total of 100 redds, 23 redds were randomly assigned construction dates within week 4. Thermal units were accumulated and emergence dates were estimated for each individual redd using daily average temperatures for each of the years in the temperature data sets described above. Using the individual redds, we constructed a distribution of emergence dates. This process demonstrated differences among the various reaches in relation to estimated emergence dates (Table 1 and Figure 6). However, it is also important to note that considerable variation occurs among years in any given reach (Table 2 and Figure 6).

In the pre-HCC era, the reach above C.J. Strike Reservoir would have had the earliest emergence. Temperatures were relatively stable during the incubation period and generally did not drop below 7 °C (Figure 4). Emergence dates ranged from February 8 through April 13, with a median date of March 15 (Table 1). The latest emergence dates occurred in the Salmon River, with median estimated emergence occurring June 4. Connor (2001) reported estimated emergence timing for the lower Clearwater River as June 17. Emergence in the Oxbow Reach during the pre-HCC era was also late, with a median date of May 23. Winter water temperatures in the Salmon River drop to very low levels. Mean monthly values for December and January were below 2 °C (Table 1). The pre-HCC Oxbow Reach also had very low temperatures and mean monthly values below 2 °C in January and February. The Salmon River has never been known to support significant numbers of fall chinook, presumably because of the colder thermal regime. Redds are occasionally observed in the lower Salmon River but generally represent a very small percentage of the total number of redds observed above Lower Granite Dam (Groves 2001). The similarities between the thermal regime of the Salmon River and the pre-dam Oxbow Reach raise questions about whether the pre-dam Hells Canyon Reach was capable of meeting its production potential because of thermal limitations.

The historic timing for emergence in the Marsing Reach was approximately 25 days later than in the upper Snake River, with a median emergence date of April 10. Emergence in the Weiser Reach and the upper Hells Canyon Reach are within 2 days of each other, with median dates at April 19 and 21, respectively. Emergence in the lower Hells Canyon Reach was just over 2 weeks later, with estimated median dates of April 30. The lower Hells Canyon Reach is thermally influenced by the colder inflow of the Salmon River during the incubation period.

The earliest estimated emergence dates for fish in the upper Hells Canyon Reach is February 24, approximately 3 weeks later than in the upper Snake River and 2 weeks earlier than in the Marsing Reach (Table 1). Emergence was complete by April 13 in the upper Snake River, whereas in the Marsing Reach, it was complete by May 2. In the upper Hells Canyon Reach, emergence is complete by May 18. Emergence was completed in the pre-HCC Oxbow Reach by June 4.

This comparison of reaches demonstrates that emergence timing was correlated with river mile and that the altered thermal regime below Hells Canyon Dam has shifted present-day emergence to an earlier date than that in the same reach in the pre-HCC era. Present-day emergence dates are similar to those of the Weiser Reach (Figure 6). The range of emergence in the upper Hells Canyon Reach is wider than what occurred in other reaches, overlapping the range of the upper Snake River and of the Marsing and Weiser reaches (Figure 7). Despite the wider range, median emergence dates are very similar between the Weiser Reach and the upper Hells Canyon Reach. The warmer winter temperatures likely allow the present-day Hells Canyon Reach to have a higher production potential than was possible in the pre-HCC era. Similarly, the present-day incubation period below the Salmon River occurs in warmer water than during the pre-HCC era, probably allowing that section of river to reach its production potential based on available habitat.

Despite the higher production potential available today below Hells Canyon Dam compared with that of the pre-HCC era, the predevelopment production areas above the HCC had a higher production potential relative to the geomorphic template (i.e., greater quantity of suitable habitat) (Battelle and USGS 2000) and a thermal regime more conducive to production than did the historical Hells Canyon Reach. Even with the improved thermal regime below the HCC, the Hells Canyon Reach will never be capable of the production that was historically available within historical spawning areas above the HCC. However, additional questions need to be addressed regarding present-day habitat condition in those historical production areas above the HCC: for example, has the production potential been reduced because of degraded habitats? Such questions will be explored further in Sections 4 and 5 of this chapter.

3.4. Juvenile Rearing/Outmigration

Although the present-day Hells Canyon Reach is warmer during the incubation period than it was before HCC construction, the entire production area available today is cooler than was the area above the HCC historically. That is, even though emergence times overlap with those that occurred both in the upper Snake River and in the Marsing reaches and though thermal unit accumulation occurs at a faster rate, fish emerge into a cooler thermal regime than did fish above the HCC (Figures 4 and 5). Similar conclusions were reached by Connor (2001). The question then becomes one of how this altered thermal regime affects both growth while rearing and the conditions that may cue outmigration.

Despite the cooler regime during the rearing/outmigration period relative to historic production areas, fall chinook growth rates in the Hells Canyon Reach appear to be exceptional. Connor et al. (1997) reported growth rates of 1.4 millimeters per day (mm/day), a rate that is among some of the highest observed. For example, growth rates reported for subyearling chinook salmon that were held at constant temperature at Lyons Ferry hatchery (Snake River) have an average growth rate of 0.7 mm/day (Lyons Ferry Hatchery, unpubl. data). Monthly mean temperature values for March, April, and May for the upper Hells Canyon Reach are 6.3 °C, 10 °C, and 13.8 °C, respectively (Table 1). Optimal temperatures for juvenile chinook range from 10 to 15 °C (Groves and Chandler 2001b). Raleigh et al. (1986) noted that chinook salmon fry tended to re-enter the gravel when temperatures were below 8 °C. In the Hells Canyon Reach, fish during the earlier portion of the emergence period may remain in the gravel and not actually emerge until sometime later, under warmer conditions. Faster growth rates are probably primarily initiated toward the beginning of April below Hells Canyon, whereas growth was initiated in the first part of March in the reaches above Hells Canyon (before HCC construction). In the pre-HCC Oxbow Reach, thermal conditions in April through May were comparable to present-day conditions below Hells Canyon Dam (Table 1).

Temperature analysis indicates that fall chinook emergence and growth initiation are positively correlated with river mile (Figure 6). Fish in the farthest upstream reaches emerged and initiated growth the earliest, but they also had the greatest distance to travel. Fall chinook in the reach above C.J. Strike Dam had at the minimum 450 km farther to migrate than did fish in the reach below Hells Canyon. Fish in the Marsing Reach had approximately 300 km farther to travel than did fish in the reach below Hells Canyon. Raymond (1979) reported that migration rates of juvenile salmon in free-flowing reaches ranged from 24 km/day to 54 km/day, depending on the magnitude of the water year. The rates reported by Raymond appear to be for spring chinook, but this is not stated. Using the highest rate, we could estimate that fish from the Marsing and upper Snake River reaches would take about 6 to 9 days to reach the area below Hells Canyon Dam. Under the lowest migration rate, migration time would essentially double. However, because fall chinook salmon commonly intersperse rearing (feeding and quiescent behaviors) and active migration (Dauble et al. 1989), their migration is not continuous, and therefore these would likely be minimum estimates.

Because of the earlier emergence and growth potential, fish in the upper Snake River on average were physically ready to migrate before fish in the lower reaches. In addition, they may have attained a larger size because of the increased growth potential. Larger size would have been beneficial, given the longer distance to migrate (based on the assumption that larger fish can migrate faster) (Tiffan et al. 2000). Despite the above travel time estimates, how much time fish in the upper reaches would have taken to arrive to the area that is now Lower Granite Reservoir is unknown. It is possible that when fish from the upriver reaches were arriving in the Hells Canyon Reach, fish in that reach were approaching readiness to smolt, so that the outmigration in the lower river may have been a single pulse of fish from all reaches of the Snake River during a relatively confined period. Mains and Smith (1964) reported that the entire migration period in the early 1950s (pre-Brownlee Dam) was completed by the end of June. This migration presumably included fish produced below Marsing and below Hells Canyon, including fish produced from areas currently inundated by Lower Granite Reservoir. If completion of the pre-HCC emergence in the Hells Canyon Reach were near the first of June, at a growth rate of 1.4 mm/day, these fish would be approaching 80 mm (based on assumed emergence length of 35 mm) (Connor 2001). This size is at the lower end of the size ranges of fish captured by Mains and Smith (1964) at Central Ferry (located on the Snake River approximately 80 km downstream of Lewiston) by the end of June. Today, fish in the Hells Canyon Reach emerge earlier than did fish in the pre-HCC Hells Canyon Reach. Even with the delayed growth potential of the earlier emergers, these fish should have outmigration times similar to, if not earlier than, those reported by Mains and Smith. Yet, today, only 50% of the fall chinook outmigration is complete by the end of June (Connor 2001).

Today's later migrations include fish produced in the lower Clearwater, Grande Ronde, and Imnaha rivers. According to Connor (2001), no evidence indicates that these rivers historically supported a viable population of fall chinook. Yet, today, increased numbers of fall chinook naturally spawn in these rivers (Groves 2001) because of increased supplementation efforts (Chandler and Abbott 2001) and possibly because of an altered thermal regime related to the construction of Dworshak Dam on the North Fork Clearwater River. Connor (2001) concluded that chinook produced in the Clearwater River emerge later than fish in the Snake River and subsequently outmigrate much later. These Clearwater River fish undoubtedly make up a significant portion of the fish migrating later through the Snake River system than what was observed by Mains and Smith (1964). Thermal conditions of the Snake River do not influence emergence timing in the Clearwater River. If salmon were produced historically in the Clearwater River (at least to the mid-1950s), they would have entered a warmer Snake River than they do today. In fact, conditions may have been such that an alternate life history of yearling migration, rather than subyearling migration, would have been prevalent, as is observed today for a small percentage of the Clearwater River fish (Connor 2001).

Another confounding factor in migration timing is the presence of the lower Snake River reservoirs. As discussed above, adult migration and spawn timing has not significantly changed from that of the pre-HCC era. All chinook historically produced above the present-day Lower Granite Dam site had completed migration by the end of June. Emergence timing is earlier today in the Hells Canyon Reach than it was historically. Growth potential, based on thermal conditions, appears to be similar to that in the pre-HCC Hells Canyon Reach. The most profound change that has occurred for migrating juvenile chinook in this reach is construction of the lower Snake River reservoirs.

Reservoir construction increased the river's mean cross-sectional area. This increase significantly reduces water velocity for an extended length of the river. Several studies have focused on factors that influence salmon migration rates through reservoirs. Raymond (1979) measured difference in migration rates in free-flowing sections and in reservoir reaches and found that fish migrating through reservoirs migrated at rates 2 to 3 times slower than in free-flowing reaches. Conducting a three-year study of migration rates of juvenile fall chinook salmon, Venditti et al. (2000) found that migration rates mirrored reservoir water velocity. They listed several factors that could influence migration rates of juvenile salmonids but found that water velocity was the only variable that followed the pattern of migration rates they observed. Connor (2001) concluded that migration rates increase with increased flow (used as a surrogate for water velocity), provided that juveniles were physiologically and behaviorally ready to migrate.

Slower migration rates through reservoir environments increase both the risk of exposure to warming temperatures and the risk of predation. Connor (2001) concluded that increases in flow and decreases in water temperature increase salmon smolt survival. If water temperatures rise too quickly to levels approaching 20 °C, fish survival can be negatively affected by reduced physiological processes, which in turn increase vulnerability to predation, stress, and disease (Connor 2001, McCullough 1999). McCullough (1999) discusses the fact that land-use practices in tributaries have led to more rapid temperature increases in spring and summer. Likely, the affect of land uses in the area upstream of the HCC was evident prior to construction of the HCC (Chandler et al. 2001). Water temperatures in the pre-HCC era increased at a faster rate than they do today below Hells Canyon Dam and were warmer in June than they are today. The mean monthly temperature for June in the pre-HCC Oxbow Reach was 19.2 °C, whereas in the recent years represented in our data, mean water temperatures are 16.8 °C in the upper Hells Canyon Reach and 15.7 °C in the lower Hells Canyon Reach. Present-day temperatures in June may be closer to the predevelopment time period than temperature conditions represented by the inflows into the HCC or conditions during the pre-HCC period.

Present-day temperature conditions below the HCC are more optimal for migrating through the month of June than are conditions represented by inflows to the HCC or during the pre-HCC period. Delays to migrations through the lower Snake River reservoirs subject later migrating smolts to elevated water temperatures. Though the later-emerging tributary fish, such as those produced in the Clearwater River, currently do not enter the Snake River under thermally favorable conditions, such temperature conditions would also have been the case during the pre-HCC era. These thermal conditions may partially explain why the Clearwater River historically was not known to support a viable population of fall chinook, and the same could probably be said for the Salmon River. However, fish produced in the Clearwater River today must also pass through Lower Granite Reservoir and possibly other lower Snake River reservoirs, further exacerbating the risks to their survival.

4. WATER QUALITY

For describing present-day habitats in the Snake River above the HCC, we divided the area between Shoshone Falls and Hells Canyon Dam into four areas (Figure 8): Rock Creek (Shoshone Falls to King Hill), Mid Snake River (King Hill to C.J. Strike Dam), Swan Falls (C.J. Strike Dam to the Boise River), and Lower Snake River (Boise River to Hells Canyon

Dam). The areas generally correspond with designations of ongoing or proposed total maximum daily loads (TMDL) for the mainstem Snake River.

4.1. Rock Creek

This reach of the Snake River is heavily influenced by springs that generally flow from the north bank of the river. For discussion purposes, we further divided this reach into two segments: 1) Shoshone Falls to Thousand Springs and 2) Thousand Springs to King Hill (Figure 9). The first, the upper reach, is directly influenced by spring flows. The lower reach is generally downstream of the majority of spring flow. Before Swan Falls Dam was constructed, the Snake River in this Rock Creek section was a major spawning area for fall chinook salmon (Evermann 1896). Now, much of the habitat is severely degraded, with high nutrient inputs and significantly reduced flows compared with predevelopment times. In addition, mainstem impoundments have inundated many of the primary spawning areas. Most of the land along this section of the Snake River is privately owned. Federal lands also account for a large percentage, most of which are under the jurisdiction of the Bureau of Land Management (BLM). Land uses are primarily rangeland and agriculture (Figure 10). Elevations are predominately above 4,500 feet (ft) mean sea level (msl) (Figure 10).

4.1.1. Shoshone Falls to Thousand Springs (RM 614.6–584.2)

This 30-mi segment of the Snake River in southern Idaho is shaped by a series of natural and anthropogenic factors. Precipitation in the region contributes little to the river flows. Most of the river’s volume comes from water released from upstream impoundments, minor tributaries, and natural springs. In this region of the state, the major land and water uses are designated for agriculture and aquaculture practices. In 1905, Milner Dam (upstream of Shoshone Falls) was constructed. Its primary purpose was to divert water out of the Snake River for irrigators in the Magic Valley region. During summer months, the project may divert as much as 100% of the Snake River flows into canal systems that deliver water throughout the region. A percentage of this diverted water then makes its way back to the Snake River through agricultural runoff or as spring flows that are supplemented by injection wells designed for that purpose. The segment from Thousand Springs to Shoshone Falls is high gradient, greater than any downstream reaches of the Snake River (Figure 11). However, most of the elevation loss occurs in a few falls and steep rapids. The river between these steep falls is better characterized as low gradient, with alluvial deposits and braided channels.

Currently, this segment of the Snake River, with associated tributaries, tops the Environmental Protection Agency’s (EPA) Section 303(d) list of impaired water for all Snake River segments (36 are listed). It is third in the state of all listed waters, following the Clearwater and St. Joe river basins. The major pollutants listed include total suspended solids, phosphorus, sediment, and nutrients.

4.1.1.1. Water Temperature

The State of Idaho has established temperature criteria for the persistence of coldwater biota and has set the maximum daily average at 19 °C. In summer months, temperatures in this segment commonly exceed the maximum daily average. Also noteworthy is the shift in this segment from predominantly coldwater species to predominantly warmwater and pollution-tolerant species, many of which have been introduced. In addition, elevated water temperatures increase growth rates in aquatic plants. The elevated temperatures and high nutrient loads in the regionhave become a major concern (IDEQ 1997, Clark et al. 1998). Some of these highly dense macrophyte beds create their own microhabitat by reducing localized water velocity to nearly zero. And when solar radiation warms the water, the productivity of aquatic plants increases.

In this section of the Snake River, only a small portion of the original mainstem spawning habitat still exists. The remaining habitat is confined essentially to areas near spring inflows where the water remains cold, clear, and well oxygenated (IDEQ 1997, Wilkison 2000). These spring areas may act as a refuge for other coldwater biota as well. Researchers have found that coldwater biota such as aquatic insects are more abundant near spring areas, declining in numbers further into the river channel (IDEQ 1997).

4.1.1.2. Nutrients

The influx of phosphate and nitrogen causes the most significant nutrient-related problems within this area. The phenomenal growth of aquatic plant material and excessive periphyton in the region clearly reflects the additional input from these nutrients, along with increased sedimentation.

Phosphorus

Phosphorus occurs naturally in the system at relatively high levels. Some of the highest reserves of phosphate-containing rock in the United States are found in the headwater region of the Snake River (USFS 2001). In addition to naturally high levels, land uses contribute additional amounts from point and nonpoint sources. Even with the high background levels, anthropogenic sources of phosphorous contribute over 70% of total amounts. Clark et al. (1998) documented that sources of phosphorus to the Snake River in 1995 were fish farms (34%), upstream sources (21%), tributary streams (18%), municipal wastewater-treatment facilities (13%), springs (12%), and irrigation drains (4%).

While this reach of the Snake River is not specifically classified as impaired by phosphorus, suspended solids—which aid in transporting phosphorus—are targets of concern. Likewise, for most of the tributaries entering this section of the river, either phosphorus or sediments are direct concerns.

Nitrogen

Nitrogen occurs naturally in surface water and is essential to productivity. Elevated levels of nitrogen in the form of nitrate (NO_3), its water-soluble form, can lead to an imbalance in the system. At extreme levels, NO_3 acts as a pollutant. The EPA has concluded that nitrogen in this reach exceeds acceptable levels (IDEQ 1997). Findings indicate that 93% of the elevated nitrate levels in the region come from fertilizers, cattle manure, and legume crops (Rupert 1996). The area southwest of Jerome, Idaho, yields the highest nitrate concentrations (IDEQ 1997).

High nitrate levels in the water have also been linked to discharges from the springs in the region. The practice of using injection wells may be partly to blame. Clark et al. (1998) reported that during most water years, 70 to 80% of the nitrate at King Hill makes its way to the river through the springs between King Hill and Milner Dam.

4.1.1.3. Sediment

In this segment of the Snake River, sedimentation and suspended solid loads are the most commonly listed impairments to water quality. Because of high sediment levels throughout the segment from Shoshone Falls to Thousand Springs, the river is classified as *water quality impaired*. Likewise, for tributaries throughout the entire reach, sedimentation is the most common impairment. Most sediments transported to the Snake River originate from nonpoint sources, such as agricultural activities, confined-animal feeding operations, rangeland grazing, recreational activities, logging, and atmospheric deposition (Clark et al. 1998).

Because of water diversions, the "scouring" effect of robust springtime flows throughout the system has diminished. Without this natural cleaning process, sediment deposits remain. Sedimentation has spoiled areas that once provided highly diverse habitats for abundant biota. Sediment deposits, combined with high rates of nutrient loading, provide ideal conditions for excessive plant growth.

This sediment accumulation combined with eutrophication drives the poor water quality conditions that exist from Milner Dam downstream to King Hill (Clark et al. 1998). Within this segment, some areas that are particularly close to a tributary or spring that feeds these conditions, show peak summertime growths of macrophytes. Sometimes the growth crosses the river channel almost completely, leaving only a narrow section near the thalweg free of floating material. While sediments provide rich beds for macrophyte development, they also accumulate pesticides, metals, and other organic compounds that benthic-oriented fish, such as suckers and carp, can ingest (Clark et al. 1998).

4.1.1.4. Tributary Influence

Several tributaries influence the water quality of the Rock Creek Reach, including Rock Creek, Mud Creek, Deep Creek, and Cedar Draw (Chandler and Chapman 2001).

4.1.1.5. Groundwater Influence

Groundwater plays a significant role in this segment of the river. During drought years, such as 2001, groundwater may contribute as much as 79% of the total Snake River flow (Clark et al. 1998) (Figure 12). Groundwater discharge may also influence temperatures in the middle Snake River. During low water years when river flows are their lowest, the proportionately higher contribution of cooler groundwater reduces instream temperatures. For example, we compared temperature data for May through August 2001 for Shoshone Falls and Upper Salmon Falls dams with data from Upper Salmon Falls Dam (Hoelscher 2001a,b). Because 2001 was a dry (low-water) year, the comparison clearly shows how water from underground springs influences instream temperatures when river flows are reduced (Figure 13). Ultimately, however, the temperature benefits may be offset by the impacts produced by reduced instream flows and the settling of sediment-bound nutrients.

While discharges from the springs may moderate temperatures near their source, the chemistry of individual spring waters is variable. Depending on an individual spring's characteristics, its contribution may improve or degrade water quality conditions. From information collected between 1980 and 1994, Clark (1995) concluded the following: "…springs contributed from 33 to 66% of the total stream flow, 32 to 57% of the dissolved solids, 26 to 50% of the total nitrogen, and 7 to 14% of the total phosphorus transported annually from the middle Snake reach."

4.1.1.6. Discharge Influence

The reduced flows in this reach lower the river's capacity to process the excessive nutrients, which tend to concentrate rather than disperse (BOR 1999). Localized upstream weather conditions cause the timing and magnitude of the spring runoff to be highly variable. Compared with historic conditions in the region, scouring and the redeposition of sediment has been greatly reduced, primarily because of water diversions upstream. Clark (1995) demonstrated that total nitrogen, total phosphorus, and suspended sediment (measured at King Hill) were transported at rates 2 to 3 times higher during 1984 (a high-flow year) compared with 1989 (a low-flow year).

4.1.2. Thousand Springs to King Hill (RM 584.2–546.2)

The Snake River from Thousand Springs to King Hill lies directly below the majority of spring inflows that recharge the river. IPC operates three "run-of-river" hydroelectric projects in this reach (Figure 9). A small high-gradient reach below Lower Salmon Falls (8 mi) and the lower 14 mi below Bliss Dam are free-flowing segments.

The first of the impoundments downstream of Thousand Springs is the Upper Salmon Falls Project (FERC no. 2777). The project comprises two separate powerhouses. Upper Salmon B Powerhouse is located at RM 580.8. The dam associated with this powerhouse impounds a small section of river. Most of the flow from Upper Salmon B passes through a power canal for a little less than a mile to Upper Salmon A Powerhouse at RM 579.6. A bypass channel (the original river channel known as the north channel) has a minimum flow of 50 cfs.

Lower Salmon Dam (FERC no. 2061, RM 573) backs water up to the base of Upper Salmon A Powerhouse. Bliss Dam (FERC no. 1975) is located at RM 560.3. The river has a relatively high gradient until it reaches the town of King Hill, where the river's character changes to that of a low-gradient, braided alluvial channel.

4.1.2.1. Water Temperature

Myers and Pierce (1997) determined that overall mean annual water temperatures tend to increase from Upper Salmon Falls to King Hill. The high spring inflows above and within this reach tend to moderate the water temperatures.

4.1.2.2. Nutrients

The following nutrient information is summarized from Myers and Pierce (1997), unless otherwise noted.

Phosphorus

Total phosphorous levels decline significantly from the Buhl bridge site downstream to Upper Salmon Falls Dam and then remain relatively constant through the impounded reaches. When comparing data that IPC collected for the years 1997−2000, we found no appreciable change in total phosphorus within the impounded upper 24-mi section of this reach. Phosphorus concentrations ranged from 0.05 milligrams per liter (mg/l), with a few peaks approaching 0.25 mg/l (Figure 14). The extreme macrophyte production occurring upstream is transported into the lower segment. From June 1991 through December 1993, approximately 5,200 cubic yards of material (primarily aquatic plants) were removed from the river at the Upper Salmon Falls B trash rack.

Impounded sections collect fine particles. High flow events (such as the 1997 freshet that corresponds to the peak measurement) trigger resuspension and transport of phosphorus-containing material from these depositional areas (Figure 14). Phosphorus concentrations entering and leaving the segment commonly exceeded the TMDL target of 0.075 mg/l.

Nitrogen

In data that Myers and Pierce collected from 1988 through 1993, nitrate was the predominant form of nitrogen in this section of the river (Myers and Pierce 1997). While no annual differences were detected between the reservoirs, some differences in monthly values were detected throughout the sample period. However, the sampling revealed that nitrogen levels declined significantly downstream of the Buhl bridge site to Upper Salmon Falls Dam. Nitrogen values were similar at all sites from Upper Salmon Falls Dam downstream to King Hill.

4.1.2.3. Sediment

Measurements for suspended solids collected from June 1988 through October 1993 showed a decreasing trend in values for samples collected between Buhl and Upper Salmon Falls Reservoir, and an increasing trend below Salmon Falls Reservoir to King Hill. Median levels ranged from 5 to 8 mg/l. Little difference was found when monthly values were compared; however, annual differences were detected. A declining trend was observed from March through October, with more elevated levels detected in May, August, and November through March of the sampling period. All the Snake River impoundments in this segment—Upper Salmon Falls, Lower Salmon Falls, and Bliss reservoirs—have water quality-limited classifications because of sediment (for which a TMDL is in place).

4.1.2.4. Tributary Influence

Only a few tributaries enter the Snake River in this lower segment. Billingsley Creek, Malad River, and Clover Creek are the major tributaries (Chandler and Chapman 2001).

4.2. Mid Snake River—King Hill to C.J. Strike Dam (RM 546.2–494.0)

Between C.J. Strike Dam and King Hill, the river meanders and has a low gradient. Before the river enters C.J. Strike Reservoir's influence some 21 mi below King Hill near Indian Cove (RM 525.3), it has multiple braided channel sections. The remaining 31-mi section lies within C.J. Strike Reservoir (Figure 15). Primary land owners are the BLM (Figure 16), followed by private owners. Rangeland is the dominant land use in this section of the river, followed by agriculture (Figure 16). Most elevations are above 3,000 ft msl (Figure 16).

Historical spawning areas still potentially exist in the free-flowing river segments between King Hill and Glenns Ferry. C.J. Strike Reservoir has inundated mainstem spawning areas near the confluence of the Bruneau River. The segment of river from Bliss Dam to C.J. Strike Reservoir currently supports the second largest white sturgeon population in Idaho (Lepla and Chandler 1995). The following descriptions of water temperatures, nutrients, and sediments for C.J. Strike Reservoir were summarized from Myers and Pierce (1997), using data collected primarily in 1994 and 1995.

4.2.1. Water Temperature

During peak summer months, water temperatures in the reservoir section regularly exceed Idaho's water quality standards for coldwater biota. The standard instantaneous upper limit is 22 °C, and the daily average upper limit is 18 °C. Temperatures are typically higher in the Bruneau River arm of the impoundment than in the Snake River arm, where mean depths are approximately one-third greater.

During summer months, C.J. Strike Reservoir develops a thermal gradient and displays a weak thermocline, with the maximum profile range yielding a 9.4 °C differential. Regarding temperatures, the reservoir section behaves like other large impoundments by decreasing summer warming and winter cooling. Predictably, when compared with the free-flowing section upstream of the impoundment, the increased thermal mass of the reservoir section causes a slight lag between the seasonal onset of cooling and heating. Diel fluctuations in tailwater temperatures also decreased.

4.2.2. Nutrients

During the sample period, levels of nutrient inflow (total phosphorus and total nitrogen) from the riverine segment into C.J. Strike Reservoir consistently exceeded outflow levels. Sample data suggests that particles settling out (as the water slows entering the impounded section) cause the net reduction in nutrient levels.

Although Idaho has not yet established a water quality standard for phosphorus, the EPA has proposed a target level of 0.05 mg/l for waters flowing into an impoundment. Of the samples collected, 98% exceeded the EPA criteria (Figure 17). Although peak total phosphorus loads to the system arrive with spring flows, peaks don't always correlate with high runoff events. For example, no noticeable freshet was present in 1994, but peak total phosphorus loads still occurred in March and April. Total nitrogen flowing through the system showed similar characteristics, with noticeably larger amounts of nitrogen retained during winter. Low dissolved oxygen (DO) levels in the reservoir resulted in elevated levels of nitrogen in the form of ammonia (caused by reduction under anoxic conditions), which we identified as a problem.

High rates of nutrient loading also encourage algae production, which may cause problems. Although algae levels leaving the reservoir were similar to those entering, high rates of algae production and surface algae blooms were observed during the study, especially in the Bruneau River arm of the reservoir.

4.2.3. Sediment

Because of sediment, C.J. Strike Reservoir is currently classified as water quality limited and is on the EPA's Section 303(d) list. A TMDL allocation is being initiated at the time of this writing. As for the Rock Creek segment, land adjacent to this segment is used primarily for agriculture.

Sediments entering the impoundment have a similar fate as nutrients: they tend to settle out with reduced velocities (Figure 18). Turbidity values (using Secchi depth measurements) were shown to be consistently higher at the entrance to the reservoir than at the tailwater section below the dam (Figure 19). Levels of suspended solids in the region commonly exceed criteria established by the State of Idaho, with minor differences between the Snake River arm and the Bruneau River arm. Related bathymetry studies (IPC, unpubl. data) conducted in 1994 and 1995 indicate that since the project was constructed in 1952, nearly 6% of the reservoir's storage capacity has been lost to sedimentation.

4.2.4. Tributary Influence

Tributary basins in this reach of the Snake River include the Bruneau River and a few smaller basins, such as Sailor Creek, Canyon Creek, and Bennett Creek (Chandler and Chapman 2001). A TMDL has been drafted for the Bruneau River. Classified as water quality limited because of nutrient levels, flow alteration, and temperature, the lower 14 mi of the river before it enters the reservoir is on the 303(d) list. Because of sediment levels, nearly all other perennial streams that make their way to the Snake River between King Hill and C.J. Strike Reservoir have been targeted for TMDLs.

4.3. C.J. Strike Dam to Boise River (RM 494.0–396.4)

The nearly 98-mile river section between C.J. Strike Dam and the Boise River (with the exception of a short canyon segment below Swan Falls Dam) can be characterized as a low-velocity, shallow alluvial river with multiple braided channels and island complexes (Figure 20). The primary land managers in the river section are the BLM, followed by private owners (Figure 21). Although rangeland is the primary land use in this section, nearly its entire length is bordered by land used for agriculture. Agricultural uses comprise approximately 15% of this river section (Figure 21). Elevations in this reach are mostly above 2,000 ft msl (Figure 21).

Swan Falls Dam operates as a run-of-the-river project and impounds 1,525 acres (617 hectares). Following construction of Swan Falls Dam and before Brownlee Dam was built, the reach between Swan Falls Dam and Marsing, Idaho, was the primary spawning area for fall chinook (Haas 1965).

Because of sediments, the entire length of this segment has been classified as water quality limited and is on the 303(d) list. A TMDL is being developed for this segment. Additionally, the section below Swan Falls Dam to the Boise River has also been included on the 303(d) list because of nutrients, pH, bacteria, DO levels, and flow alterations.

The following summaries include information from Worth and Braun (1993), Harrison et al. (2000), Hoelscher and Myers (2001), and IDEQ (2001).

4.3.1. Water Temperature

Idaho established 22.0 °C as the maximum instantaneous temperature for coldwater biota, while Oregon established 17.8 °C over a seven-day average as the maximum allowable for salmonid rearing areas. These criteria are commonly exceeded during summer months within this segment.

Mean daily temperatures between Swan Falls Reservoir (RM 458.0) and Nyssa, Oregon (RM 383.2), from March 1996 through May 2001 (IPC, unpubl. data) show few variations. The only fluctuations occurred at the downstream Nyssa site, where measurements showed slight increases in summer maximums and slight decreases in winter minimums (Figure 22). Harrison et al. (2000) presented mainstem temperatures between Murphy (RM 449.3) and Nyssa (RM 385.0) between April and September 1995. Median temperatures increased gradually through Adrian (RM 403.0) and then decreased 1.4 °C between Adrian and Nyssa (RM 385.0). Summer maximum measurements exceed 22.0 °C at all stations measured (Table 3). When Worth and Braun (1993) recorded temperatures in 1992 at Homedale (RM 417.0) and downstream of Weiser (RM 351.0), they found values slightly higher (0.2 °C) at Homedale on August 19, and then lower on August 26 (3.3 °C) and September 4 (1.8 °C).

4.3.2. Nutrient and Sediment

Harrison et al. (2000) presented nutrient data from April through September 1995 for sites between Murphy (RM 449.3) and Weiser (RM 340.0). The following summarizes their findings:

- Total phosphorus and total nitrogen loads tend to increase downstream throughout the segment from the continuous additions from tributaries.
- More soluble reactive phosphorus (representing the amount of phosphorus most readily available for algal growth) enters the segment than leaves it, a condition that is indicative of processing by primary production.
- Total suspended sediment exceeds the 80.0 mg/l target that Idaho and Oregon suggest as necessary for supporting the designated beneficial uses (Table 4).

- Median total phosphorus concentrations exceed the 0.07 mg/l target proposed by the Idaho and Oregon Departments of Environmental Quality (Table 4).

4.3.3. Tributary Influence

Generally, tributaries entering the Snake River within this segment contribute little to the overall discharge. Although discharge is limited, contributions of elevated nutrient and sediment concentrations are not. Of the tributaries on the 303(d) list, 40.0% (19) are listed because of sediment levels, 19.0% (9) because of temperatures, and 12.5% (6) for flow alterations. The rationale for other listings (ranked according to occurrence) are bacteria, nutrients, chlorophyll *a*, DDT, oil or gasoline, and others.

4.4. Lower Snake River—Boise River to Hells Canyon Dam (RM 396.4–247.0)

This reach of the Snake River was subdivided into two segments: 1) the reservoir segment, including the HCC, which impounds water to RM 335.0 at full pool, and 2) the riverine segment upstream of the reservoirs. Combined, these segments include approximately 211 mi of river (Figure 23). These two segments behave quite differently regarding physical and biological processes. For example, temperature and oxygen stratification in the reservoir segment does not occur in the riverine segment. Yet the quality of the riverine segment greatly influences conditions in the reservoir environments (Figure 24).

Although the HCC was constructed for multiple uses, it is primarily used for hydroelectric generation and flood-control storage. Brownlee Reservoir has an active storage of approximately 1 million acre-feet of water. The reservoir morphometry of the three impoundments are typical canyon-type impoundments, with depths approaching 300 ft (90 meters [m]) in the forebay of Brownlee Reservoir. During a normal water year and with water elevation at full pool, water retention time in Brownlee Reservoir is approximately 66 days. During low inflow years, such as 1992, retention time as much as doubled.

The free-flowing section upstream of the impoundments is characterized as a low-gradient river dominated by multiple island complexes and shallow braided channels. Several large tributaries enter the Snake River above Brownlee Dam and significantly influence the water quality of the riverine section and the reservoirs. Tributaries include the Boise, Owyhee, Payette, Malheur, and Burnt rivers (Chandler and Chapman 2001). These tributaries contribute nearly 40% of the volume reaching Brownlee Reservoir. Tributary discharges, ranked by contribution, are as follows: the Snake River entering the segment (59%) and the Payette (20%), Boise (11%), Weiser (7%), Owyhee (3%), Malheur (1%), and Burnt (< 1%) rivers (Table 5). Most tributary hydrographs have been altered to some degree by flood control, irrigation, power generation, and recreation, which all contribute to high variability and annual flow (IDEQ 2001).

4.4.1. Water Temperature

Summer temperatures commonly exceed Idaho and Oregon water quality standards throughout the free-flowing segment. Temperatures have ranged from an average of 4 °C in winter to 24 °C in summer just upstream of Murphy (IDEQ 2001). River morphometry and local weather conditions seem to be more important determinants of surface temperatures within the reach. However, anthropogenic increases in temperature from tributary inflows and mainstem inflows into the reach may be significant. Historical records from 1957 suggest that pre-impoundment temperatures were probably above the current temperature criteria that Idaho and Oregon have set for water quality standards. However, during the predevelopment era (prior to the effects of land uses), the thermal regime was probably significantly cooler. Land uses over the previous century have severely reduced riparian habitats on a large geographic scale and have undoubtedly altered the thermal regime of the Snake River (Chandler and Chapman 2001).

Water temperatures within the impounded segment largely reflect the basin’s corresponding water year, with higher discharge resulting in cooler water. Except during years of extreme inflow (such as 1997), temperature stratification and the development of a hypolimnion occur annually in all three impoundments (Myers and Pierce 1999). Summer water temperatures in the impounded section regularly exceed Idaho and Oregon water quality standards, and the segment is on the EPA’s 303(d) list. Brownlee Reservoir is considered to be in a mesotrophic to eutrophic state, increasing in trophic status downstream toward the dam (Milligan et al. 1983, Myers and Pierce 1999). Data IPC collected from 1991 through 1998 showed temperatures in Brownlee Reservoir exceeding Idaho’s water quality standard for coldwater biota (19.0 °C daily average) for 51 days, and Oregon’s standard (17.8 °C daily average) for 72 days (Myers and Pierce 1999).

Excluding spill events, discharge from Brownlee Dam through the project draws water from the reservoir at a depth of 30 m (at full pool). During normal summer generation periods and normal water years, this results in drawing and passing cooler, lower oxygenated water through the plant into downstream Oxbow and Hells Canyon reservoirs. IPC data collected during the same period indicates the average number of days that temperatures exceeded Idaho’s instantaneous maximum standard of 22 °C was 19 (Myers and Pierce 1999). But during higher than normal flow years, inflows that exceed the projects’ storage capacities lead to spilling the warmer surface water. Such spilling increases the number of days that both Idaho’s and Oregon’s temperature standards are exceeded (Myers and Pierce 1999). This is largely a phenomenon related to the large flood-control drawdowns of Brownlee Reservoir that are associated with higher than normal flow years.

4.4.2. Dissolved Oxygen

Although DO levels in the riverine segment vary seasonally and with water year discharge, they have not fallen below 6.0 mg/l (Idaho’s minimum water quality standard). Fifteen years of data that the EPA collected at RM 351 (near Weiser) show midday records ranging from 14.2 mg/l in December 1979 to 6.7 mg/l in June 1979 (IDEQ 2001).

In the HCC, low DO levels are common from late spring to early fall. Between 1991 and 1998, daily samplings for DO levels were taken in the HCC. Discharge samples from Brownlee Dam failed (at some point during the daily sampling) to meet state water quality standards for an average of 173 days/year (Myers and Pierce 1999). During the same years, Oxbow and Hells Canyon reservoirs each averaged over 100 days/year of below-standard DO levels (Tables 6 and 7). The onset of low DO levels in the system relates to the strong stratification that occurs in Brownlee Reservoir. The degree and depth of stratification is inversely related to annual inflow and elevation of reservoir water, both of which help establish the longitudinal location of the transitional and lacustrine zones.

Extended periods of low DO levels in Brownlee Reservoir negatively affect fish populations. In July 1990, at least 28 adult sturgeon deaths in Brownlee Reservoir were linked to low DO conditions. DO levels collected near the same time were less than 0.86 mg/l throughout the water column in the reservoir's transitional zone near where the fish kill probably occurred (IPC, unpubl. data).

While Oxbow and Hells Canyon reservoirs fail to meet the state's water quality minimum criteria, Brownlee Reservoir largely controls the water-quality values in these two reservoirs. While the average oxygen level leaving Brownlee Dam is lower than levels entering Brownlee Reservoir (Figure 25), the average levels leaving Hells Canyon Dam are greater than those leaving Brownlee Dam (Figure 26). These levels suggest that some aeration is occurring within the system (Myers and Pierce 1999). So hypoxic conditions in the dam complex may be attributable to low DO levels in Brownlee Reservoir, which in turn is driven largely by the influx of excessive organic and nutrient loads entering the reservoir (Myers and Pierce 1999).

4.4.3. Nutrients

The two nutrients of particular concern that the Idaho Department of Environmental Quality (IDEQ), Oregon Department of Environmental Quality (ODEQ), IPC, and others have identified in the HCC are nitrogen and phosphorus. Excessive loading of either of these elements degrades water quality and contributes to eutrophication (IDEQ 2001).

Excessive nutrient loading has been linked to excessive algae and periphyton growth. According to the IDEQ, this growth may result in "…low dissolved oxygen, increased methylmercury production, elevated pH, cyanotoxins from blue-green algae production, trihalomethane production in drinking-water systems, and maintenance issues associated with domestic water supplies" (IDEQ 2001). The IDEQ lists nutrients as primary pollutants within this segment of the Snake River (IDEQ 2001).

Phosphorus

Total phosphorus levels measured in the riverine segment consistently exceed 0.05 mg/l, the EPA's benchmark for concern (Hoelscher and Myers 2001). Average concentrations of total nitrogen increase downstream through the segment. During 1996 through 1999 from June through September, IPC collected data on phosphorus levels in the riverine segment. This data was summarized in the Hells Canyon TMDL (IDEQ 2001), and the results follow. During the four-year period, total phosphorus averaged 0.09 mg/l at RM 413 (segment inflow), 0.12 mg/l at

RM 385 (below the Boise River), 0.13 mg/l at RM 351 (above the Weiser River), and 0.13 mg/l at RM 340 (above Brownlee Reservoir). Likewise, data summarized by Harrison et al. (2000) showed total phosphorus levels increasing downstream to Brownlee Reservoir (Table 4). Data collected between 1970 and 1999 reveal that tributaries entering the Snake River within this segment have varying influences on the amount of total phosphorus present, as Figure 27 shows (IDEQ 2001).

Downstream, the HCC shows similar trends for phosphate levels (Figure 28), with the Snake River and Brownlee Reservoir displaying excessive algae growth during normal to low-water years (Myers and Pierce 1999). The highest concentrations of phosphate in the reservoirs are generally found at the upstream end of Brownlee Reservoir (Myers and Pierce 1999, IDEQ 2001), with reductions occurring downstream toward the dam (Figure 29). Brownlee Reservoir traps a percentage of the total phosphate entering the reservoir. As shown in Figure 30, the inflow of phosphate exceeds the outflow. This difference might result from settling that occurs in the transitional zone (Myers and Pierce 1999).

Inflows and reservoir elevations also influence the amount of phosphorus cycled through the system. During the high-water year of 1997, a lower percentage of total phosphorus was retained in Brownlee Reservoir than in 1995 (a normal water year). However, the export quantity of orthophosphate was greater than the inflow of the dissolved form because of resuspension that the scouring flows created (Myers and Pierce 1999). With Brownlee Reservoir acting as the phosphate sink, nutrients are reduced in the downstream reservoirs. During 1991 through 1997, the data indicated that the total and orthophosphate load varied little between outflows from Brownlee and Hells Canyon reservoirs (Myers and Pierce 1999).

Nitrogen

Similar to phosphorus in the system, total nitrogen also tends to increase in load downstream to Brownlee Reservoir (Figure 31). Nitrogen, both in the forms of nitrate and ammonia, can be important in algae development. From 1991 through 1997, ammonia nitrogen was sampled at all three reservoirs. The results were published in Myers and Pierce (1999). All the ammonia levels detected were within the limits Idaho set for coldwater biota. In general, more ammonia left Brownlee Reservoir than entered it. Elevated ammonia levels are attributable to hypoxic conditions in the water column and to sediments.

4.4.4. Sediment

In developing a TMDL for the Hells Canyon Subbasin Assessment, IDEQ has not yet established levels for minimum total suspended solids (TSS), although 50 mg/l has been recently proposed in the TMDL (IDEQ 2001). Nonetheless, TSS levels have been identified as an area of concern. Within the riverine segment above Brownlee Dam, IDEQ has listed sediment as a primary pollutant (IDEQ 2001). While the data is somewhat incomplete, a composite graph of mainstem and tributary sediment information developed as part of the Hells Canyon TMDL draft appears in Figure 32 (IDEQ 2001). Additional concerns regarding the transport of sediment-bound pollutants (primarily mercury) have been noted in this region.

Within the reservoir segment, sediments are also a cause of concern. The complex serves to concentrate sediments and their bound particulate contents within the depositional areas. These deposits can then be resuspended during infrequent high-flow events, when abundant pollutants move through the system in a short time span. Under this scenario, mercury is a particular element of concern. The Hells Canyon TMDL draft (IDEQ 2001) illustrates the depositional mechanism at play in Brownlee Reservoir (Figure 33). While deposition in Brownlee Reservoir degrades the local environment, it may be beneficial to areas downstream that would otherwise experience higher levels of sediment and pollutants. The effect may be especially beneficial to critical spawning areas for fall chinook salmon below Hells Canyon Dam.

5. HISTORIC SPAWNING HABITAT

Water quality conditions, especially below Swan Falls, characterize the cumulative effects of multiple land uses that occur in the subbasins and along the mainstem Snake River. Compared with predevelopment times, the historic production area for anadromous fish above the present-day Hells Canyon Dam site has been severely degraded and altered. These degraded water quality conditions likely affect the feasibility of reintroducing anadromous fish, and we must examine the life stages that could be impaired. Clearly, much of the mainstem Snake River would not support rearing of stream annulus salmonids during the summer months. For ocean annulus salmonids such as fall chinook, exposure to the conditions previously discussed could be limiting for later migrants. However, fall chinook spawn and incubate in the mainstem environment and then begin migrating out of the area relatively soon after emergence. Because of their early migration, fall chinook may not be exposed to potential lethal conditions that occur later in the summer months. A more critical habitat question relates to the quality of the intragravel or hyporheic environment and how that environment may have been affected by land uses.

High organic and nutrient loads into the Snake River, along with high-suspended sediments, can directly affect the hyporheic environment. In this environment, fine particulates can accumulate in the interstitial spaces of the gravel and increase microbial action and biological demand within the substrates. Further, these particulates can reduce the permeability of the substrates and affect their ability to support egg and embryo survival. Sediment permeability is positively correlated to salmonid embryo survival and negatively correlated to the percentage of fines (Shirazi et al. 1981 and Chapman 1988). Embryo survival is enhanced in areas of high permeability because high rates of water movement within the redd pocket irrigate embryos with potentially oxygen-rich water and maintain pathways for emerging fry. We lacked the necessary measurements of sediment permeability to fully evaluate the quality of salmonid spawning habitat in the upper Snake River basin. Further, we wanted to measure levels of DO that incubating embryos might be exposed to in a redd environment. So we constructed artificial redds within the historical sites to monitor intragravel DO levels through what would constitute an incubation period.

5.1. Sediment Permeability

To evaluate the quality of the hyporheic environment within the historic spawning areas, we chose gravel beds at three sites (Figure 34). According to aerial photos from fall chinook redd surveys conducted in the mid-1950s, the upper and middle sites have historically supported fall chinook spawning (IDFG 1955). The third site is in close proximity and had similar physical characteristics as the two known spawning areas. The sites fall within the reach between Swan Falls Dam and the Boise River, described in Section 3.3. This area supported the majority of fall chinook spawning above Brownlee Dam after Swan Falls Dam was constructed (Haas 1965). Sediment permeability was measured at the two known spawning areas to assess the habitat's potential quality for spawning. Battelle Pacific Northwest Labs and IPC collected data. Battelle conducted the analysis under contract with IPC. The information throughout Section 5.1 is from a report Battelle prepared for IPC (Hanrahan et al. 2001).

5.1.1. Study Sites

The upper (RM 479.7, river kilometer [RKM] 722) and middle (RM 445.5, RKM 717) sites are approximately 15 and 20 river kilometers downstream from Swan Falls Dam (RKM 737), respectively. In this section of the valley, the river flows through alluvial deposits of cobble, gravel, and sand, but is also often confined by basalt bedrock, particularly near the upper site (Figures 35 and 36). Both study sites are located at the proximal (upriver) end of vegetated mid-channel islands (Figure 37). The width of the active channel at both sites is approximately 230 m. The surface water hydrology in this section of river is characterized as riverine, which means that Brownlee Reservoir's backwater effect does not influence the fluvial hydraulics at the study sites. During the study period (February 28−March 3, 2000), the hourly discharge near Murphy (USGS gauge 13172500) below Swan Falls Dam ranged from 253 to 392 m^3/second (8,942−13,854 cfs).

At each site (upper and middle), 15 sampling locations were chosen at random from all appropriate sampling locations within the historic spawning areas. (Appropriateness was determined by the acceptable ranges of substrate, depth, and velocity defined by Groves and Chandler [1999].) Of the 15 locations, 10 were used for sampling and 5 were retained as backup in case unsuitable microscale conditions existed at one of the other locations. All sampling points were located within the wetted perimeter of the channel, in water depths ranging from 0.1 to 1.0 m. To identify the locations in the river, real-time differential global positioning system (DGPS) navigation was used. Two approaches to evaluate sediment permeability were used: substrate grain size distribution and slug testing.

5.1.2. Sediment Grain Size Distribution

Bulk riverbed samples from seven locations within each study site were sampled (Figures 38 and 39). A tri-tube freeze core method was used to extract the samples from the riverbed (Lotspeich and Reid 1980, Rood and Church 1994). To collect each sample, an assembly of three stainless-steel tubes were driven into the riverbed to a depth of 50.0 centimeters (cm) below the riverbed surface. Each tube was 152.0 cm long, with a 2.4 cm inside diameter and 3.3 cm outside diameter. Two triangular 0.6 cm-thick aluminum plates separated the tubes by a distance of

15.0 cm (on center). After placing the tri-tube assembly, liquid nitrogen was poured into each of the three tubes until a sufficient volume of the riverbed was frozen (Figure 40). Each core required approximately 15 to 20 liters of liquid nitrogen applied during a 30- to 45-minute time span. Cores were extracted from the riverbed using a chain hoist and tripod assembly. After extraction from the riverbed, the cores were placed over an aluminum sample collection box and thawed with a portable propane heater (Figure 41). Finally, each thawed core sample was transferred into a vinyl double-bag, placed inside a plastic transport box, and then labeled for transport back to the laboratory for grain-size analysis.

At the laboratory, each sample was transferred to a canvas cloth bag and dried inside a vented oven at 65 °C for 5 to 6 days. The dried samples were then sieved into ½-phi size classes from 128 mm (–7 phi) down to 1 mm (0 phi). The sediment passing through the 1-mm sieve was treated as one size class. For each sample, the weight of the substrate in each size class was determined, yielding a percentage-by-weight value for each size class. All laboratory sample handling, quality assurance, and quality control followed the guidelines of Guy (1969).

The tri-tube freeze core method was not used to sample the riverbed's surface layer because the core thaws at the riverbed surface (Figure 42). Other methods were used to estimate the distribution of substrate sizes from riverbed surfaces.

The riverbed surface substrate at each site was sampled using the Wolman (1954) pebble count method (Figure 43). The method typically dictates sampling 100 stones, randomly selected from specific geomorphic features (Wolman 1954, Church et al. 1987, Kondolf 2000). At each site, a total of 120 rocks were sampled, with each site representing a specific geomorphic unit (such as the proximal end of a mid-channel bar). The same observer performed all pebble count sampling to eliminate errors that multiple-observer sampling can cause (Wohl et al. 1996). To reduce measurement error and obtain samples directly comparable with sieve analysis, all grain size measurements were made with an aluminum template with square openings in ½-phi size classes from 128 mm (−7 phi) down to 2 mm (−1 phi) (Hey and Thorne 1983).

In addition to providing total grain size distributions, several indices of substrate composition provide a means to evaluate the quality of spawning gravels. The geometric mean (d_g) provides a measure of central tendency, while emphasizing the extremes of the distribution rather than the median (Kondolf 2000). This measure is favored over the disadvantages of using the fredle index (see summary in Kondolf 2000). The geometric mean is calculated as

$$d_g = (d_{84} \times d_{16})^{0.5}$$

The geometric sorting coefficient (s_g) indicates the sorting (or grouping) of similarly sized particles (Kondolf 2000). When particles of all sizes are well mixed together (also known as dispersion), s_g values increase. Conversely, when particles of the same size are grouped together (i.e., a deposit is well-sorted by particle size classes), s_g values decrease. The geometric sorting coefficient is calculated as

$$s_g = (d_{84} / d_{16})^{0.5}$$

The sampling effort from February 28 through March 3, 2000, resulted in 7 bulk substrate samples (freeze cores) from each site (middle and upper) for a total of 14 sediment cores. The freeze core sampling yielded very large sample sizes, allowing for reliable estimates of grain size distribution at both sites. Individual sample sizes ranged from 18 to 42 kg, with an average weight of 31 kg. The combined sample weights for the middle and upper sites were 208 kg and 222 kg, respectively. Where maximum stone sizes in a sample are greater than or equal to 64 mm, guidelines suggest that any one stone should represent no more than 1% (by weight) of the total sample (Church et al. 1987, Rood and Church 1994). Based on these guidelines, the sample size necessary to describe the mean grain size distribution at both study sites is approximately 100 kg. The sample sizes for the study far exceeded this criterion.

The grain size distributions at both the middle and upper sites were typical of gravel-bed rivers. At both sites, the riverbed surface was coarser than the underlying substrate in the bed (Table 8 and Figure 44). Characteristically, the surface at both sites was deficient of the finer-sized grains (such as sands) in the distribution. Though finer-sized grains were more prevalent in the bed composition, they represented a relatively small percentage of the total distribution. The percentage of fines (< 1 mm) in the bed was 10 and 8% at the middle and upper sites, respectively (Table 9). Toward the upper end of the grain size distributions (e.g., d_{75} and d_{84}), the substrate sizes of the surface and bed were very similar, suggesting that the larger clasts on the surface were indicative of the grain sizes comprising the bed's framework. The riverbed surface at both sites may be described as armored. Determining whether the armoring is a function of an inactive bed (resulting from insufficient bed-mobilizing flows) or evidence of persistent coarsening in an active bed (despite frequent bed mobilization) requires an analysis of the flow regimes in the study area.

Determining the quality of substrate required for salmonid habitat is complicated by two factors: 1) the natural variability of fluvial sediments and 2) the various definitions of substrate quality. Typically, substrate characteristics are used as surrogate indicators for the substrate's permeability, which is an attribute that affects removing metabolic wastes from egg pockets and replenishing oxygen-rich water (Sowden and Power 1985). Substrate permeability depends not only on fine sediments, but also on the presence of coarser gravel and cobble (Fetter 1994). Permeability is also affected by pore sizes, particle shapes, degree of sorting or mixing, and modality of the size distribution (Fetter 1994). Moreover, substrate characteristics important to salmonids differ among the various life stages from spawning to emergence. So for salmonid habitat, there is no single descriptor of substrate quality. Rather, several elements of substrate composition should be evaluated to determine quality. These include 1) determining framework gravel sizes to evaluate the quality of spawning substrate and 2) determining percentages of fine grain sediments to evaluate the quality of incubation and emergence substrate (Kondolf 2000).

Similar to the results of the total grain size distributions, the values of geometric mean diameter (d_g) and geometric sorting coefficient (s_g) at both sites indicated an armored riverbed surface. The d_g values for the surface at both sites were much larger than those of the bed. The finer material (i.e., d_{16}, sands) present in the bed resulted in a lower geometric mean diameter. Armoring was also evidenced by the geometric sorting coefficients (s_g). The s_g values were lower for the riverbed surface (well sorted) and higher for the bed (well mixed) (Table 10).

Despite the armored nature of the bed, the size of the largest material ($> d_{84}$) present on both the riverbed surface and in the bed was well within the size limit of material capable of being excavated by spawning fall chinook salmon (Groves and Chandler 1999). At both the upper and middle sites the median grain size (d_{50}) was within the range of grain sizes observed at fall chinook salmon redds within the Snake River system (Groves and Chandler 1999).

A review of literature values suggests that the geometric mean values (d_g) from both sites were conducive to relatively moderate to high incubation and emergence success (Shirazi et al. 1981, Chapman 1988, Reiser and White 1988, Eaton 1997). For example, the d_g values from the middle and upper site would translate into a 60 to 80% survival-to-emergence rate based on the data in Chapman's (1988) comprehensive review, and a 55 to 65% rate based on the data from Eaton (1997).

It is more difficult to obtain accurate estimates of substrate quality (based on percentage of fines) for embryo survival. Data from other studies indicate that the entire substrate composition and bed morphology (sorted, mixed, or packed, for example) play an important role in embryo survival (Shirazi et al. 1981, Chapman 1988, Kondolf 2000). Nevertheless, based on comparable data (Chapman 1988, Eaton 1997), the percentage of fines (< 1 mm) at both sites indicated relatively good quality substrate for incubating embryos. The mean percentages of fines in the bed were 10.0 and 8.0% in the middle and upper sites, respectively. If these values are adjusted for the effects of redd excavation by spawning females (Kondolf 2000), the resulting percentages of fines are 6.7 and 5.4% at the middle and upper sites, respectively. Some studies suggest there may not be a need to account for the effects of redds excavation, based on evidence of egg pocket persistence (Peterson and Quinn 1996). Regardless of the complexities regarding the effects of redd excavation on fines in the egg pocket, unadjusted data from all the samples indicate relatively low percentages of fines in the bed (Table 11).

Although there is no consensus among fisheries researchers regarding a unified definition of substrate quality, intrusion of finer material within a gravel/cobble matrix is generally believed to cause a reduction in survival from incubation to emergence (Shirazi et al. 1981). The intrusion of fines may decrease substrate permeability, which along with hydraulic gradient affects intragravel flow. Intragravel flow controls DO and water exchange in the egg pocket, and these conditions contribute to embryo survival (Chapman 1988). Indeed, intragravel flow of groundwater can be a much better predictor of survival than the percentage of fine sediments (Sowden and Power 1985). Thus, direct measures of substrate permeability and hydraulic gradient provide additional insight into the quality of substrate for salmonid habitat.

5.1.3. Slug Testing

Slug testing was performed by using piezometers installed within the riverbed. Piezometers were placed near the point of the freeze core samples (Figures 38 and 39) and performed slug tests prior to the freeze core sampling. At each site, 10 piezometers were installed to approximately the same depth below the riverbed (top of screen at 13.5 cm, bottom of screen at 44.5 cm) to estimate hydraulic conductivity (K) of the sediments within the zone of a fall chinook salmon redd pocket.

Each piezometer was screened with a 31.0-cm length of Johnson Screen^{TM} (0.038-cm slot size) with an inside diameter of 3.2 cm. The screen was welded on one end to a 12.0-cm drive point, and on the other end to a variable-length section of galvanized steel pipe (3.2 cm inside diameter) that was threaded on top. Three different lengths of steel pipe were used to make the piezometers' overall lengths either 90.0, 120.0, or 151.0 cm.

Piezometers were placed within the river channel in water depths ranging from 0.1 to 1.0 m. Individual piezometers were placed in the riverbed by inserting a solid steel drive-rod into the piezometer and manually pounding the piezometer until the desired depth below the riverbed surface was achieved (Geist et al. 1998). The top of all piezometers remained above the water surface to allow for installation of a pressurizing assembly. Once the piezometer was in place, the internal drive-rod was removed, and the piezometer was developed by removing fine sediment (<1.0 mm) with a hand pump. Pumping continued until a connection with the subsurface water was established.

Pneumatic slug tests were used to estimate hydraulic conductivity in the piezometers. To perform the test, an airtight pressure-regulating wellhead assembly was threaded to the top of the piezometer. The assembly consisted of a 5.0-cm ball valve coupled to a 20.0-cm section of schedule-40 PVC containing a small valve stem for pressurizing. A pressure transducer was lowered into the piezometer to measure changes in hydraulic head during the test (Figure 45). The system was pressurized with a portable battery-powered air compressor, causing the water level in the piezometer to be depressed downward (Figure 46). Changes in pressure were measured by the transducer and recorded to an electronic data logger. When the water level in the well was sufficiently depressed, the air compressor was shut off and the ball valve simultaneously opened, marking the beginning of the slug test. When the pressure was released, the data logger recorded the pressure response (rising water level) with respect to time. To ensure precision, the slug tests were repeated three to five times in each piezometer (Butler et al. 1996), resulting in over 30 slug tests at each site.

Methods for estimating hydraulic conductivity from slug test data have been summarized by Butler (1997). For the case of a partially penetrating well in an unconfined aquifer (riverbed substrate conditions), reasonable data analysis techniques include the Hvorslev method (Hvorslev 1951) and the Bouwer and Rice method (Bouwer and Rice 1976, Bouwer 1989). Both methods involve plotting the natural logarithm of the head response against time. The slope of this plot, together with data regarding piezometer geometry, is used to solve for hydraulic conductivity.

The Hvorslev slug test method to determine hydraulic conductivity (K) is defined as

$$K = \frac{r^2 \ln(L_e/R)}{2L_e T_0}$$

where
K = hydraulic conductivity (length/time)
r = radius of the well casing
R = radius of the well screen
L_e = length of the well screen

T_0 = time for the water level to rise or fall to 37% of the initial change (Fetter 1994)

Note that $1/T_0$ is equivalent to the slope of $LN(H_0/H_t)$ vs. time for the case where $(H_0/H_t) = 0.37$ (Butler 1997)

H_0 = drawdown at time $t = 0$
H_t = drawdown at time $t = t$

Hydraulic conductivity using the Bouwer and Rice Slug-Test Method is determined via the Bouwer and Rice equation:

$$K = \frac{r_c^2 \ln\left(R_e/R\right)}{2L_e} \frac{1}{t} \ln\left(\frac{H_0}{H_t}\right)$$

where
K = hydraulic conductivity
r_c = radius of the well casing
R_e/R = the ratio of radius of gravel envelope to distance away from the well over which the average value of K is being measured (this is obtained as outlined in Fetter 1994)

L_e = length of the screen or open section of the well
H_0 = drawdown at time $t = 0$
H_t = drawdown at time $t = t$
t = time from $H = H_0$

A representative description of average hydraulic conductivity near each piezometer was estimated by calculating the geometric mean of all tests performed within each piezometer (Fetter 1994).

Hydraulic head measurements were taken at each piezometer to estimate vertical hydraulic gradient (*VHG*), which was calculated as

$$VHG = \frac{\Delta h}{L}$$

where Δh was the hydraulic head inside the piezometer minus the hydraulic head of the river and L was the distance from the top of the piezometer screen to the riverbed surface. The *VHG* is a unitless index with positive values indicating upwelling and negative values indicating downwelling (Freeze and Cherry 1979, Dahm and Valett 1996).

The magnitude of intragravel flow at each site was estimated by calculating the specific discharge (v, cm/second) of hyporheic water into the Snake River, based on the Darcy relationship (Freeze and Cherry 1979).

$v = K \times VHG$

where K and *VHG* were as previously defined.

The slug test results indicated moderate to high hydraulic conductivity (*K*) values at both sites (Tables 12 and Figures 47 and 48). Mean *K* values estimated with the Hvorslev method (*K_H*) were consistently higher than those estimated with the Bouwer and Rice method (*K_BR*), which is typical for fluvial sediments. In typical hydrogeological investigations, the differences in *K* values estimated from the two methods generally differ by a factor of 2.0 or 3.0 (Palmer and Paul 1987). In this study, on average, estimates of *K_H* were greater than *K_BR* by a factor of 1.5.

Mean *K_H* values at the middle site (0.0870 cm/second) were significantly greater ($p = 0.0070$) than mean *K_H* values (0.0420 cm/second) at the upper site (Figure 49). Similarly, mean *K_BR* values at the middle site (0.0560 cm/second) were significantly greater ($p = 0.0070$) than mean *K_BR* values (0.0270 cm/second) at the upper site. As mentioned earlier, these hydraulic conductivity values were indicative of moderate to high conductivity sediments. Relative permeability is often described in terms of sediment size, and hydraulic conductivity values in this study fell within those typical of well-sorted sands and gravels (Fetter 1994). Because of variability in hydraulic conductivity estimates, standard hydrology references do not provide definitive classifications (low, medium, or high) with different sediment types (Freeze and Cherry 1979, Fetter 1994, Butler 1997). However, based on the literature, hydraulic conductivity values of 0.0116 to 0.0174 cm/second can be characterized as low to moderate, while values from 0.0174 to greater than 0.1800 cm/second are relatively high (Butler et al. 1996, Weight and Wittman 1999).

The results of the hydraulic head measurements (Δh) and vertical hydraulic gradient (*VHG*) calculations indicate that hyporheic water was predominantly upwelling into the river at both sites (Table 12 and Figures 50 and 51). Calculations of specific discharge (v) resulted in an average flux out of the riverbed of 4.0×10^{-3} cm/second at the upper site and 14.0×10^{-3} cm/second at the middle site. Estimates of mean specific discharge at the middle site were significantly greater ($p = 0.02$) than at the upper site (Figure 52). These estimates are one to two orders of magnitude greater than specific discharge estimates in fall chinook salmon spawning areas of the Hanford Reach of the Columbia River (Geist 2000).

Comparing the hydraulic conductivity values reported here with those values estimated from other similar studies provides a means of reference (Table 13). Mean *K_BR* values in the Hanford Reach were estimated at 0.00500 cm/second, with a maximum value of 0.04300 cm/second (E. Arntzen, PNNL, unpubl. data). The study area from which these values were estimated is characterized by spatially heterogeneous hydraulic conductivity, but is generally regarded as containing high conductivity sediments. Hydraulic conductivities near fall chinook salmon spawning areas in the Hanford Reach have been estimated at 0.02000 to 0.03000 cm/second (Geist 2000). Springer et al. (1999) described the hydraulic conductivity of sand bars in the Colorado River as high. Their estimates of *K* from shallow wells ranged from 0.00070 to 0.04870 cm/second, with an average of 0.01700 cm/second. Estimates of *K* from alluvial deposits (including sand, gravel, and cobble) adjacent to three headwater streams ranged from 0.00013 to 0.00410 cm/second (Morrice et al. 1997). Estimates of *K* from alluvial deposits near the Boise River indicated that sand-dominated deposits have higher *K* values than cobble-dominated deposits (Barrash et al. 1997). Average *K* estimates from the sand deposits ranged from 0.01000 to 0.10000 cm/second, while the average *K* estimate for the cobble deposit was 0.00400 cm/second.

Comparing *K* values from the Hanford Reach with those from the upper Snake River (as well as those from other locations) is useful for interpreting the magnitude of *K* values at any location. However, fundamental differences in stratigraphy, channel morphology, and alluvial deposit characteristics (such as packing or sorting) prevent direct comparisons between locations. Evaluating hydraulic conductivity within each river system would allow more salient comparisons. To accomplish this with a higher degree of confidence, estimates of sediment permeability from slug tests should be compared to estimates using other techniques in the same environment.

Extensive research has evaluated the general relationship between soil properties, grain size, and permeability (Shepherd 1989). The same factors that limit the ability to compare hydraulic conductivity (such as packing, sorting, or grain shape) for different sites also limit the ability to determine the grain size-permeability relationship. Consequently, general relationships to compare grain size to hydraulic conductivity within a location as specific as the upper and middle sites of the Snake River don't exist. To verify and or calibrate slug test results, bulk sediment samples should be tested in a laboratory using a permeameter (or other related device) to determine hydraulic conductivity. Because freeze cores are extracted with sediment structure intact, this structure could be preserved in transit to the lab. Such a calibration would allow for widespread use of the less cumbersome slug tests within a small-scale environment (such as Hells Canyon Reach) and would not attempt to account for the complications introduced by particle shape, packing, or sorting. Particle size analysis could still be conducted on samples to determine suitability for spawning.

5.1.4. Sediment Permeability Conclusions

At the two historic spawning sites we studied on the upper Snake River, sediment permeability and substrate quality appear to be suitable for fall chinook salmon spawning and egg incubation. This conclusion is based on the following findings: 1) hydraulic conductivity and specific discharge values were moderate to high, 2) the percentage of fines was relatively low, and 3) the sediment size distribution suggested relatively moderate to high incubation and emergence success. Although the surface of the bed appeared armored, the maximum size of the surface sediment was within the size range that adult fall chinook salmon are capable of moving. These results provide additional insight into the quality of substrate for salmonid habitat in the upper Snake River. But other metrics of habitat quality (for example, water quality of hyporheic and surface water, such as DO levels) should also be considered before deciding on the feasibility of reintroducing salmon above the HCC.

5.2. Hyporheic Water Quality

To describe the quality of the hyporheic environment within the historic spawning areas, we constructed artificial redds at the same two sites (upper and middle) that we used to assess sediment permeability. We also chose an additional site (lower) that had the physical characteristics of the known spawning areas, although available information could not verify it as an actual spawning area (Figure 34).

Artificial redds were constructed and monitored during two consecutive years (year 1: 1999−2000; year 2: 2000−2001) during time periods comparable to actual redd construction and incubation. The redds were constructed at locations with suitable depth, mean water-column velocity, and substrate type as described in Groves and Chandler (1999). Although the exact morphology of natural redds is difficult to mimic, Burton et al. (1990) and King and Thurow (1991) found that intragravel DO, temperatures, and fine sediments in artificially constructed redds did not significantly differ from conditions in nearby natural redds. Other work by Maret et al. (1993) concluded that it was possible to relate environmental factors to survival in artificial redds and recommended using artificial redds as monitoring tools. Soulsby et al. (2001) also used simulated redds to describe the hyporheic environment of a redd.

Hyporheic DO levels were measured in both artificial redds as well as in ambient (undisturbed) hyporheic water. The sampling design of the redd monitoring was to construct 4 redds in close proximity, referred to as a redd cluster (Figure 53). In year 1, two clusters of redds were sampled in the upper and middle sites, and one cluster was sampled in the lower site (Table 14). In year 2, two clusters were sampled in the upper and lower sites, and one cluster was sampled in the middle site (Table 15). However, some redds scoured, leaving some clusters with only 3 redds. At each redd cluster, at least one piezometer was placed in the ambient gravel to compare conditions in the artificial redds (Tables 14 and 15 and Figure 53). During construction of the artificial redds, we planted an intragravel water sampling probe, similar to that described by Hoffman (1986) and Maret et al. (1993), within the area of the redd associated with the egg pocket (Figure 54). During the second year of sampling, we buried a miniature constant-recording thermograph in at least one redd cluster at each of the three sampling locations. Water column temperature and DO were also monitored (Tables 14 and 15).

Measurements of DO began at the time of redd construction and continued monthly through June of the following year, with some exceptions (Tables 14 and 15). During each sampling period, the probes, tubes leading to the probes, and piezometers were pumped to ensure that fresh hyporheic water was obtained in the samples. DO was measured using a calibrated Yellow Springs Instrument^{TM} (YSI) probe. In both years, some water samples had the smell of hydrogen sulfide (H_2S). Such samples were noted during both years, and when possible, water samples were measured for H_2S concentrations by transporting water samples to Alchem Laboratories in Boise, Idaho. Detection levels in the laboratory for H_2S (0.005 parts per million [ppm]) are above the lethal level (0.002 ppm) for developing embryos (Piper et al. 1982). So nondetection (in the laboratory) could not assure us that samples were not lethal. A general rule was that if H_2S could be detected by smell, levels were high enough to be lethal to developing embryos (Dare et al. 2001).

5.2.1. Dissolved Oxygen

Water column DO levels followed similar patterns over both years that we monitored, reflecting saturation at water temperature (Figures 55 and 56). During both years, levels of DO in the water column were higher than those measured in the hyporheic waters. The pattern of ambient hyporheic water measured from piezometers differed between the two sample years (Figures 57 and 58). During year 1, hyporheic DO levels at all the sites followed a similar pattern, with peak DO levels occurring in January and then declining steadily through April and May, reaching

DO levels of 4 mg/l or less. However, DO levels in different locations were variable. The lower sites generally had lower hyporheic DO levels than the middle and upper sites. Hyporheic DO levels during year 2 were lower than during year 1 throughout the entire incubation period. During year 2, DO levels generally remained below 4 mg/l during the entire period. By March in year 2, hyporheic DO levels were below 2 mg/l at all piezometers, with less variation overall among the clusters than was observed in year 1.

Between the two years, the DO levels in the redds differed both in their patterns and in their relationships to the corresponding hyporheic water. During year 1, DO levels measured in redds generally followed the same pattern as the levels measured in the hyporheic water; however, the DO levels in redds remained slightly higher than in the hyporheic water (Figure 59). During year 2, DO levels in the redds followed a different pattern than in the hyporheic water. Initially, DO levels in the redds were much higher than in the hyporheic water. The levels remained high until a sharp decline began after the February sampling (Figure 60).

The most notable difference between the two sampling years was the hydrograph, which probably accounts for the differences we observed in the hyporheic and redd environments between the two years. Discharge (surface flow) was much higher during year 1 (Figure 61). Because of the higher flows, surface water may have had a greater influence in the hyporheic zone and redd environment than influx from groundwater. This explanation may account for similar patterns of DO between the redds and the piezometers. During the first few sampling periods in year 2, surface water may have had greater influence on the redd environment. The initial cleansing of fines from the gravels during redd construction increases the permeability of the gravels in redds and allows oxygen-rich surface water to have greater influence than groundwater influx on the redd environment.

As mentioned previously, at least two of the sites demonstrated upwelling hyporheic environments. However, with aging of the redds (especially during periods of lower flows, such as year 2), fine particulates that begin to infiltrate the redds and riverbed reduce the permeability from surface water (Soulsby et al. 2001). Groundwater influx may become more of an influence in the redd and hyporheic environment. Higher flows, as observed during year 1, may have prevented infiltrated fines from capping the redds. Those higher flows may have also provided the conditions necessary for predominately river water to downwell into the redd environment. Thus, DO levels in the redds during year 2 reached lower levels than during year 1.

5.2.2. Water Temperature

Surface water temperature differed substantially between the two study years (Figure 62). The low flow of year 2 was cooler than year 1. Accumulation of thermal units from November 10 in each of the years demonstrated a 20-day difference in estimated time of hatch (500 thermal units). Estimated emergence dates for the two years differed by two weeks, with emergence for year 1 occurring on April 6, and for year 2, on April 20. No difference was observed between the redd water temperature and surface water temperature during year 2, the only year of continuous hyporheic temperature collection (Figure 62).

5.2.3. Hydrogen Sulfide

During year 1, none of the piezometers had detectable limits of H_2S, either through laboratory techniques or smell (Table 16). However, one redd in the middle site had lethal levels of H_2S measured at 0.007 ppm in the March sample. Hydrogen sulfide was detected in 4 redds during the May sample. These measurements were probably taken after what would be fry emergence, so embryo survival would not have been affected.

A greater number of redds and piezometers had detectable levels of H_2S during year 2 (Table 16). Only two redds had detectable amounts before May 1. However, four of the piezometers had detectable amounts in February. Two piezometers in March and three in April had detectable amounts. The greater amount of H_2S detections is consistent with the overall lower DO levels observed during year 2.

5.3. Incubation Survival

Based on findings from the sediment permeability analysis, the historic spawning areas below Swan Falls Dam appear to be suitable for incubating fall chinook. However, analysis of the environment in artificial redds suggests that survival may be impaired by low DO levels in the redd environment toward the end of the incubation period.

Developing embryos have a variable requirement for DO (Alderdice et al. 1958, Silver et al. 1963, Shumway et al. 1964, Garside 1966, Davis 1975). DO requirements relate to intragravel water velocity and the embryo's development stage. In summary, what these authors have reported is that oxygen requirement is lowest in early stages of development (survival is not significantly affected at levels as low as 2.0 mg/l). However, as development progresses, eggs and larvae demand more oxygen. For example, for chum salmon (*O. keta*), developing eggs at early stages required 1.0 mg/l of oxygen, while those about to hatch required 7.0 mg/l (Alderdice et al. 1958).

The most critical period (requiring higher DO levels) occurs after hatching. Davis (1975) reported that the mean incipient oxygen response thresholds (indication of the onset of hypoxic stress) ranged from 9.65% saturation for early salmonid eggs to 76.30% saturation for hatching eggs and larvae. Reduced oxygen levels in the mature egg and post-hatch larvae can retard growth, reduce yolk-sac absorption, and cause developmental deformities and mortality (Davis 1975). Davis further defined three levels of DO for protection of salmonids. Level A represents more or less ideal conditions, and Level B represents a point where the average member of a species in a community starts to exhibit symptoms of oxygen stress. The lowest level, Level C, could have negative consequences "as a large portion of a given fish population or fish community may be affected by low oxygen. This deleterious effect may be severe if prolonged beyond a very few hours." For mature eggs and larvae, the DO level was set at 6.4 mg/l at 9 °C.

DO levels measured in our artificial redds suggest that oxygen levels are adequate for redd environments to support survival of pre-hatch eggs through the hatch stage. However, whether the post-hatch period, with its higher oxygen requirement, has adequate DO is questionable at best. During year 1, DO levels in some of the redd clusters during the post-hatch to preemergence period were above 6.4 mg/l. However, most DO levels were below 4.0 mg/l (Figure 59). Approaching the estimated emergence period during year 2, none of the redd clusters had DO levels above 4.0 mg/l (Figure 60).

Nonetheless, it is important to emphasize the dynamic and complex nature of the hyporheic and redd environment. The variability of the hyporheic environment results, in part, from the riverbed topography, the alluvium's permeability and depth (Geist and Dauble 1998), and (as we have observed) the magnitude of the surface flow. For example, as Soulsby et al. (2001) discuss, highly localized effects may occur. The relatively low DO levels that Soulsby et al. reported in their simulated redds could have related to high mortality. However, despite these conditions, overall survival rates in the Soulsby et al. study were estimated at 80%, with a range of individual redd survival from 0 to 100%. In year 1 of our study, the high variability among our redd clusters suggested a similar phenomenon. In year 2, we observed much less variability. During that year, DO levels in the redd environment reached much lower levels than Soulsby et al. reported.

6. ACKNOWLEDGMENTS

We thank the crew from Battelle who conducted the sediment permeability study, especially Tim Hanrahan, David Geist, and Evan Arntzen. We also extend our appreciation to Rob Warburton, Brad Alcorn, and many other field personnel for assistance in conducting artificial redd monitoring. We thank Ralph Myers and Jack Harrison for their reviews of this chapter.

7. LITERATURE CITED

Abbott, P. E., and M. H. Stute. 2001. Evaluation of Idaho Power hatchery mitigation program. In: Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-4.

Alderdice, D. F., and F. P. J. Velsen. 1978. Relation between temperature and incubation time for eggs of chinook salmon (*Oncorhynchus tshawytscha*). Journal of the Fisheries Research Board Canada 35:69–75.

Alderdice, D. F., W. P. Wickett, and J. R. Bret. 1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. Journal of the Fisheries Research Board of Canada 15(2):229–249.

Arntzen, E. V., D. R. Geist, and T. P. Hanrahan. 2001. Substrate quality of fall chinook salmon spawning habitat, Hells Canyon Reach, Snake River, Idaho. Battelle, Pacific Northwest Division. 40 p. Prepared for: Idaho Power Company, Boise, ID.

Barrash, W., Morin, R. H., and Gallegos, D. M. 1997. Lithologic, hydrologic, and petrophysical characterization of an unconsolidated cobble-and-sand aquifer: Capital Stations site, Boise, Idaho. In: Proceedings of the 32nd symposium on engineering geology and geotechnical engineering; March 26–28, 1997; Boise, ID.

Battelle and USGS (Battelle Pacific Northwest Labs and U.S. Geological Survey). 2000. Assessment of the impacts of development and operation of the Columbia River hydroelectric system on mainstem riverine processes and habitats, final report. Bonneville Power Administration, Portland, OR.

BOR (Bureau of Reclamation). 1999. Snake River flow augmentation impact analysis appendix. BOR, Pacific Northwest Region, Boise, ID.

Bouwer, H. 1989. The Bouwer and Rice slug test: an update. Ground Water 111:304–309.

Bouwer, H., and Rice, R. C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research 12:423–428.

Burton, T. A., G. W. Harvey, and M. McHenry. 1990. Monitoring the effects of nonpoint sources of sediment pollution on salmonid incubation and eggs to alevin survival. In: Proceedings of the annual conference Western Association Fish and Wildlife Agencies 70:104–113.

Butler, J. J. 1997. The design, performance, and analysis of slug tests. CRC Press, LLC, Boca Raton, FL. 252 p.

Butler, J. J., Jr., C. D. McElwee, and W. Liu. 1996. Improving the quality of parameter estimates obtained from slug tests. Ground Water 34:480–490.

Carey, C. H., editor. 1931. The journals of Theodore Talbot, 1843 and 1849–52. Metropolitan Press, Portland, OR. 59 p.

Chandler, J. A., and D. Chapman. 2001. Existing habitat conditions of tributaries formerly used by anadromous fish. In: J. A. Chandler, editor. Chapter 4. Feasibility of reintroduction of anadromous fish above or within the Hells Canyon Complex. Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-2.

Chandler, J. A., and P. E. Abbott. 2001. Pathogen assessment and suitability of stocks and for reintroduction above the Hells Canyon Complex. In: J. A. Chandler, editor. Chapter 10. Feasibility of reintroduction of anadromous fish above or within the Hells Canyon Complex. Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-2.

Chapman, D. 2001. History of the Hells Canyon Complex. In: J. A. Chandler, editor. Chapter 2. Feasibility of reintroduction of anadromous fish above or within the Hells Canyon Complex. Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-2.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117:1−21.

Chapman, D., and J. A. Chandler. 2001. Historical abundance of anadromous fish upstream of the Hells Canyon Complex. In: J. A. Chandler, editor. Chapter 6. Feasibility of reintroduction of anadromous fish above or within the Hells Canyon Complex. Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-2.

Church, M. A., D. G. McLean, and J. F. Wolcott. 1987. River bed gravels: sampling and analysis. 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. p. 43−88

Clark, G. M., 1997. Assessment of nutrients, suspended sediment and pesticides in surface water of the upper Snake River Basin, Idaho and western Wyoming, Water Years 1991−95. U.S. Geological Survey. Water Resources Investigation Report 97-4020. 45 p.

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

Connor, W. P. 2001. Juvenile life history, downstream migration rate, and survival of wild Snake River fall chinook salmon. A dissertation. University of Idaho. Moscow, ID. 100 p.

Connor, W. P., A. P. Garcia, A. H. Connor, E. O. Garton, P. A. Groves, and J. A. Chandler. Forthcoming. Estimating the carrying capacity of the Snake River for fall chinook salmon redds. Northwest Science.

Connor, W. P., T. C. Bjornn, H. L. Burge, A. P. Garcia, and D. W. Rondorf. 1997. Early life history and survival of natural subyearling fall chinook salmon in the Snake and Clearwater rivers in 1995. In: D. W. Rondorf and K. F. Tiffan, editors. Identification of the spawning, rearing, and migratory requirements of fall chinook salmon in the Columbia River basin. Project Number 91-029. 1995 annual report to: Bonneville Power Administration, Portland, OR.

Dahm, C., and H. M. Valett. 1996. Hyporheic zones. In: F. R. Hauer and G. A. Lamberti, editors. Methods in stream ecology. Academic Press, San Diego, CA. p. 107−199.

Dare, M. R., W. A. Hubert, and J. S. Meyer. 2001. Influence of stream flow on hydrogen sulfide concentrations and distributions of two trout species in a Rocky Mountains tailwater. North American Fisheries Management 21:971−975.

Dauble, D. D., and D. G. Watson. 1997. Status of fall chinook salmon populations in the mid-Columbia River, 1948–1992. North American Journal of Fisheries Management 17:283−300.

Dauble, D. D., T. L. Page, and R. W. Hanf, Jr. 1989. Spatial distribution of juvenile salmonids in the Hanford Reach, Columbia River. Fishery Bulletin 87:775−790.

Davis, J. C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: A review. Journal of the Fisheries Research Board Canada 32:2295−2332.

Eaton, C. A. 1997. Evaluation of substrate quality for incubation of fall chinook salmon embryos in the Snake River. M. Sc. thesis. University of Idaho, Moscow. 27 p.

Evermann, B. 1896. A preliminary report upon salmon investigations in Idaho in 1894. Bulletin of the U.S. Fish Commission. Volume XV for 1895. U.S. Government Printing Office, Washington, D.C. p. 253−284.

Fetter, C. W. 1994. Applied hydrogeology, 3rd edition. Merrill Publishing Company, Upper Saddle River, NJ. 458 p.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ. 604 p.

Fulton, L. A. 1968. Spawning areas and abundance of chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River Basin—past and present. U.S. Fish and Wildlife Service Special Scientific Report No. 571.

Garside, E. T. 1966. Effects of oxygen in relation to temperature on the development of embryos of brook trout and rainbow trout. Journal of the Fisheries Research Board of Canada 23(8):1121−1134.

Geist, D. R. 2000. Hyporheic discharge of river water into fall chinook salmon (*Oncorhynchus tschawytscha*) spawning areas in the Hanford Reach, Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 57:1647−1656.

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

Geist, D. R., M. C. Joy, D. R. Lee, and T. Gonser. 1998. A method for installing piezometers in large cobble-bed rivers. Ground Water Monitoring and Remediation 18:78−82.

Gilbert, C., and B. Evermann. 1894. A report on investigations in the Columbia River basin, with descriptions of four new species of fishes. In: Report of the Commissioner of Fish and Fisheries on investigations in the Columbia River basin in regard to the salmon fisheries. U.S. Senate Miscellaneous Documents, No. 200, Serial No. 3174. Washington, D.C. p 19−57.

Gregg, J. R. 1950. Pioneer days in Malheur County. Loren L. Morrison Printing and Publishing, Los Angeles, CA.

Groves, P. A. 2001. The timing and distribution of fall chinook salmon spawning downstream of the Hells Canyon Complex. In: P. A. 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 Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-3.

Groves, P. A., and J. A. Chandler. 1999. Spawning habitat used by fall chinook salmon in the Snake River. North American Journal of Fisheries Management 19:912−922.

Groves, P. A., and J. A. Chandler. 2001a. The quality and availability of fall chinook salmon spawning and incubation habitat downstream of the Hells Canyon Complex. In: P. A. 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 Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-3.

Groves, P. A., and J. A. Chandler. 2001b. Physical habitat and water quality criteria for chinook salmon associated with the Hells Canyon Complex. In: P. A. 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 Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-3.

Guy, H. P. 1969. Laboratory theory and methods for sediment analysis. In: Techniques of water-resources investigations of the United States Geological Survey, Book 5, Chapter C1, U.S. Geological Survey, editor. U.S. Government Printing Office, Washington, D.C.

Haas, J. 1965. Fishery problems associated with Brownlee, Oxbow, and Hells Canyon dams on the middle Snake River. Fish Commission of Oregon, Portland OR. Investigational Report No. 4. 95 p.

Hanrahan, T. P., D. R. Geist, E. V. Arntzen, and G. A. McMichael. 2001. Sediment permeability of historic fall chinook salmon spawning habitat: upper Snake River, Idaho. Battelle, Pacific Northwest Division—3072. 27 p. Prepared for: Idaho Power Company, Boise, ID.

Harrison, J., S. Wells, R. Myers, S. Parkinson, M. Kasch, C. Berger. 2000. Status report on southwest Snake River water quality and model development. Draft. Idaho Power, Boise, ID. 54 p.

Hey, R. D., and C. R. Thorne. 1983. Accuracy of surface samples from gravel bed material. Journal of Hydraulic Engineering 109: 842−851.

Hoelscher, B. 2001a. Monthly water quality report. Upper Salmon Falls Project. FERC compliance report #2777, May−August 2001. 1 p.

Hoelscher, B. 2001b. Monthly water quality report. Shoshone Falls Project FERC compliance report #2778, May−August 2001. 1 p.

Hoelscher, B., and R. Myers. 2001. Tributary pollutant sources in the Hells Canyon Complex. In: Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.2.2-1.

Hoffman, R. J. 1986. A horizontal intergravel pipe for sampling water quality in salmonid spawning gravel. North American Journal of Fisheries Management 6:445−448.

Huelsbeck, D. R. 1981. Fish remains from 10GG1 and 10TF352. Appendix III. In: M. G. Plew, editor. Archaeological test excavations at four prehistoric sites in the western Snake River canyon near Bliss, Idaho. A final report on Phase 2, archaeological investigations in the proposed A. J. Wiley dam project: the prehistoric resources. p. 270−285. Prepared for: Idaho Power Company, Boise, ID.

Hvorslev, M. J. 1951. Time lag and soil permeability in ground water observations. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Bulletin 36.

IDEQ (Idaho Division of Environmental Quality, now the Idaho Department of Environmental Quality). 1991. Cedar Draw, Twin Falls County, Idaho, 1982−1988. IDEQ, Twin Falls Regional Office, Twin Falls. Water Quality Status Report No. 100.

IDEQ. 1997. The middle Snake River watershed management plan: phase 1 TMDL—total phosphorus. IDEQ. 122 p.

IDEQ. 2001. Snake River–Hells Canyon total maximum daily load (TMDL). Draft. IDEQ, Boise Regional Office, Boise. 239 p.

IDFG (Idaho Department of Fish and Game). 1955. The size and timing of runs of adult fall chinook salmon in the Columbia and Snake rivers and their tributaries above the confluence of the Snake River. Annual report. IDFG, Boise, ID. Contract DA 35-026-eng-20608. Prepared for: U.S. Army Corps of Engineers.

IFG (Idaho Fish and Game). 1922. Ninth biennial report of the Fish and Game Warden of the State of Idaho 1920−1921. IFG, Boise, ID.

Irving, R. B, and P. E. Cuplin. 1956. The effects of hydroelectric developments on the fishery resources of the Snake River. Idaho Department of Fish and Game. Boise. 168 p.

ISHS (Idaho State Historical Society). 1987. The fishing falls. Idaho State Historical Society Reference Series Number 192.

King, J., and R. Thurow. 1991. Sediment monitoring techniques validation, year 2. Intermountain Research Station. Contract report to: Idaho Department of Health and Welfare, Division of Environmental Quality, Water Quality Bureau, Boise.

Kondolf, G. M. 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society 129:262−281.

Lavier, D. C. 1976. Distribution of salmon and steelhead in the Columbia River Basin, 1850−1976: summary of data from maps. Prepared for: Columbia Fisheries Project, Pacific Northwest Regional Commission, Washington Department of Game, Olympia, WA.

Lepla, K. B., and J. A. Chandler. 1995. A survey of white sturgeon in the Bliss Reach of the middle Snake River, Idaho. In: Technical appendices for new license application: C.J Strike Hydroelectric Project. Volume 1. Idaho Power, Boise, ID. Technical Report E.3.1-E.

Lotspeich, F. B., and B. H. Reid. 1980. Tri-tube freeze-core procedure for sampling stream gravels. The Progressive Fish-Culturist 42:96−99.

Mains, E. M., and J. M. Smith. 1964. The distribution, size, time and current preferences of seaward migrant chinook salmon in the Columbia and Snake rivers. Fisheries Research Papers. Washington Department of Fisheries 2:5–43.

Maret, T. R., T. A. Burton, G. W. Harvey, and W. H. Clark. 1993. Field testing of new monitoring protocols to assess brown trout spawning habitats in an Idaho stream. North American Journal of Fisheries Management 13:567−580.

McCullough, D. A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater lifes stages of salmonids, with special reference to chinook salmon. Prepared for: U.S. Environmental Protection Agency, Region 10, Seattle, WA. 279 p.

Milligan, J. H., R. A. Lyman, C. M. Falter, E. E Krumpe, and J. E. Carlson. 1983. Classification of Idaho’s freshwater lakes. Idaho Water and Energy Resources Research Institute, University of Idaho, Moscow. 67 p.

Morrice, J. A, H. M. Valett, C. N. Dahm, and M. E. Campana.1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. Hydrological Processes 11:253−267.

Murphy, K. A., and M. J. Crutchfield. No date. Archeological test excavations at the Crutchfield site: Hagerman Valley, Idaho. University of Idaho Anthropological Reports. 86 p.

Myers, L. D. 1998. Anthropological literature and oral histories interviews pertaining to the C.J. Strike Study Area, middle Snake River, Idaho, for C.J. Strike Hydroelectric Relicensing Project (FERC No. 2055). In: Technical appendices for new license application: C.J. Strike Hydroelectric Project. Volume 4. Idaho Power, Boise, ID. Technical Report E.4.1-C.

Myers, R., and S. A. Pierce. 1997. Limnological survey of the C.J. Strike Hydroelectric Project. In: Technical appendices for new license application: C.J. Strike Hydroelectric Project. Volume 1. Idaho Power, Boise. Technical Report E.2.2-A. 71 p.

Myers, R., and S. A. Pierce. 1999. Descriptive limnology of the Hells Canyon Complex. In: Project Progress Report, November 1999. Draft. Idaho Power, Boise, ID. 26 p.

Myers, R., J. Harrison, S. K. Parkinson, B. Hoelscher, J. Naymik, and S. E. Parkinson. 2002. Pollutant transport and processing in the Hells Canyon Complex Hydroelectric Project. In: Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.2.2-2.

Olson, P. A., and R. F. Foster. 1955. Temperature tolerance of eggs and young of Columbia River chinook salmon. Transactions of the American Fisheries Society 85:203−207.

Palmer, C. D., and D. G. Paul. 1987. Problems in the interpretation of slug test data from fine-grained glacial tills. In: Proceedings of the focus conference on northwestern ground water issues; Portland, OR. p. 99−123.

Parkhurst, Z. E. 1950. Survey of the Columbia River and tributaries. Part 6, Area V. Snake River system from the mouth through the Grande Ronde River. U.S. Fish and Wildlife Service, Washington, D.C. Special scientific report—Fisheries Number 39.

Peterson, N. P., and T. P. Quinn. 1996. Persistence of egg pocket architecture in redds of chum salmon, *Oncorhynchus keta*. Environmental Biology of Fishes 46:243−253.

Piper, R. G., I. B. McElwain, L. E. Orme, J. P. McCraren, L. G. Fowler, and J. R. Leonard. 1982. Fish hatchery management. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. 515 p.

Plew, M. G. 1981. Archaeological test excavations at four prehistoric sites in the western Snake River canyon near Bliss, Idaho. Idaho Archaeological Consultants, Boise, ID.

Plew, M. G. 1983. Implications of nutritional potential of anadromous fish resources of the western Snake River Plain. Journal of California and Great Basin Anthropology 5 (1&2):58-65.

Poole, G., and 11 coauthors. 2001. Technical synthesis—scientific issues relating to temperature criteria for salmon, trout, and char native to the Pacific Northwest; a summary report submitted to the Policy Workgroup of the EPA Region 10—Water Quality Criteria Guidance Project. Environmental Protection Agency, Region 10, Seattle, WA. 21 p.

Pratt, K. L., M. Kozel, J. Mauser, L. Mauser, and R. Scarpella. 2001. Annotated bibliographies on the chronology of decline of anadromous fish in the Snake River basin above Hells Canyon Dam. In: J. A. Chandler, editor. Special Appendices A−N. Feasibility of reintroduction of anadromous fish above or within the Hells Canyon Complex. Technical appendices for Hells Canyon Complex Hydroelectric Project. Idaho Power, Boise, ID. Technical Report E.3.1-2.

Raleigh, R. F., W. J. Miller, and P. C. Nelson. 1986. Habitat suitability index models and instream flow suitability curves: chinook salmon. U.S. Fish and Wildlife Service Biological Report 82 (10.122).

Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile fall chinook salmon and steelhead from the Snake River, 1966−1975. Transactions of the American Fisheries Society 108:505−529.

Reiser, D. W., and White, R. G. 1988. Effects of two sediment size-classes on survival of steelhead and chinook salmon eggs. North American Journal of Fisheries Management 8:432−437.

Richards, M. 1959. Snake River fall chinook spawning ground survey, 1959. Idaho Department of Fish and Game, Boise. 15 p.

Richards, M. 1973. Average run size by time period. Exhibits MRR 1−3 in testimony before Federal Power Commission for Idaho Department of Fish and Game on issue of substitution of spring chinook for fall chinook in hatchery compensation programs in Project 1971.

Rood, K., and M. Church. 1994. Modified freeze-core technique for sampling the permanently wetted streambed. North American Journal of Fisheries Management 14:852−861.

Rupert, M. G. 1996. Major sources of nitrogen input and loss in the upper Snake River basin, Idaho and western Wyoming, 1990. U.S. Geological Survey. Water-Resources Investigations Report 96-4008. 15 p.

Shepherd, R. G. 1989. Correlations of permeability and grain size. Ground Water 27:633−638.

Shirazi, M. A., W. K. Seim, and D. H. Lewis. 1981. Characterization of spawning gravel and stream system evaluation. In: Proceedings—salmon-spawning gravel: a renewable resource in the Pacific Northwest? State of Washington Water Research Center, Pullman, WA.

Shumway, D. L., C. E. Warren, and P. Doudoroff. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. Transactions of the American Fisheries Society 93:342−356.

Silver, S. J., C. E. Warren, and P. Doudoroff. 1963. Dissolved oxygen requirements of developing steelhead trout and chinook salmon embryos at different water velocities. Transactions of the American Fisheries Society 92:327−343.

Soulsby, C., I. A. Malcolm, and A. F. Youngson. 2001. Hydrochemistry of the hyporheic zone in salmon spawning gravels: a preliminary assessment in a degraded agricultural stream. Regulated Rivers: Research & Management 17:651−665.

Sowden, T. K., and G. Power. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. Transactions of the American Fisheries Society 114:804−812.

Springer, A. E., W. D. Petroutson, and B. A. Semmens. 1999. Spatial and temporal variability of hydraulic conductivity in active reattachment bars of the Colorado River, Grand Canyon. Ground Water 37:338−344.

Stanford, L. M. 1942. Preliminary studies in the biology of the Snake River. Ph. D. dissertation. University of Washington, Seattle. 120 p.

Steward, J. H. 1970. Basin-Plateau aboriginal socio-political groups. Smithsonian Institution, Washington, D.C., and U.S. Government Printing Office, Washington, D.C. Bureau of American Ethnology Bulletin 120.

Swinney H. J., and M. W. Wells. 1962. Fort Boise: from imperial outpost to historic site. Idaho Yesterdays 6(1):15-6 and 33−39.

Tiffan, K. F., D. W. Rondorf, and P. G. Wagner. 2000. Physiological development and migratory behavior of subyearling fall chinook salmon in the Columbia River. North American Journal of Fisheries Management 20:28−40.

USFS (U.S. Forest Service). 2001. Caribou revised forest plan. Draft environmental impact statement. U.S. Department of Agriculture, USFS, Caribou−Targhee National Forest, Idaho Falls, ID.

Van Dusen, H. 1903. Annual report, Department of Fisheries, State of Oregon. Oregon State Printer, Salem.

Van Hyning, J. M. 1968. Factors affecting the abundance of fall chinook salmon in the Columbia River. Ph. D. dissertation. Oregon State University, Corvallis. 424 p.

Venditti, D. W., D. W. Rondorf, and J. M. Kraut. 2000. Migratory behavior and forebay delay of radio-tagged juvenile fall chinook salmon in a lower Snake River impoundment. North American Journal of Fisheries Management 20:41−52.

Weight, W. D., and G. P. Wittman. 1999. Oscillatory slug-test data sets: a comparison of two methods. Ground Water 37:827−835.

Wilkison, R. A. 2000. Response to FERC additional information request #32, salmonid spawning conditions. FERC projects numbers: 2777, 2061, 1975, and 2778. Idaho Power, Boise.

Wohl, E. E., D. J. Anthony, S. W. Madsen, and D. M. Thompson. 1996. A comparison of surface sampling methods for coarse fluvial sediments. Water Resources Research 32:3219−3226.

Wolman, M. G. 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union. 35:951−956.

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

This page left blank intentionally.

Table 1. Comparison of summary statistics for temperature and emergence dates in six reaches of the Snake River and the one reach of the Salmon River.

	River Reach						
	Above C.J. Strike	**Marsing**	**Weiser**	**Pre-HCC at Oxbow**	**Upper Hells Canyon**	**Lower Hells Canyon**	**Salmon River**
River Mile of Thermal Recorder	522	458	345	270	192–247	147–170	1
Years Represented in Data Set	93–94 94–95 95–96 96–97	90–91 97–98 99–00 00–01	90–91 97–98 99–00 00–01	54–55 55–56	91–92 92–93 93–94 94–95 96–97 97–98 98–99	91–92 93–94 94–95 98–99 99–00	91–92 92–93 93–94 94–95 98–99 99–00
Summary Temperature Statistics							
Entire Adult Migration Period (Aug. 15–Nov. 1), ºC							
Mean	15.8	17.1	17.2	17.1	19.1	17.9	15.4
Minimum	11.2	10.7	10.4	9.2	13.7	10.9	7.4
Maximum	20.9	22.6	23.8	23.9	21.8	21.7	21.5
Pre-peak Migration (Aug. 15–Sept. 15), ºC							
Mean	18.3	20.8	21.3	22.3	21.4	20.8	19.5
Peak Adult Migration Period (Sep 15–Oct. 7), ºC							
Mean	15.6	17.1	17.1	15.3	19.5	18.3	15.3
Minimum	14.2	14.7	14.3	13.5	18.0	16.7	12.8
Maximum	16.9	19.4	20.1	18.3	20.6	19.5	17.0
Mean Temperature at Initiation of Spawning[a] (Oct. 10), ºC	14.1	14.6	14.2	13.5	17.5	16.1	11.9
Average Date of Temperature Reaching 14.5 ºC (month/day)	10/4	10/11	10/7	9/27	10/26	10/18	10/2
Mean Weekly Temperatures, ºC							
Week 1 (Oct. 10–16)	13.8	13.6	13.4	12.8	17.1	15.6	11.6
Week 2 (Oct. 17–23)	12.7	11.8	11.1	13.0	15.6	13.7	9.9
Week 3 (Oct. 24–30)	11.6	11.2	10.8	9.9	14.4	11.9	8.3
Week 4 (Oct. 31–Nov. 6)	10.5	10.1	9.4	8.3	13.0	10.2	6.4
Week 5 (Nov. 7–13)	10.1	9.2	8.4	7.9	11.8	9.3	5.5
Week 6 (Nov. 14–20)	9.8	8.3	7.4	4.8	10.7	8.6	5.3
Week 7 (Nov. 21–27)	9.2	7.6	6.9	5.8	9.5	7.3	3.8

Table 1. (Cont.)

		River Reach						
		Above C.J. Strike	**Marsing**	**Weiser**	**Pre-HCC at Oxbow**	**Upper Hells Canyon**	**Lower Hells Canyon**	**Salmon River**
Mean Julian Dates of Emergence								
	First	39	72	90	124	55	82	130
	Median	74	100	111	143	109	116	155
	Last	103	122	125	155	138	139	166
Mean Monthly Temperatures								
	September	16.7	18.8	18.9	18.9	20.5	19	17.2
	October	13.3	13.1	12.7	12.3	16.4	14.6	10.9
	November	9.8	8.6	7.8	6.5	10.9	8.6	4.9
	December	7.7	4.7	3.7	2.2	6.8	5.1	1.8
	January	7.5	4.3	3.3	1.5	4.0	3.4	1.2
	February	8.1	5.9	5.5	1.7	3.6	3.8	2.7
	March	10.0	8.6	8.4	5.7	6.3	6.6	6.4
	April	12.3	12.0	12.2	10.1	10.0	10.0	9.3
	May	15.8	15.4	15.5	14.5	13.8	12.5	10.8
	June	17.7	19.0	19.0	19.2	16.8	15.7	13.9

Table 2. Estimated julian dates of fall chinook emergence for different years from six reaches of the Snake River and one reach in the Salmon River.

		Julian Date		
Location (River Mile)	**Incubation Years**	**Minimum**	**Median**	**Maximum**
Above C.J. Strike (RM 522)	93–94	34	69	96
	94–95	35	61	83
	95–96	28	73	111
	96–97	58	92	121
Marsing Reach (RM 458)	90–91	85	110	125
	97–98	71	96	126
	99–00	57	90	113
	00–01	74	103	122
Weiser Reach (RM 345)	90–91	98	119	127
	97–98	84	106	125
	99–00	80	101	120
	00–01	97	116	128
Pre-HCC at Oxbow (RM 270)	54–55	126	143	159
	55–56	122	142	151
Upper Hells Canyon Reach (RM 192–247)	91–92	49	99	130
	92–93	35	120	150
	93–94	78	120	146
	94–95	55	110	142
	96–97	57	107	132
	97–98	53	102	134
	98–99	58	103	135
Lower Hells Canyon Reach (RM 147–170)	91–92	68	106	129
	93–94	95	123	143
	94–95	91	122	144
	98–99	82	120	145
	99–00	75	107	133
Salmon River (RM 1)	91–92	120	133	144
	92–93	132	155	167
	93–94	139	156	160
	94–95	145	198	202
	98–99	129	148	167
	99–00	113	137	154

Table 3. Summary of mainstem Snake River temperatures, dissolved oxygen levels, conductivity, pH, and turbidity metrics collected April through September 1995 (from Table 4-1 in Harrison et al. [2000]).

Sampling Locations	Temperature (ºC)	Dissolved Oxygen (mg/l)	Conductivity (uS)	pH (SU)	Turbidity (ntu)
Snake River near Murphy (RM 449.3)					
Median	16.6	9.3	0.45	8.4	11.3
Minimum	11.8	8.4	0.40	8.1	8.8
Maximum	22.9	10.9	0.52	8.8	21.7
Number of measurements	7	7	7	7	8
Snake River near Marsing (RM 425.0)					
Median	17.5	9.9	0.45	8.5	18.5
Minimum	11.8	8.3	0.40	8.2	8.4
Maximum	22.6	11.9	0.55	8.7	31.9
Number of measurements	9	9	9	9	8
Snake River near Homedale (RM 417.0)					
Median	18.2	10.3	0.46	8.5	13.7
Minimum	10.5	7.7	0.00	8.0	9.2
Maximum	22.4	12.5	1.29	8.8	44.3
Number of measurements	14	14	14	14	10
Snake River near Adrian (RM 403.0)					
Median	19.9	10.6	0.46	8.6	15.3
Minimum	11.7	8.8	0.39	8.2	9.9
Maximum	23.7	13.6	0.53	8.9	72.4
Number of measurements	11	11	11	11	9
Snake River near Nyssa gauge (RM 385.0)					
Median	15.2	10.5	0.42	8.5	23.4
Minimum	7.9	8.4	0.02	7.1	7.3
Maximum	23.0	12.7	0.53	8.9	74.2
Number of measurements	9	9	9	9	7
Snake River near Weiser gauge (RM 340.0)					
Median	19.1	11.4	0.46	8.7	26.9
Minimum	9.6	7.8	0.25	8.3	17.6
Maximum	24.8	14.1	0.53	9.0	38.9
Number of measurements	11	11	11	11	6

Table 4. Summary of mainstem Snake River nitrogen, phosphorus, total suspended sediments (TSS), and chlorophyll *a* metrics collected April through September 1995 (from Table 4-2 in Harrison et al. [2000]).

	Nitrogen				**Phosphorus**			
Sampling Locations	**Ammonia (mg/l)**	**Nitrate (mg/l)**	**TKN (mg/l)**	**Total (mg/l)**	**SRP (mg/)**	**Total (mg/l)**	**TSS (mg/l)**	**Chlorophyll *a* (ug/l)**
Snake River near Murphy (RM 449.3)								
Median	0.03	0.97	0.54	1.50	0.03	0.10	17	15.6
Minimum	0.03	0.30	0.38	0.87	0.01	0.07	10	3.7
Maximum	0.05	1.17	0.86	1.91	0.06	0.13	41	102.5
Number of measurements	11	11	11	11	11	11	10	8
Snake River near Marsing (RM 425.0)								
Median	0.03	0.87	0.61	1.68	0.02	0.10	27	20.4
Minimum	0.03	0.23	0.37	0.79	0.01	0.08	12	0.9
Maximum	0.07	3.44	1.20	4.00	0.05	0.14	50	108.6
Number of measurements	11	11	11	11	11	11	10	11
Snake River near Homedale (RM 417.0)								
Median	0.03	0.90	0.68	1.55	0.02	0.12	27	17.2
Minimum	0.03	0.31	0.05	0.97	0.01	0.08	16	6.2
Maximum	0.22	9.61	0.80	9.66	0.08	0.23	104	115.3
Number of measurements	12	12	12	12	12	12	9	9
Snake River near Adrian (RM 403.0)								
Median	0.03	0.79	0.68	1.60	0.01	0.11	35	29.5
Minimum	0.03	0.24	0.35	0.89	0.01	0.09	15	0.2
Maximum	0.05	1.21	1.04	1.85	0.04	0.23	130	118.4
Number of measurements	10	10	10	10	10	10	9	12
Snake River near Nyssa gauge (RM 385.0)								
Median	0.03	0.86	0.80	1.58	0.02	0.15	42	75.3
Minimum	0.03	0.31	0.47	0.78	0.01	0.12	1	11.1
Maximum	0.15	1.24	1.13	2.06	0.06	0.26	150	107.3
Number of measurements	11	11	11	11	11	11	11	7
Snake River near Weiser gauge (RM 340.0)								
Median	0.03	0.48	0.89	1.30	0.03	0.17	64	53.8
Minimum	0.03	0.20	0.42	0.89	0.01	0.13	28	15.2
Maximum	0.20	1.16	1.16	2.02	0.05	0.89	685	92.5
Number of measurements	12	12	12	12	12	12	7	10

Table 5. Relative tributary flow contribution to the lower Snake River Basin segment (from Table 2-1 in Harrison et al. [2000]).

Tributary	Average Annual Flow (cfs)	Percentage of SWSR Flow (%)	Watershed Area (mi^2)	Percentage of SWSR Watershed Area (%)
Snake River above C.J. Strike Dam	8,900	59	40,800	63
Owyhee River	420	3	11,160	17
Boise River	1,600	11	3,970	6
Malheur River	130	1	3,880	6
Payette River	3,000	20	3,240	5
Weiser River	1,100	7	1,460	2

Table 6. Summary of days for years 1992 to 1998 that dissolved oxygen in the Brownlee Dam tailrace fell below the 3.5 and 6.0 mg/l criteria (from Myers and Pierce 1999).

	Brownlee Discharge				
Year	When Instantaneous DO < 3.5 mg/l		When Instantaneous DO < 6.0 mg/l		When Average Daily DO < 6.0 mg/l
	Date Range	Number of Days	Date Range	Number of Days	Number of Days
1992	6/3–10/28	147	5/19–12/20	215	150
1993	8/25–10/30	66	4/5–12/04	243	77
1994	7/16–10/26	102	5/25–12/07	196	127
1995	8/5–10/10	66	6/23–11/21	151	78
1996	7/27–11/15	111	6/24–11/19	148	45
1997	9/2–10/28	56	5/5–10/30	178	47
1998	8/2–10/26	85	7/22–10/27	97	51
Summary	6/3–11/15	91	4/5–12/20	175	82

Table 7. Summary of days for years 1992 to 1998 that dissolved oxygen in the Hells Canyon Dam tailrace fell below the 3.5 and 6.0 mg/l criteria (from Myers and Pierce 1999).

	Hells Canyon Discharge				
Year	**When Instantaneous DO < 3.5 mg/l**		**When Instantaneous DO < 6.0 mg/l**		**When Average Daily DO < 6.0 mg/l**
	Range of Dates	Number of Days	Range of Dates	Number of Days	Number of Days
1992	8/4–8/31	27	7/3–10/12	102	96
1993	9/11–10/25	44	7/30–11/12	86	78
1994	8/8–8/23	56	6/8–10/24	94	89
1995	9/4–9/17	13	7/24–10/31	95	89
1996	9/22–10/9	17	8/15–11/19	77	68
1997	Never	0	8/10–11/6	61	46
1998	9/3–10/7	34	8/5–10/28	86	86
Summary	8/4–10/25	27	6/8–11/19	86	79

Table 8. Grain size distributions at the upper and middle sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores. The values d_{16}, d_{25}, d_{50}, d_{75}, and d_{84} represent the grain size in mm at which 16%, 25%, 50%, 75%, and 84%, respectively, of the sampled grains were finer.

	Bed		**Surface**	
	Middle site	**Upper site**	**Middle site**	**Upper site**
d_{16}	2.5	3.5	30.0	10.0
d_{25}	6.0	9.0	35.0	14.5
d_{50}	26.0	35.0	46.0	28.0
d_{75}	48.0	58.5	59.0	58.5
d_{84}	56.0	69.0	65.0	67.0

Table 9. Percentage of fines (< 1 mm) in the bed for individual freeze-core samples.

Site	Sample	Sediment < 1.0 mm (%)
Middle	A	11.3
	5	11.3
	15	9.7
	6	9.2
	14	9.1
	7	8.8
	2	8.7
Upper	A	9.9
	C	9.6
	1	9.0
	13	8.3
	9	7.3
	D	7.0
	E	7.0

Table 10. Geometric mean diameter (d_g) in mm and geometric sorting coefficient (s_g) at the middle and upper sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores.

	Bed		Surface	
	Middle site	**Upper site**	**Middle site**	**Upper site**
d_g	11.8	15.5	44.2	25.9
s_g	4.7	4.4	1.5	2.6

Table 11. Geometric means of hydraulic conductivity estimates at the middle and upper sites.

Site	Piezometer	Hvorslev K (cm s^{-1})	Bouwer and Rice K (cm s^{-1})
Upper	12	0.076	0.050
	9	0.069	0.045
	2	0.058	0.037
	3	0.053	0.034
	C	0.050	0.032
	A	0.040	0.026
	1	0.037	0.024
	E	0.030	0.019
	D	0.024	0.016
	B	0.015	0.010
	13	0.005	0.003
Middle	15	0.218	0.141
	A	0.106	0.069
	1	0.102	0.066
	5	0.091	0.059
	8	0.082	0.053
	3	0.072	0.046
	6	0.066	0.043
	14	0.054	0.035
	2	0.042	0.027
	7	0.039	0.025

Table 12. Hydraulic head (∆*h*), vertical hydraulic gradient (*VHG*), and specific discharge (*v*) at the middle and upper sites.

Site	Piezometer	∆*h* (cm)	*VHG*	*v* (cm s^{-1})
Upper	9	3.00	0.22	0.0100
	12	3.00	0.20	0.0100
	A	3.00	0.22	0.0058
	3	1.90	0.14	0.0048
	1	2.40	0.18	0.0042
	D	4.00	0.24	0.0039
	2	1.20	0.09	0.0033
	C	0.50	0.04	0.0012
	13	1.50	0.10	0.0003
	B	–0.60	–0.04	–0.0004
Middle	15	3.50	0.27	0.0379
	A	4.80	0.37	0.0254
	5	4.00	0.31	0.0180
	1	3.50	0.27	0.0178
	6	4.20	0.32	0.0138
	7	4.30	0.32	0.0081
	3	2.00	0.15	0.0071
	8	1.50	0.12	0.0061
	14	1.40	0.10	0.0036
	2	0.80	0.06	0.0016

Table 13. Other hydraulic conductivity results from riparian environments.

Reference	Location	Sediment type	Hydraulic Conductivity Range (cm/s)
Fetter 1994	General	Well sorted gravel	0.01 to 1.00
Butler et al. 1996, Weight and Wittman 1999	General	Low to moderate conductivity gravels	0.0116 to 0.0174
Butler et al. 1996, Weight and Wittman 1999	General	High conductivity gravels	0.0174 to > 0.1800
Arntzen, unpubl. data	Hanford Reach, Columbia River	Riverbed sediments including silt, sand, gravel, and cobble	0.00004 to 0.03000
Geist 2000	Hanford Reach, Columbia River	Riverbed sediments including silt, sand, gravel, and cobble	0.02 to 0.03
Springer et al. 1999	Colorado River	Sand bars	0.0007 to 0.0487
Morrice et al. 1997	Headwater streams	Sand, gravel, and cobble	0.00013 to 0.00410
Barrash et al. 1997	Boise River	Alluvial sands	0.01 to 0.10
Barrash et al. 1997	Boise River	Alluvial cobble	0.004 (average)
This study	Upper Snake River	Riverbed sediments including sand, gravel, and cobble	0.01 to 0.22

Table 14. Year 1 (1999–2000) data collection events. UPS = upstream study site, DNS = downstream study site, WC = water column, Piezo = peizometer.

Site and Cluster	Type	Sampling Date							Total
		11/29/99	1/5/00	2/9/00	3/9/00	4/10/00	5/17/00	6/8/00	
Lower UPS	Piezo	2	2	2	2	2	2	2	14
Middle DNS	Piezo	2	2	2	2	2	2	2	14
Middle UPS	Piezo	2	2	2	2	2	2	2	14
Upper DNS	Piezo	2	2	2	2	2	2	2	14
Upper UPS	Piezo	2	2	2	2	2	2	2	14
Lower UPS	Redd	4	4	4	4	4	4		24
Middle DNS	Redd	4	4	4	2	2	2	1	19
Middle UPS	Redd	4	4	4	4	4	4		24
Upper DNS	Redd	4	4	4	4	4	4		24
Upper UPS	Redd	4	4	4	4	4	4		24
Lower UPS	WC	6	2	2	2	1	2		15
Middle DNS	WC	6	2	2	1	1			12
Middle UPS	WC	6	2	2	2	1	2		15
Upper DNS	WC	6		2	2	1			11
Upper UPS	WC	6	1	2	2	1	3		15

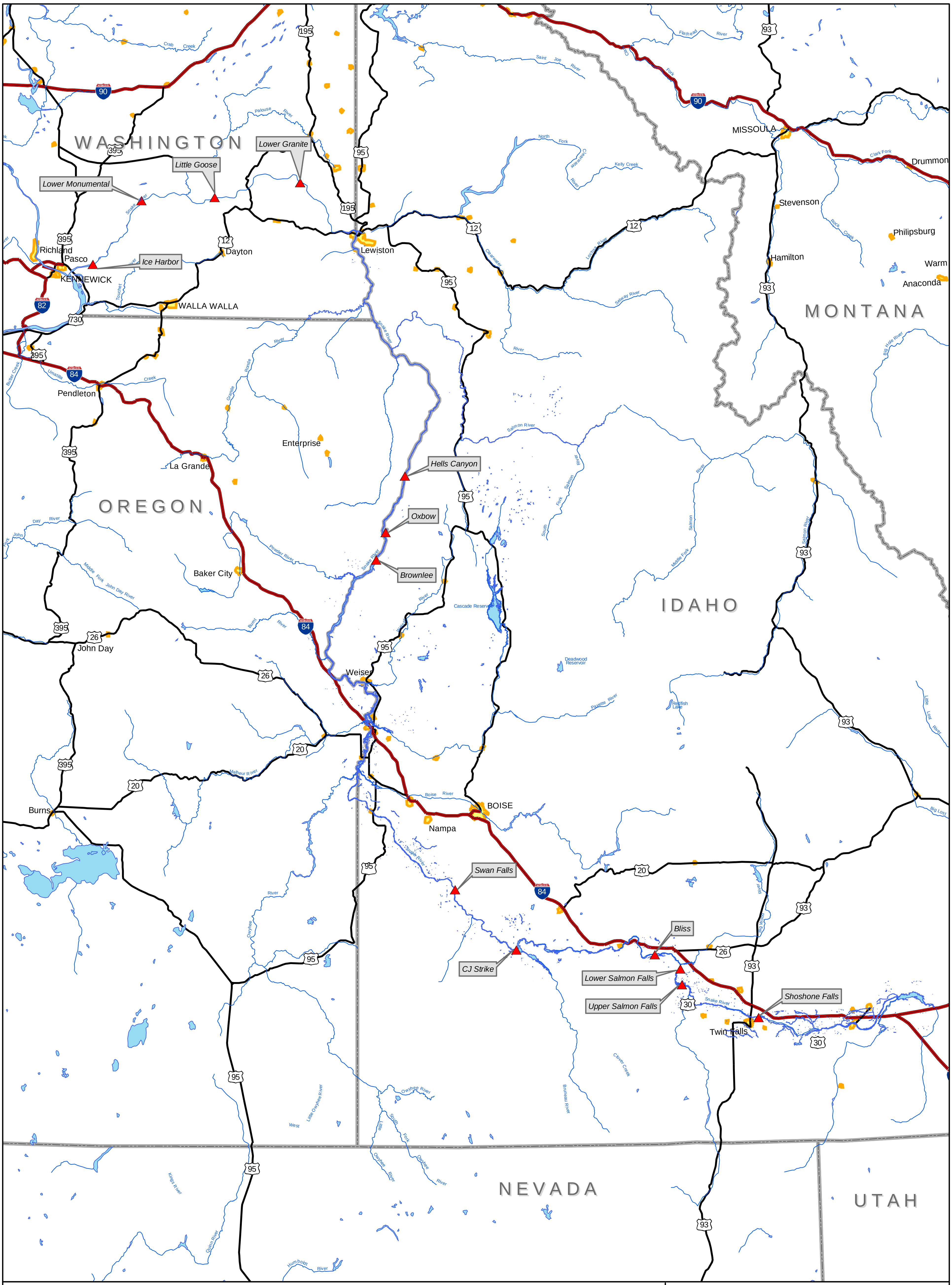
Table 15. Year 2 (2000–2001) data collection events.

Site and Cluster	Type	Sampling Date									Total
		11/9	12/14	12/28	1/31	2/27	3/20	4/25	5/10	6/5	
Lower UPS	Piezo	1	1		1	1	1	1		1	7
Lower DNS	Piezo	2	2		2	2	2	2		2	14
Middle UPS	Piezo	3	3		3	3	3	3		3	21
Upper DNS	Piezo	2		2	2	2	2		2	2	14
Upper UPS	Piezo	2		2	2	2	2		2	2	14
Lower UPS	Redd	3	3		3	3	3	3		3	21
Lower DNS	Redd	4	4		4	4	4	4		4	28
Middle UPS	Redd	4	4		4	4	4	4		4	28
Upper DNS	Redd	4		4	4	4	4		4	4	28
Upper UPS	Redd	4		4	4	4	4		4	4	28
Lower UPS	WC	2	2		2	2	2	2		2	14
Lower DNS	WC	2	2		2	2	2	2		2	14
Middle UPS	WC	2	2		2	2	2	2		2	14
Upper DNS	WC	2		2	2	2	2		2	2	14
Upper UPS	WC	2		2	2	2	2		2	2	14

Table 16. Number of events from year 1 (1999–20000) and year 2 (2000–2001) where H_2S was detected in a redd or piezometer sample from artificial redd locations between Swan Falls Dam and Marsing.

		Redd Cluster location		Piezometer locations	
Sites	**Month/Year**	**Upper (north)**	**Lower (south)**	**Upper (north)**	**Lower (south)**
Upper	2/00				
	3/00				
	4/00				
	5/00		1		
	6/00				
Middle	2/00				
	3/00		1		
	4/00				
	5/00				
	6/00				
Lower	2/00				
	3/00				
	4/00				
	5/00	3			
	6/00				
Upper	2/01			1	
	3/01				
	4/01				
	5/01	1	2	1	
	6/01	1	1		
Middle	2/01				
	3/01				
	4/01	1		1	
	5/01				
	6/01		1	1	
Lower	2/01				3
	3/01	1			2
	4/01			1	1
	5/01				
	6/01			3	2

Theme: i:\relic\hellscan\aquatic\e312c5f01.mxd



Vicinity Map

Features Legend

- Primary Route
- Secondary Route
- Streams
- State Boundary
- Urban Areas
- Lakes
- ▲ Snake River Dams

IDAHO POWER
An IDACORP Company

Tech. Report E.3.1-2_c5 Figure 1

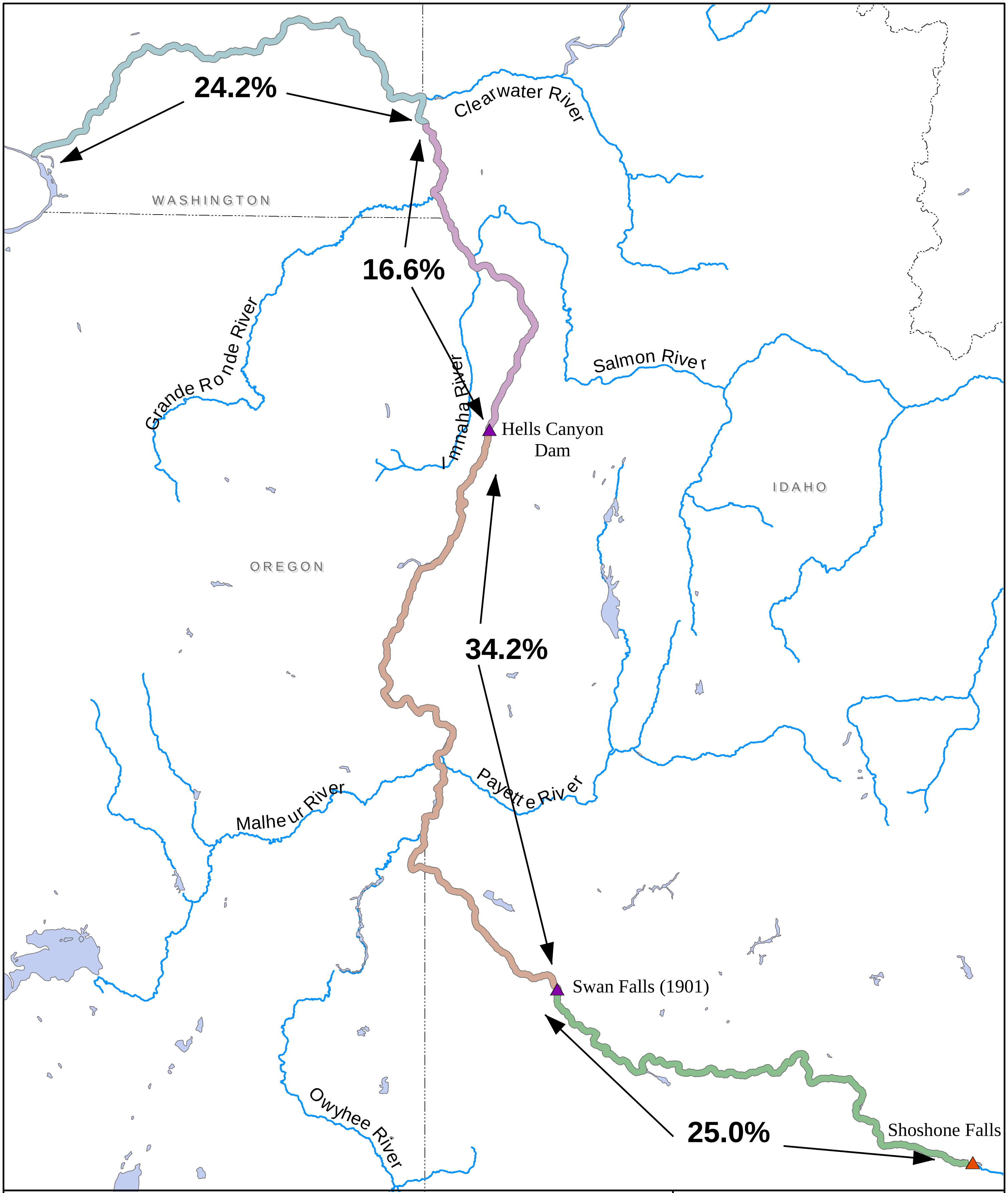
HELLS CANYON HYDROELECTRIC COMPLEX

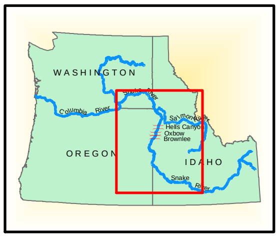
Vicinity Map

0 10 20 40 60 Miles

Scale = 1:1999106

This page left blank intentionally.





● Habitat Lost by Lower Snake Dams

● Present Day Available Habitat

● Habitat Eliminated by HCC

● Habitat Eliminated 1901

N

IDAHO POWER
An IDACORP Company

Hells Canyon Hydroelectric Project - FERC No. 1971

Tech. Report E.3.1-2_c5 Figure 2

Present and Historic Habitat Distribution

30 15 0 30 Miles

This page left blank intentionally.

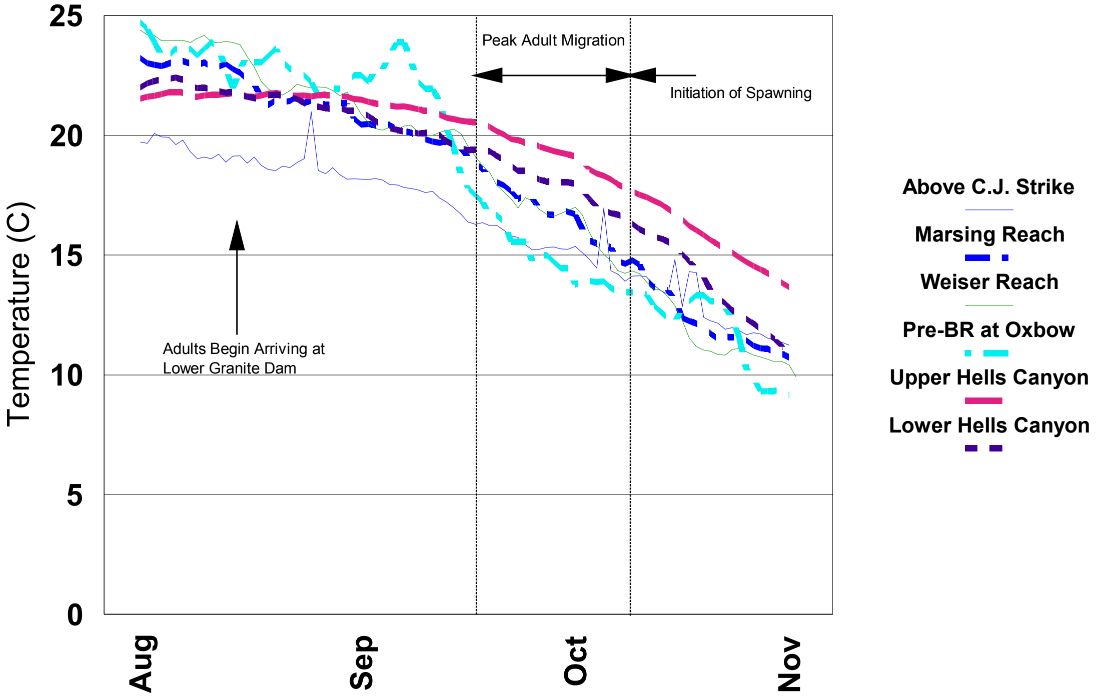


Figure 3. Mean daily water temperatures in six reaches of the Snake River from August 1 to November 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set.

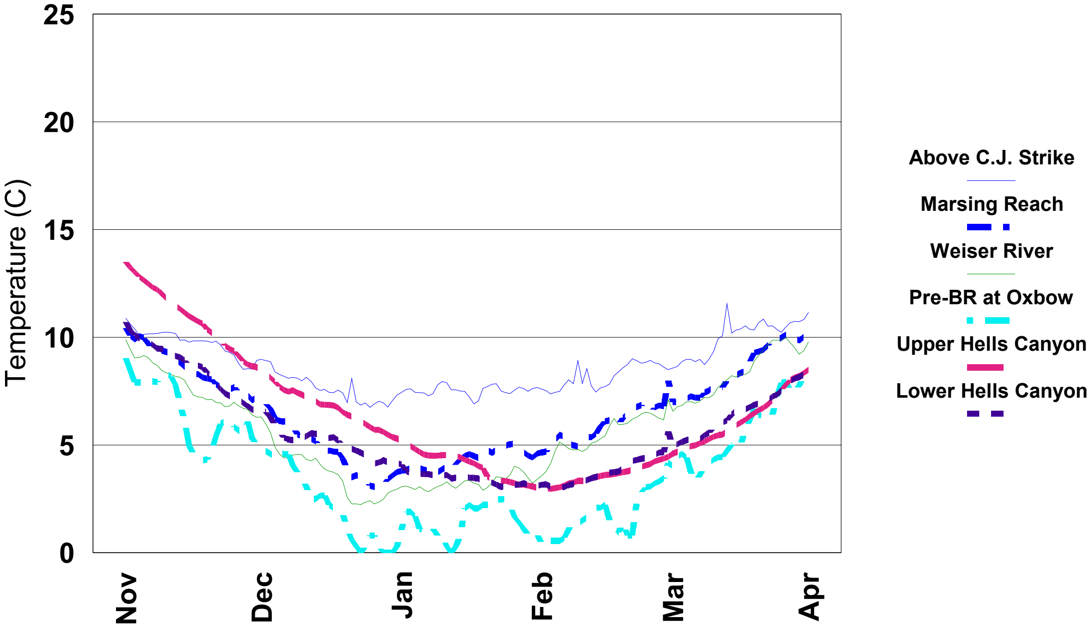


Figure 4. Mean daily water temperatures in six reaches of the Snake River from November 1 to April 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set.

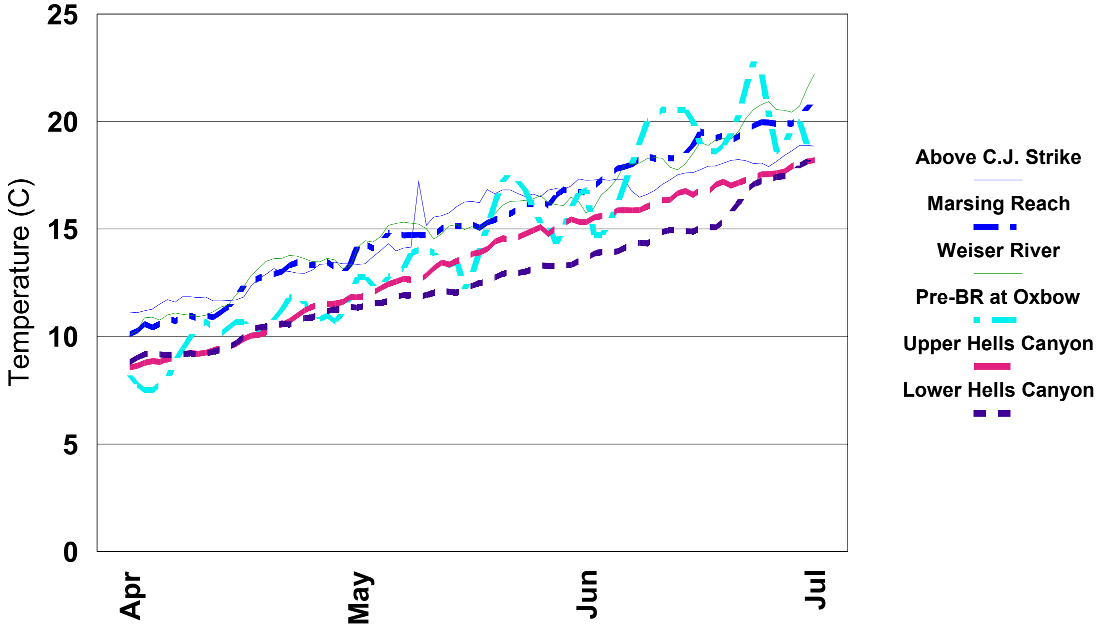


Figure 5. Mean daily water temperatures in six reaches of the Snake River from April 1 to July 1 (BR = Brownlee Reservoir). See text for years representing each temperature data set.

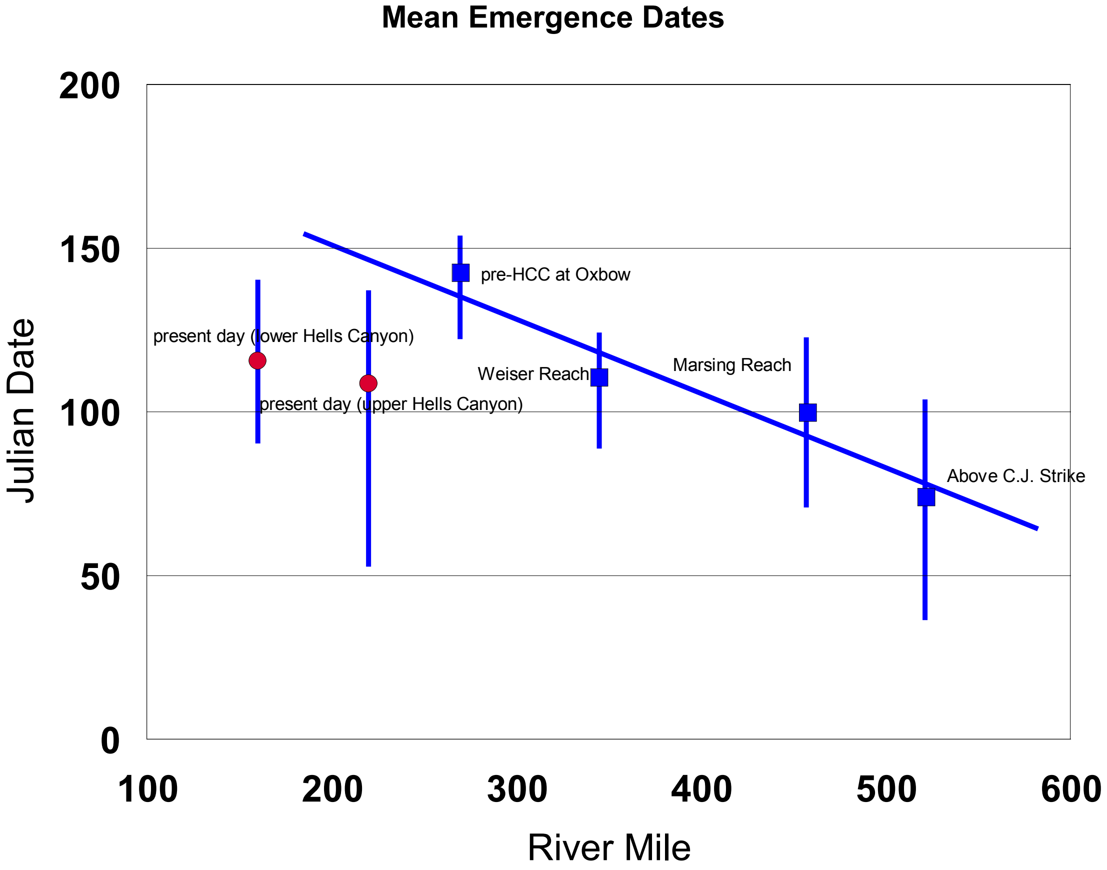


Figure 6. Estimated mean emergence dates of juvenile fall chinook salmon representing the correlation between river mile and emergence day during the pre-Hells Canyon Complex era (blue squares and trend line) and the post-Hells Canyon Complex era (red circles). Vertical bars represent the range of emergence estimated for individual year for each of the data sets.

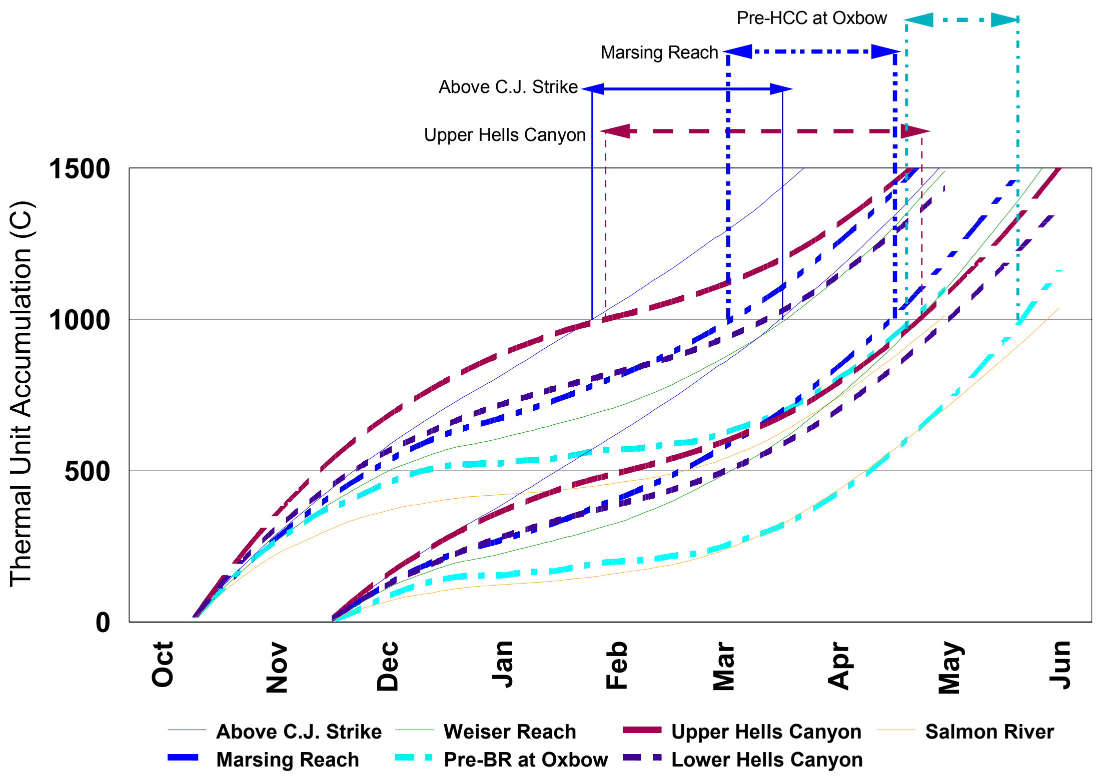
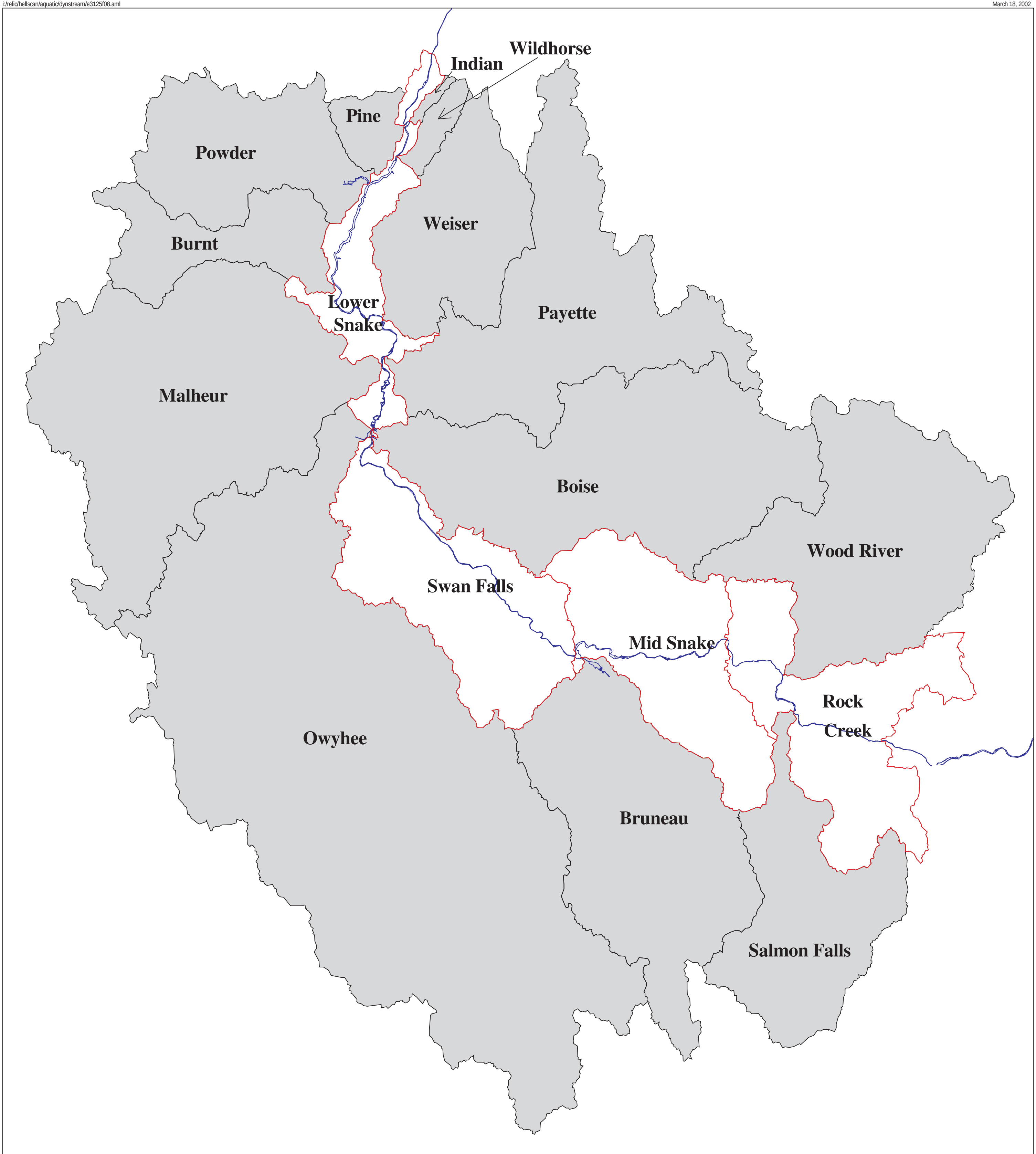


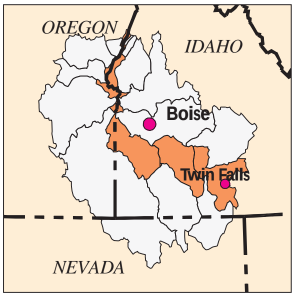
Figure 7. Mean thermal unit accumulation of six reaches on the Snake River and one reach on the Salmon River from October 10 and November 15. Arrows above the graph indicate the range of dates of emergence for four of the six reaches of the Snake River depicting the overlap in emergence of the reaches.

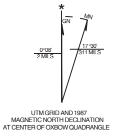
This page left blank intentionally.

i:/relic/hellscan/aquatic/dynstream/e3125f08.aml

March 18, 2002





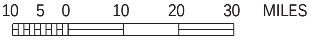


UTM GRID AND 1987
MAGNETIC NORTH DECLINATION
AT CENTER OF OXBOW QUADRANGLE

Tech. Report E.3.1 –2_c5 Figure 8

HELLS CANYON HYDROELECTRIC COMPLEX

Mainstem Snake River Basins of
the Hells Canyon Study Area

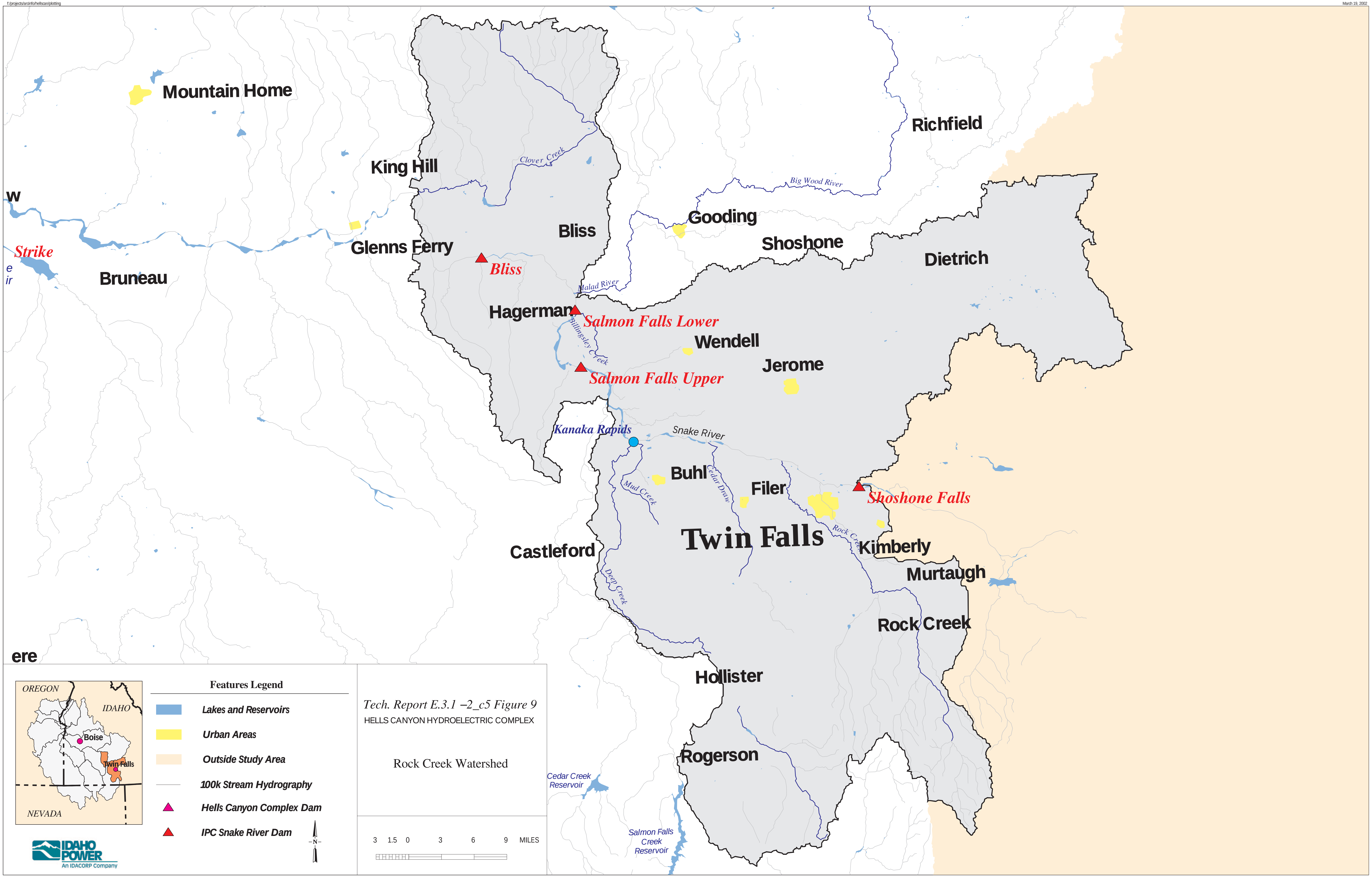


IDAHO POWER
An IDACORP Company

This page left blank intentionally.

f:/projects/arcinfo/hellscan/plotting

March 19, 2002



Tech. Report E.3.1 –2_c5 Figure 9

HELLS CANYON HYDROELECTRIC COMPLEX

Rock Creek Watershed

This page left blank intentionally.

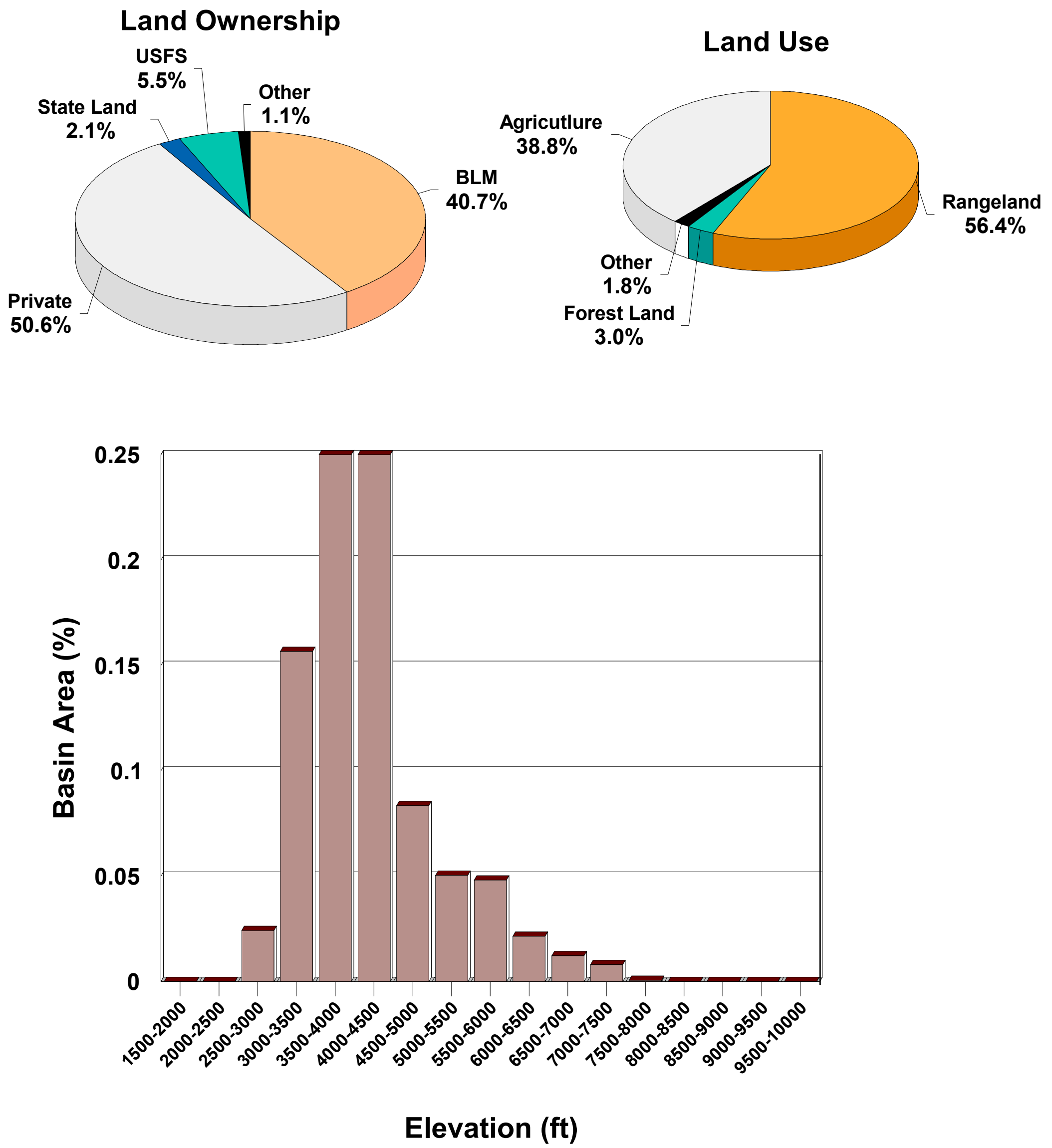


Figure 10. Land uses, land ownership, and elevation ranges as a percentage of basin area for the Rock Creek section of the Snake River, Idaho.

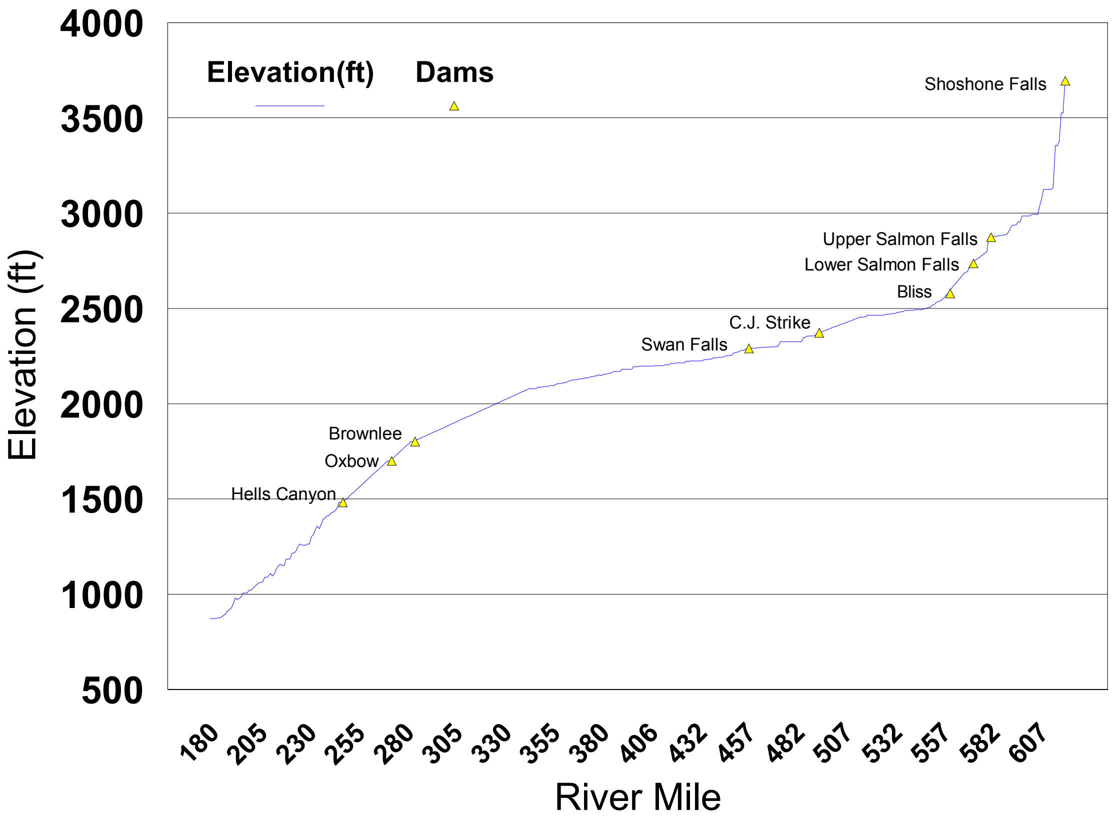


Figure 11. Elevation profile of the Snake River depicting the river gradient from Shoshone Falls to approximately the confluence of the Salmon River. Yellow triangles represent locations of mainstem dams.

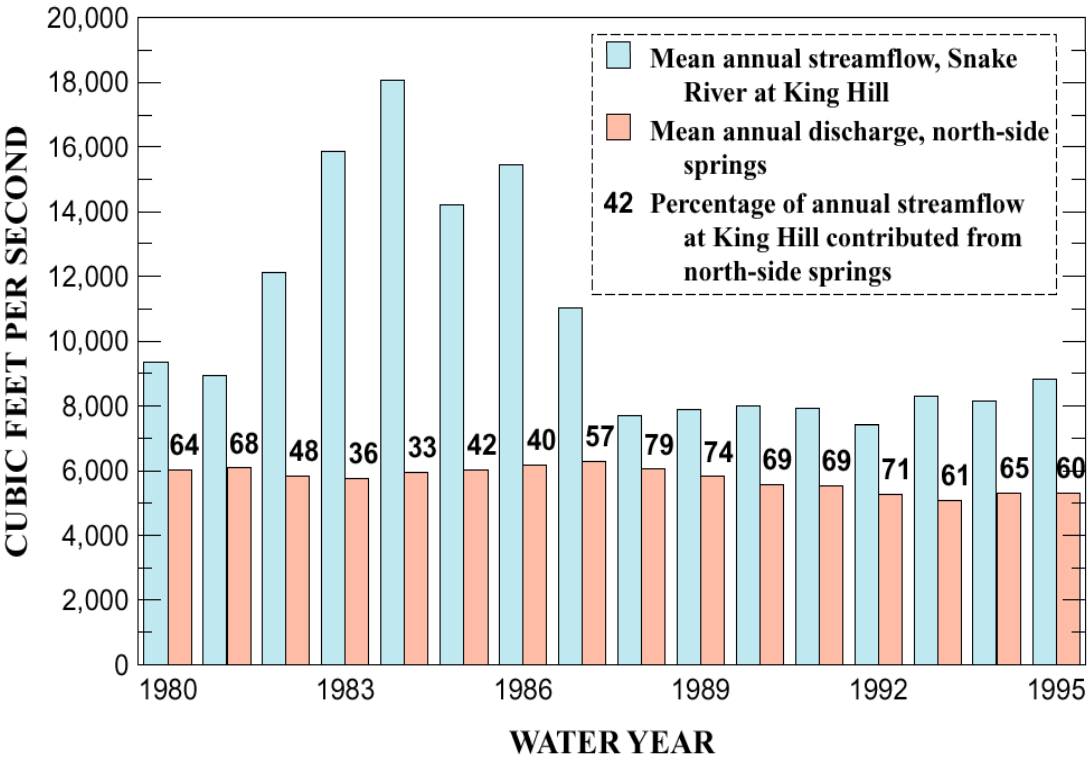


Figure 12. Annual contribution of water to the Snake River from springs along the north bank of the Snake River between Milner Dam and King Hill (from Clark et al. 1998). Numbers above bars represent percentages of annual streamflow.

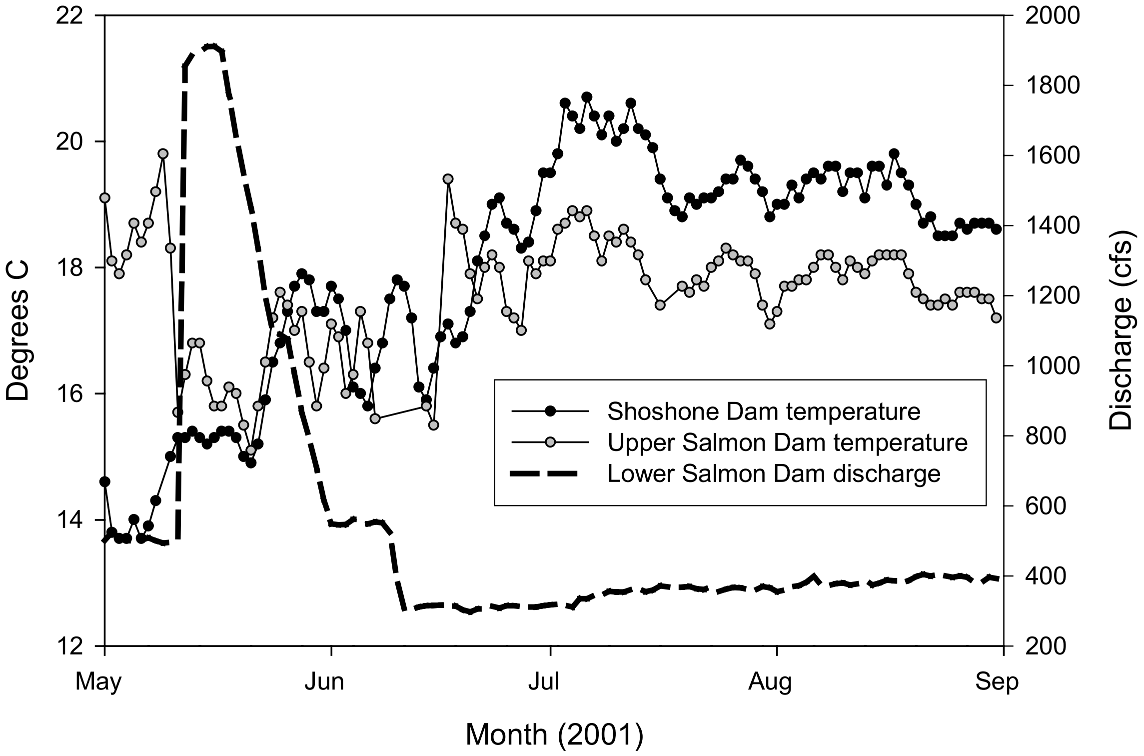


Figure 13. Temperature influence of spring flows on the Snake River between Shoshone Falls and Upper Salmon Falls Dam relative to discharge (measured at Lower Salmon Falls Dam) in 2001.

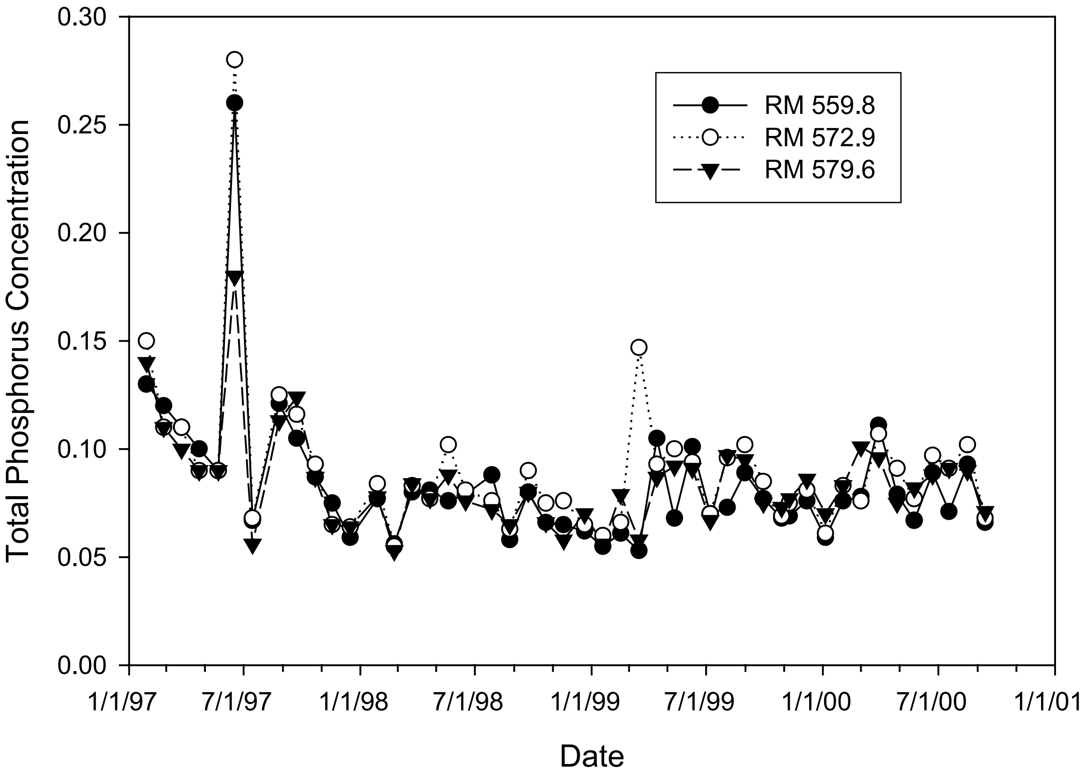
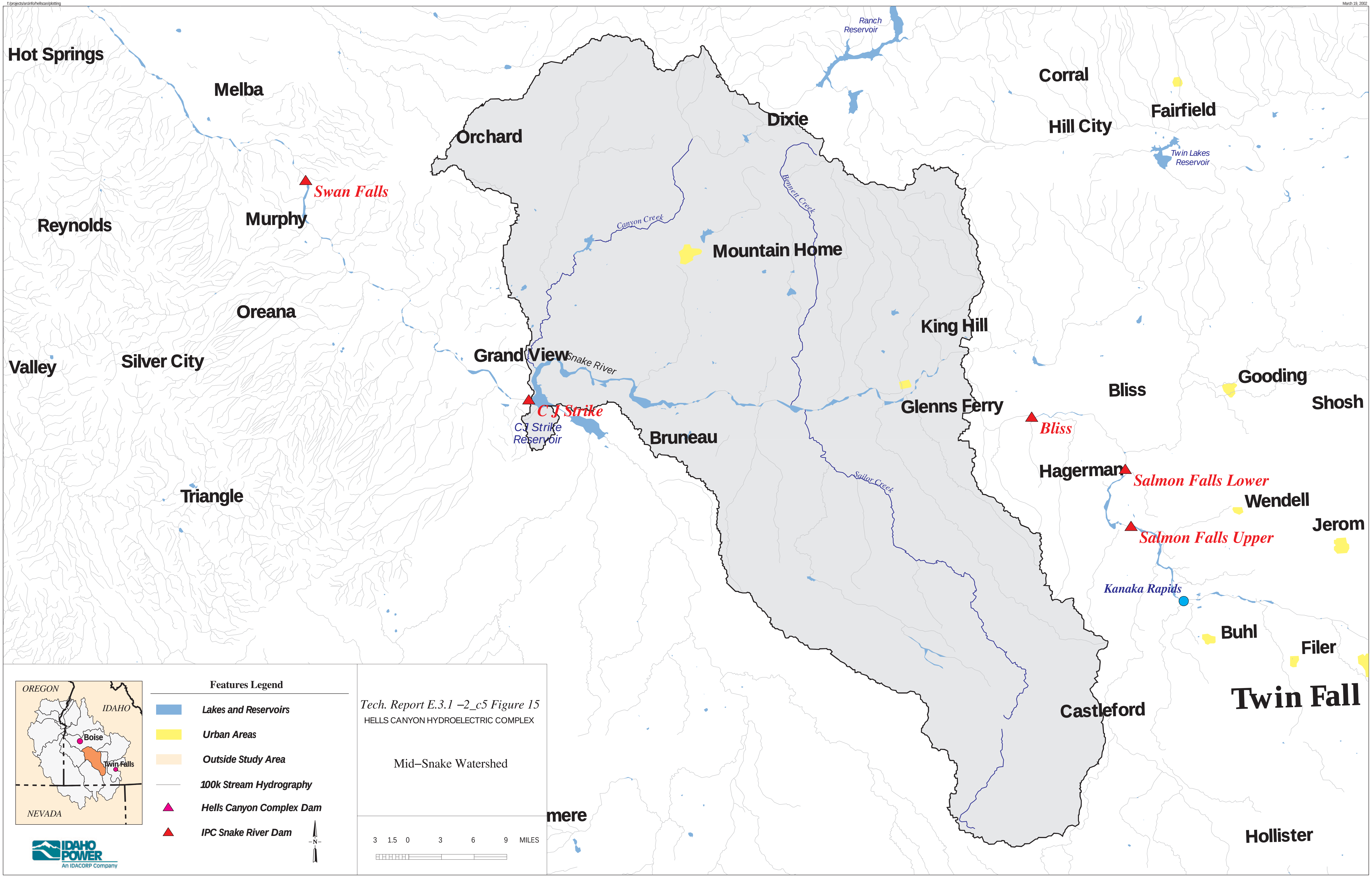


Figure 14. Total phosphorus concentrations (mg/l) within the impounded segment collected at Bliss (RM 559.8), Lower Salmon Falls (RM 572.9), and Upper Salmon Falls (RM 579.6) tailraces.

This page left blank intentionally.

f:/projects/arcinfo/hellscan/plotting

March 19, 2002



Tech. Report E.3.1 –2_c5 Figure 15

HELLS CANYON HYDROELECTRIC COMPLEX

Mid–Snake Watershed

This page left blank intentionally.

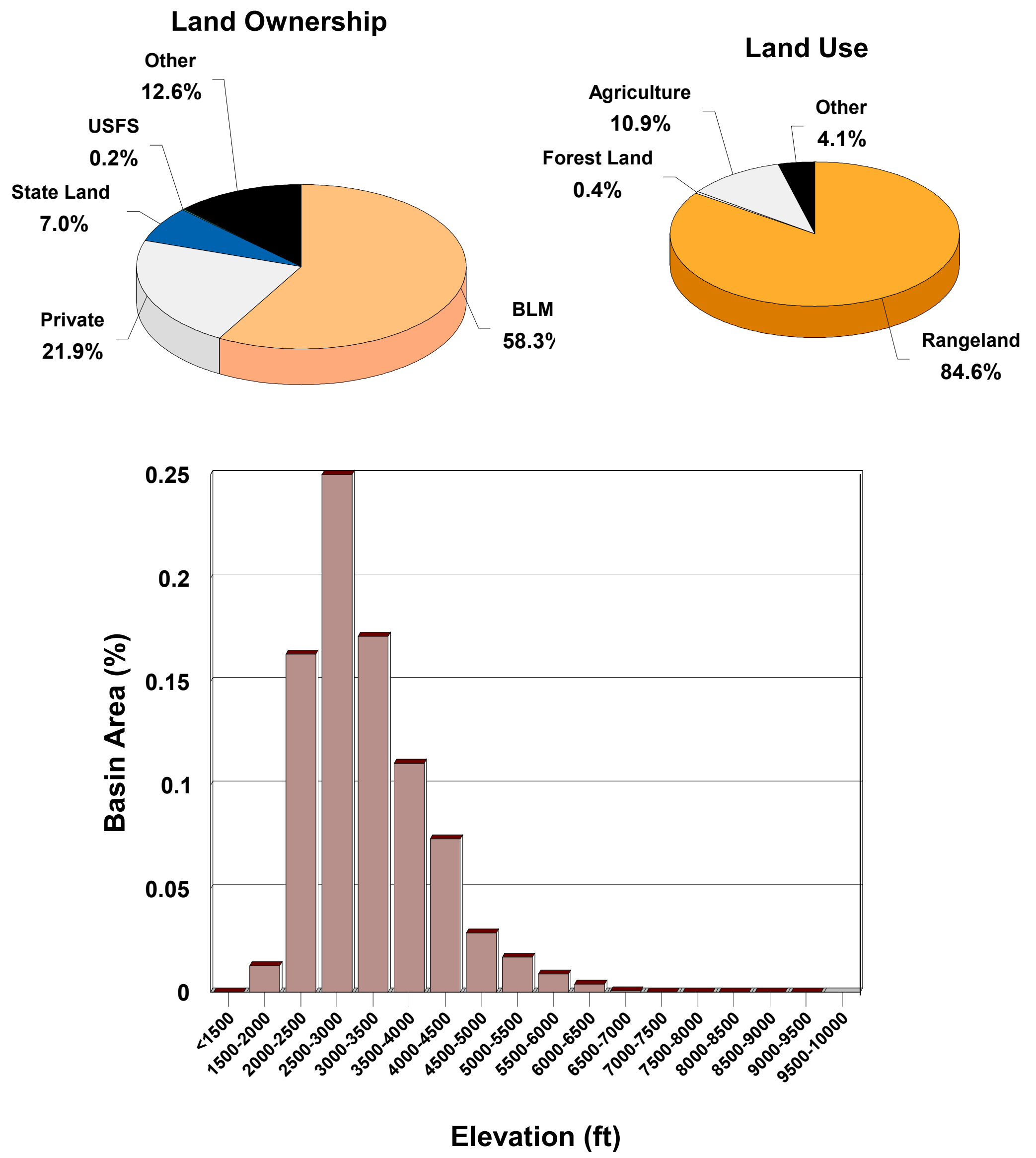
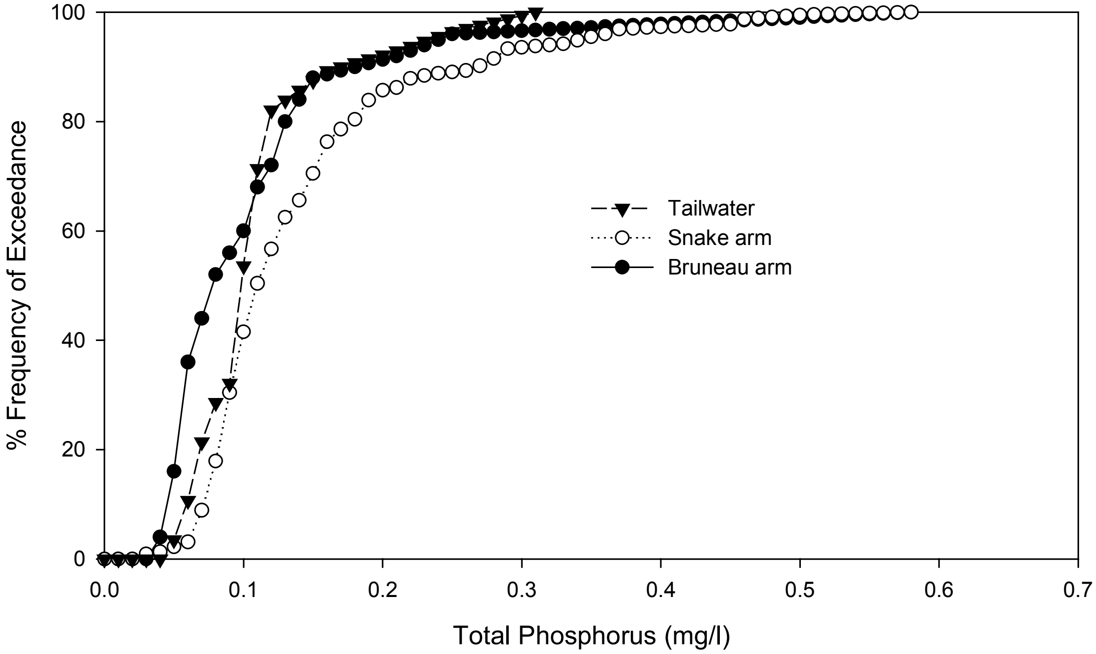


Figure 16. Land uses, land ownership, and elevation ranges as a percentage of basin area for the middle section of the Snake River, Idaho.



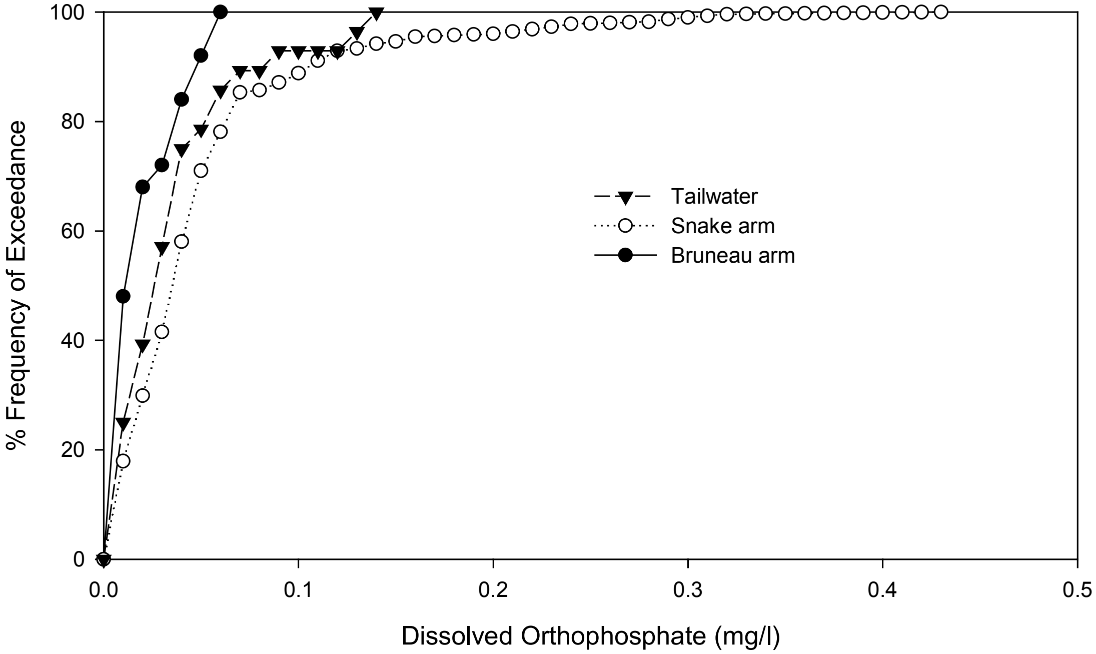


Figure 17. Percentage of exceedance curves for total phosphorus and dissolved orthophosphate in the tailwaters of the C.J. Strike Project, the Snake River arm, and the Bruneau Reservoir arm (from Figure 6 in Myers and Pierce [1997]).

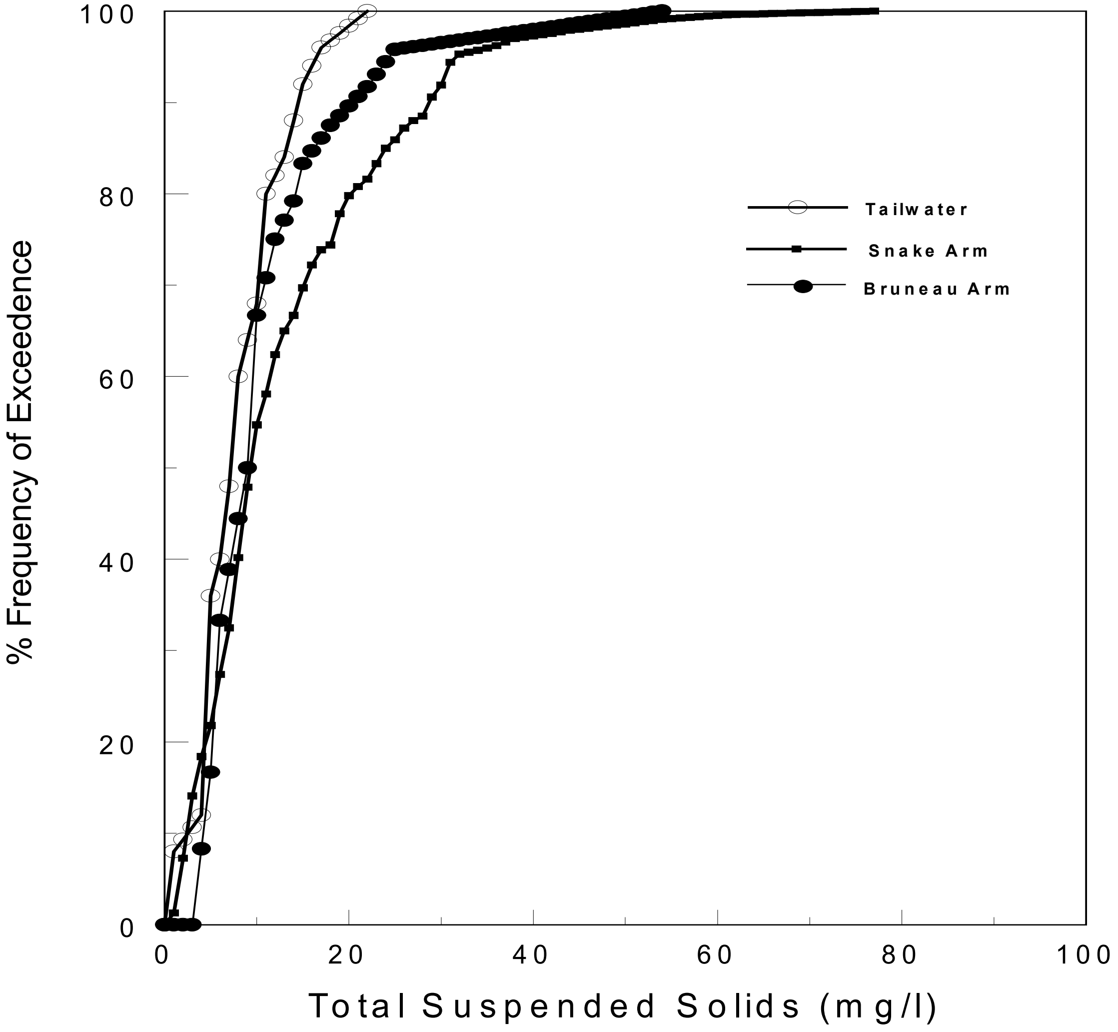


Figure 18. Percentage of exceedance curves for levels of total suspended solids in the tailwaters of the C.J. Strike Project, the Bruneau arm, and the Snake River arm (from Figure 5 in Myers and Pierce [1997]).

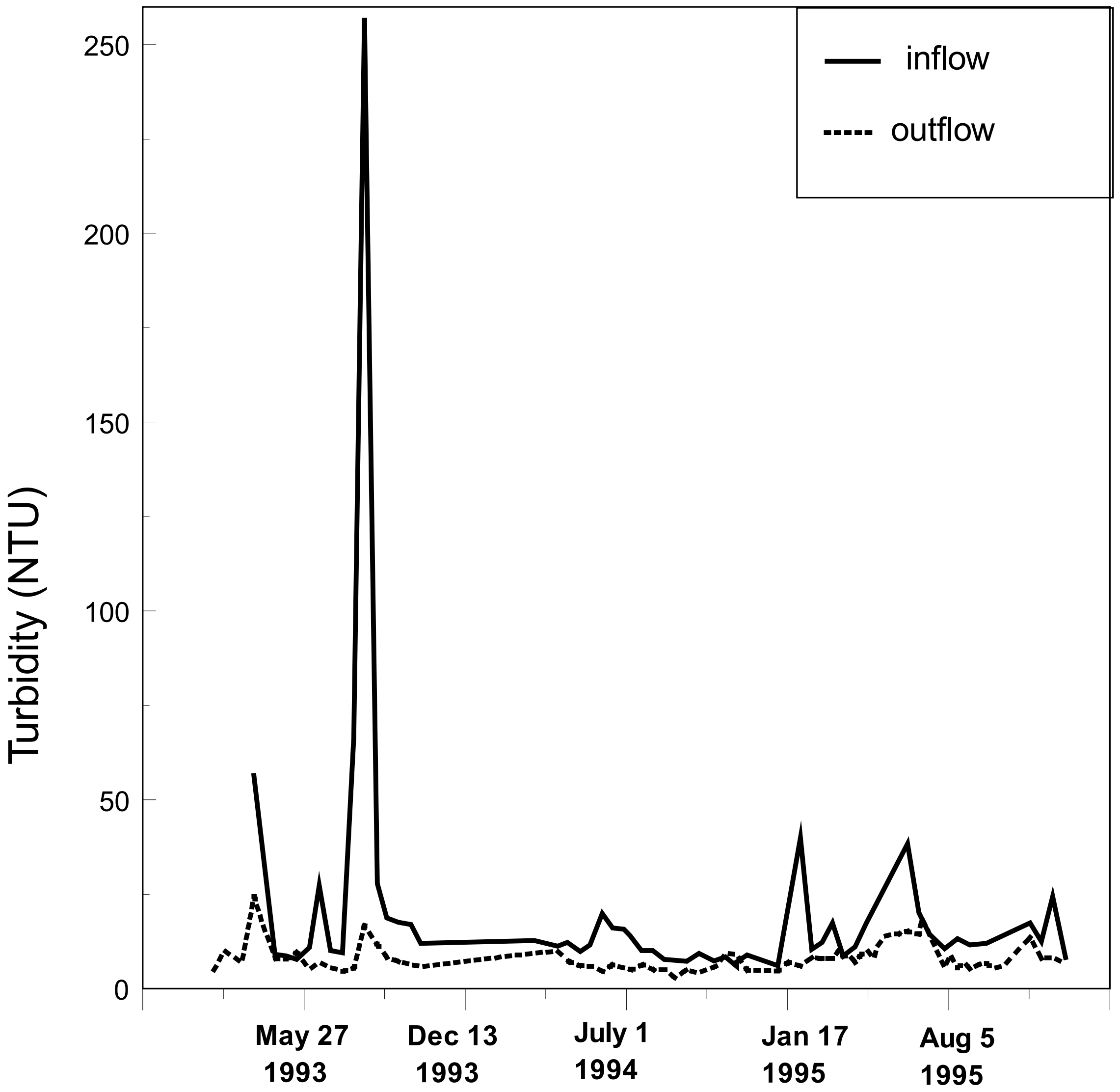
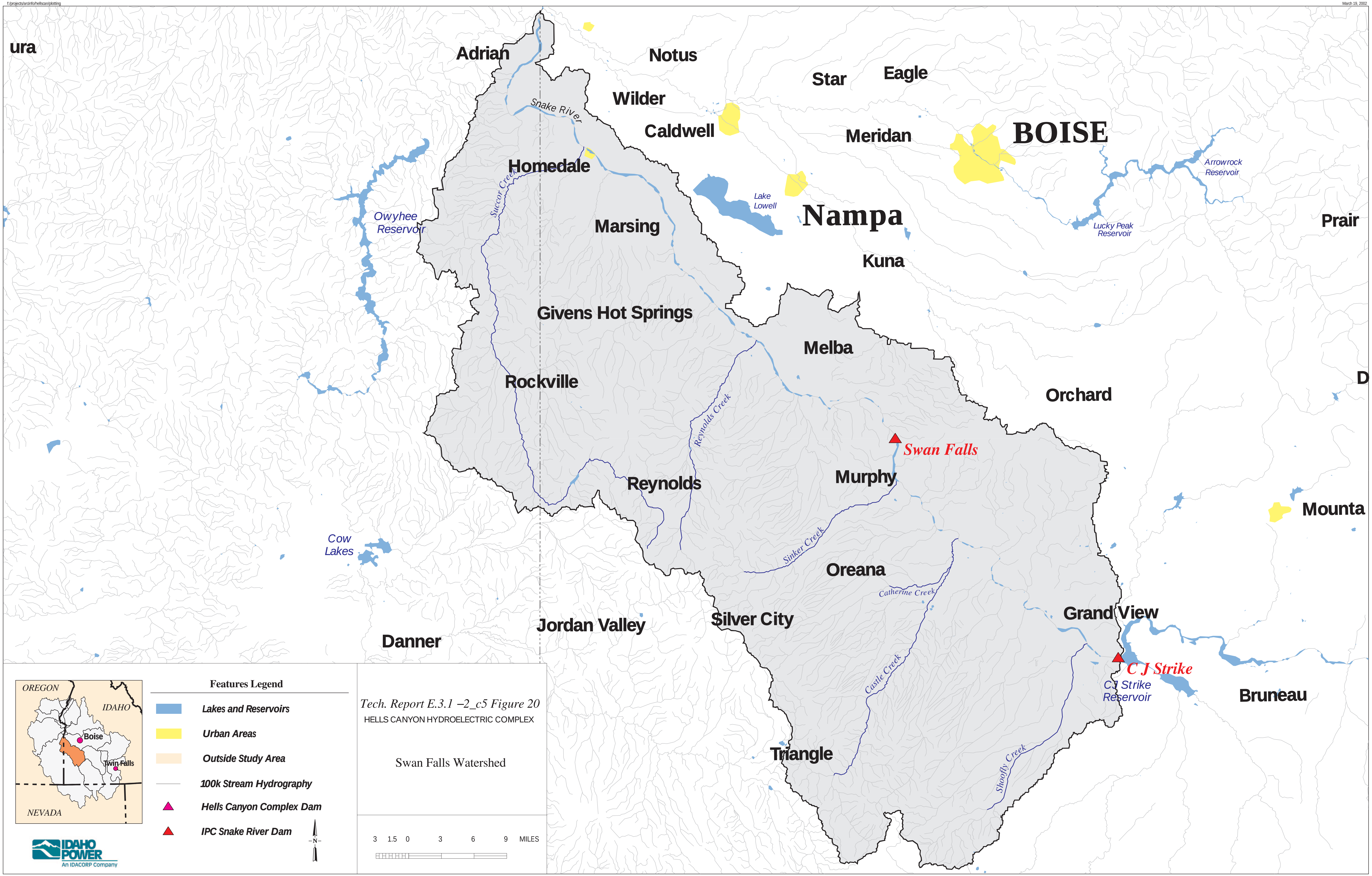


Figure 19. Turbidity of water flowing into C.J. Strike Reservoir at Indian Cove Bridge (RM 525.3) and leaving the reservoir (RM 493.7) (from Myers and Pierce 1997).

f:/projects/arcinfo/hellscan/plotting

March 19, 2002



Tech. Report E.3.1 –2_c5 Figure 20

HELLS CANYON HYDROELECTRIC COMPLEX

Swan Falls Watershed

This page left blank intentionally.

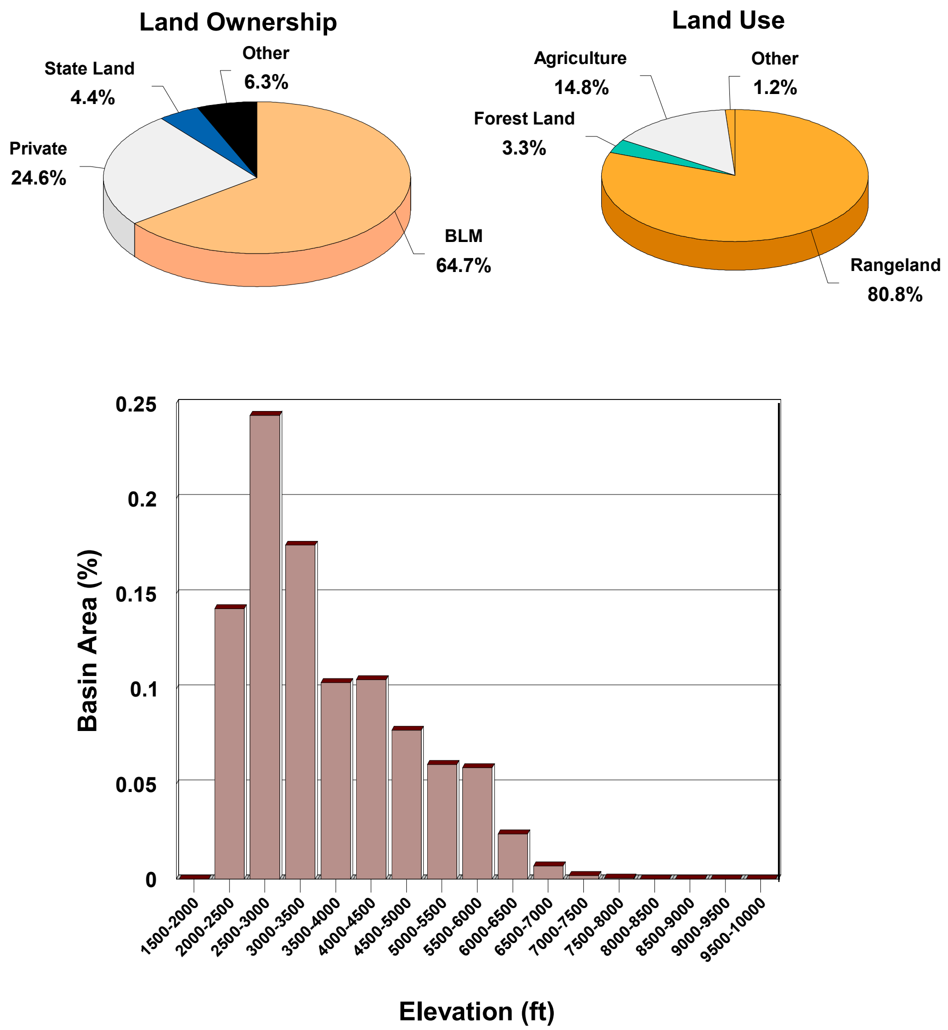


Figure 21. Land uses, land ownership, and elevation ranges as a percentage of basin area for the Swan Falls section of the Snake River, Idaho.

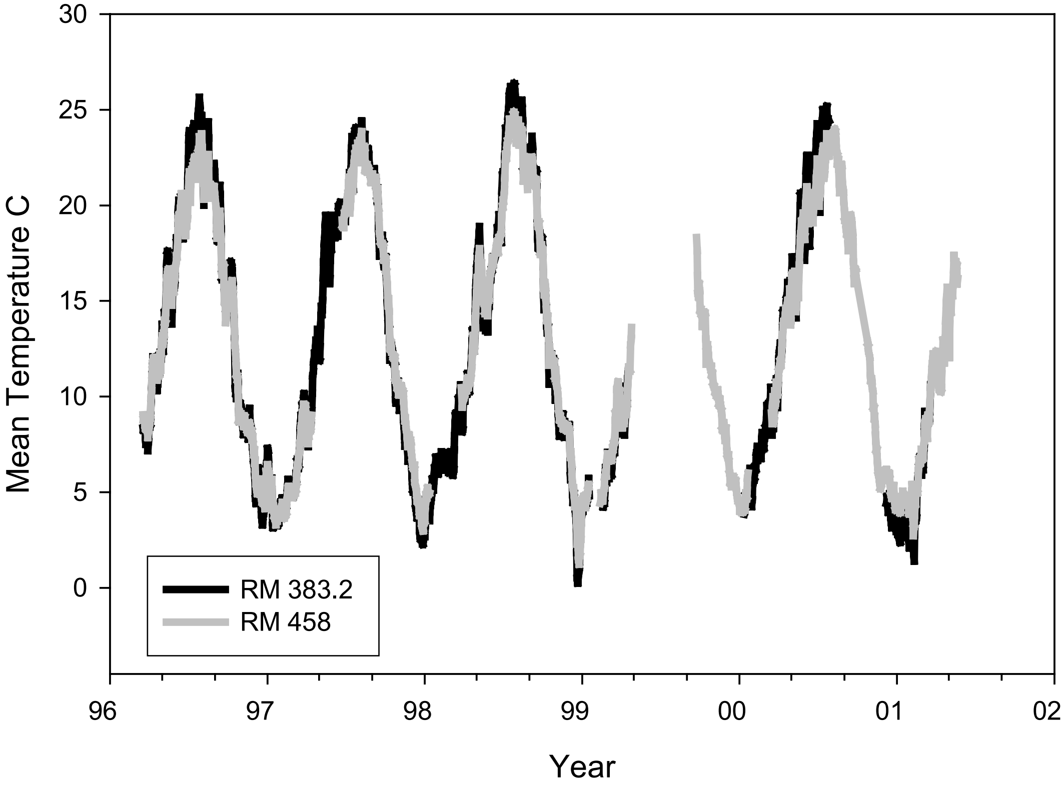
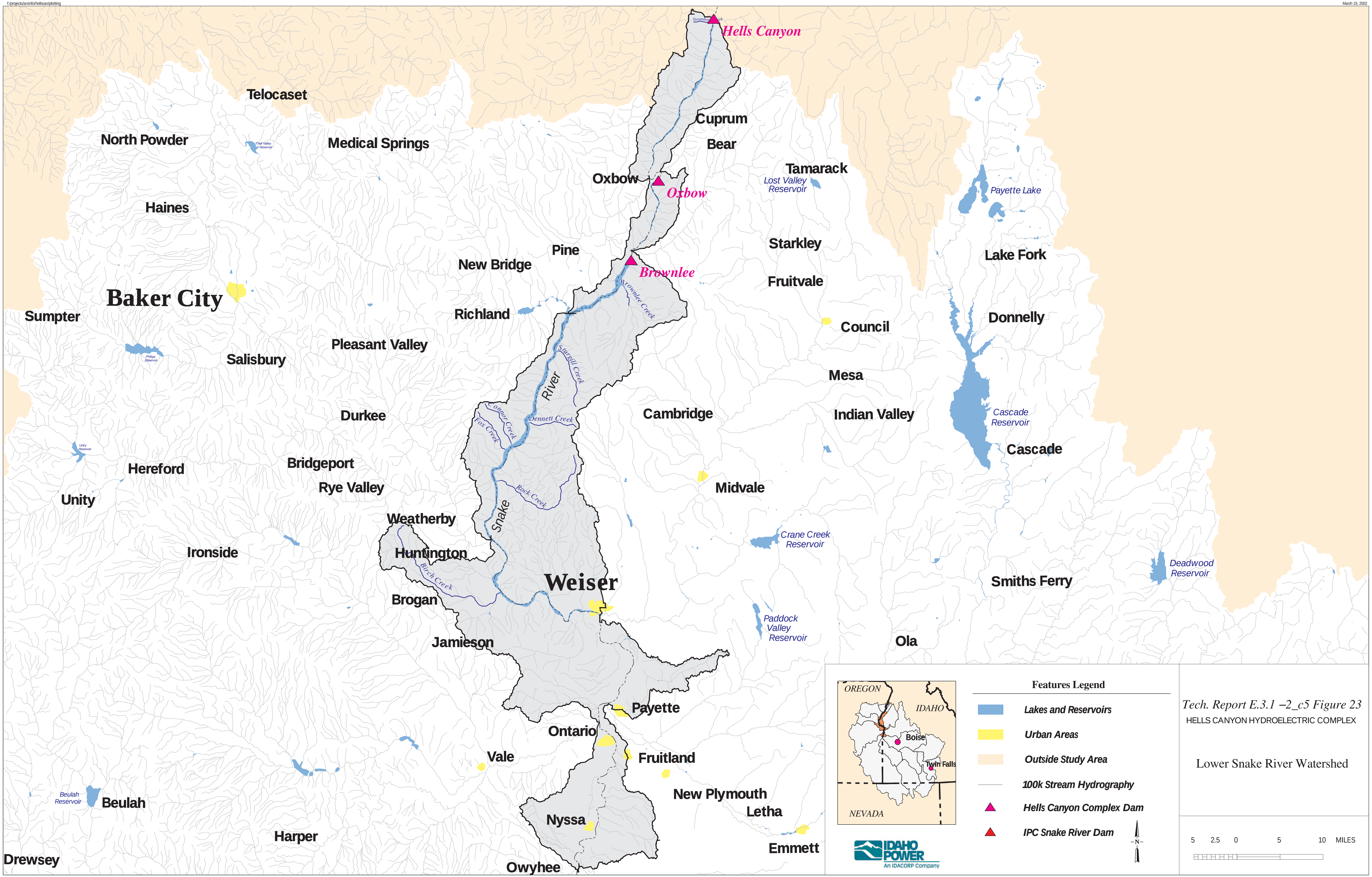


Figure 22. Mean daily temperatures from Swan Falls Reservoir (RM 458.0) and Nyssa (RM 383.2) from March 1996 through May 2001 (IPC, unpubl. data).

f:/projects/arcinfo/hellscan/plotting

March 19, 2002



Tech. Report E.3.1 –2_c5 Figure 23

HELLS CANYON HYDROELECTRIC COMPLEX

Lower Snake River Watershed

This page left blank intentionally.

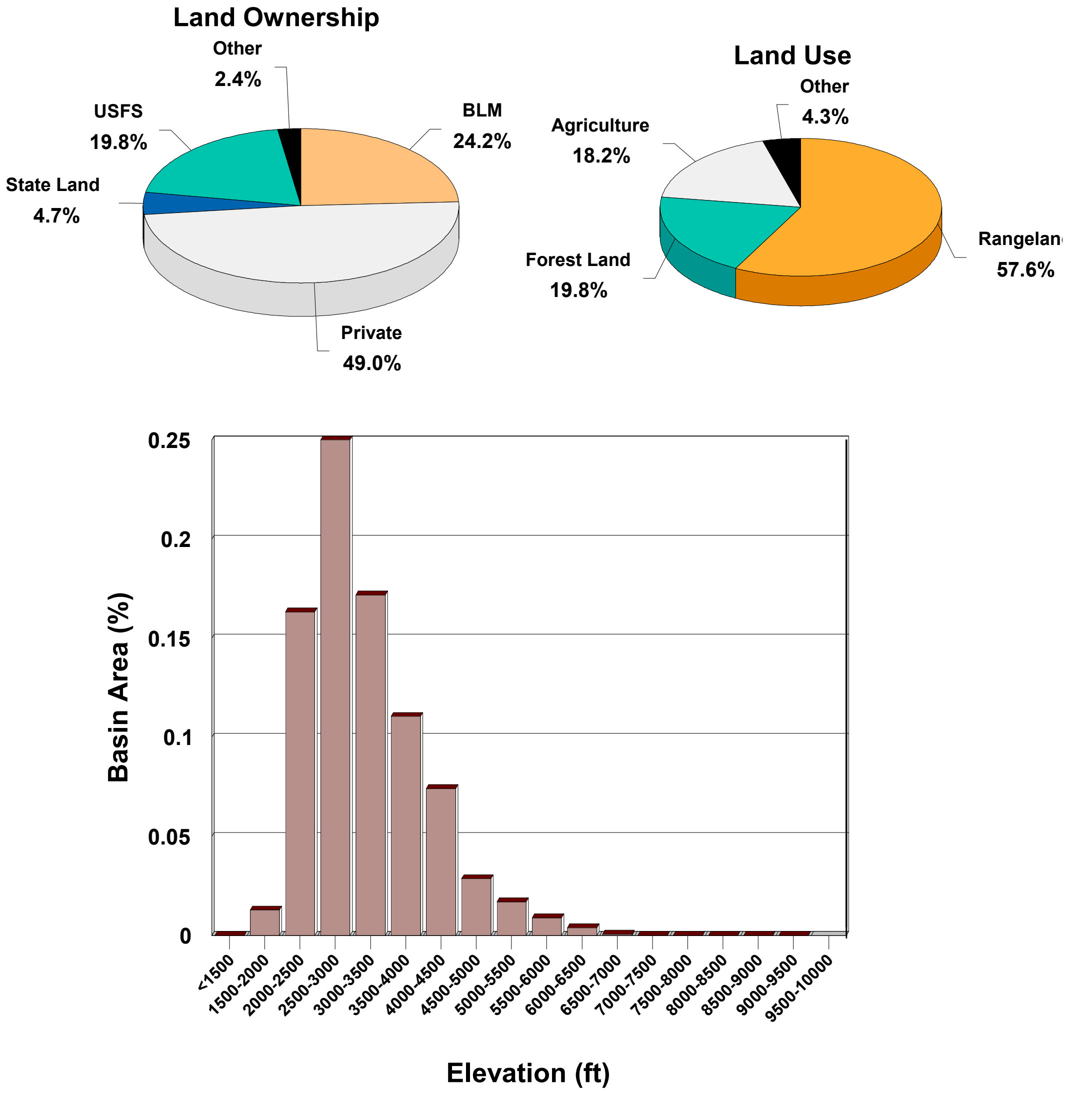


Figure 24. Land uses, land ownership, and elevation ranges as a percentage of basin area for the lower section of the Snake River, Idaho.

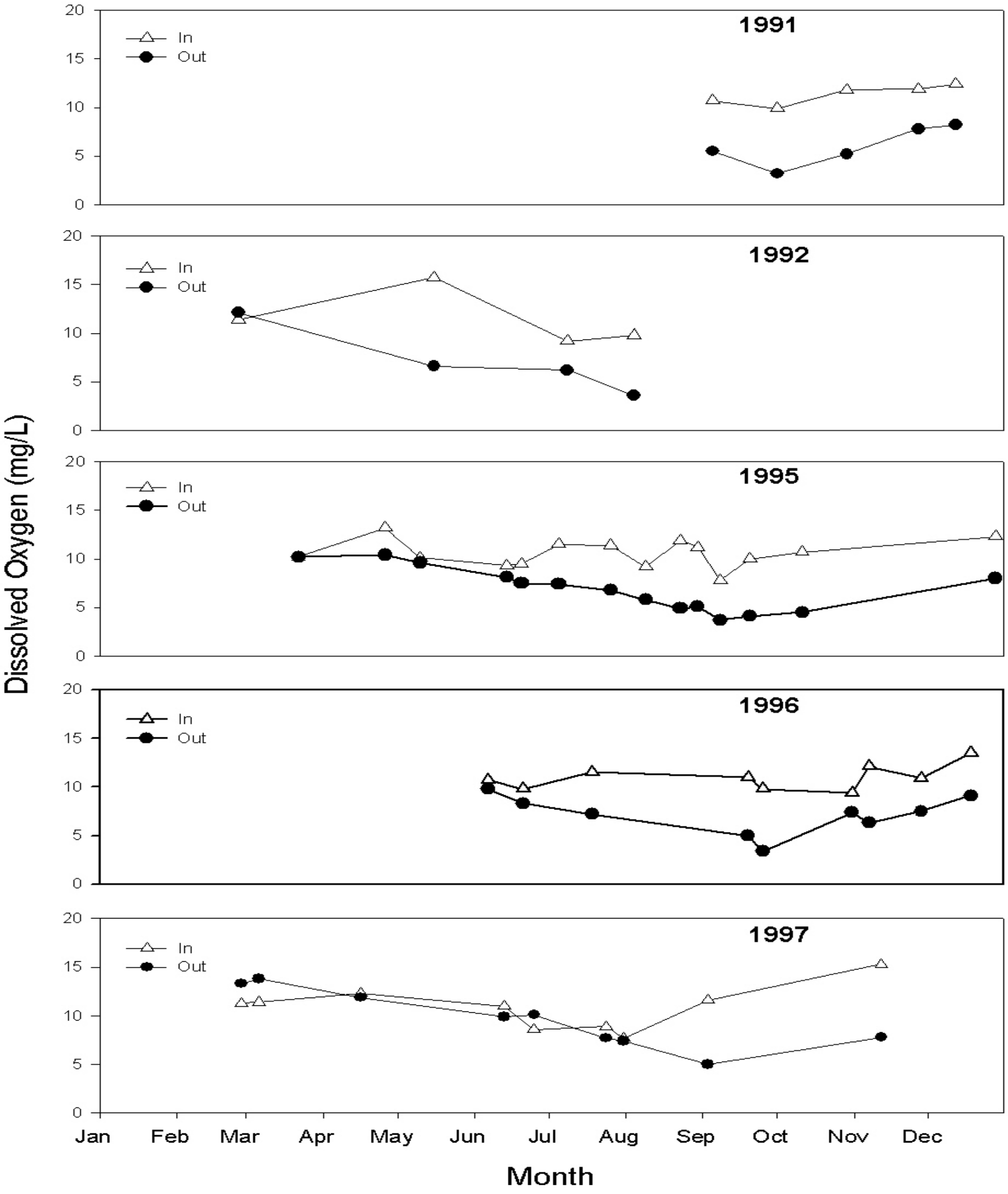


Figure 25. Plots of dissolved oxygen levels entering Brownlee Reservoir and those leaving Brownlee Dam (from Figure 12 in Myers and Pierce [1999]).

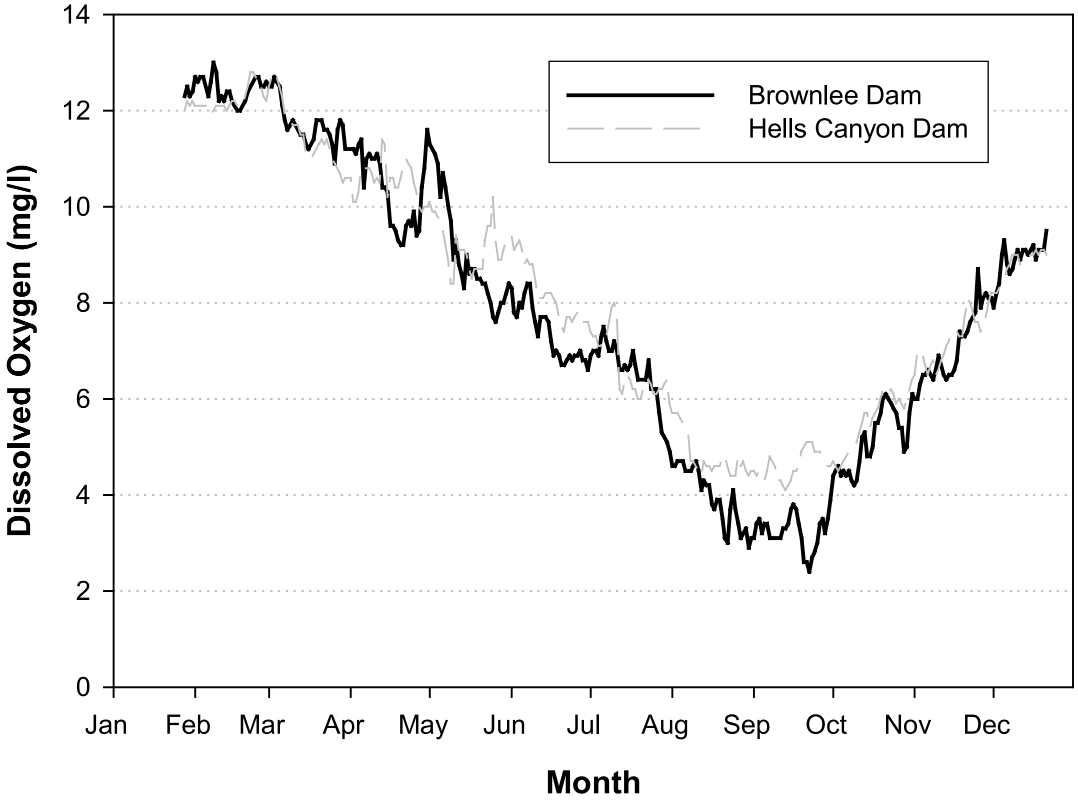


Figure 26. Summarized daily average of dissolved oxygen levels in water leaving Brownlee Dam and Hells Canyon Dam from data collected from 1992 through 1998 (from Figure 13 in Myers and Pierce [1999]).

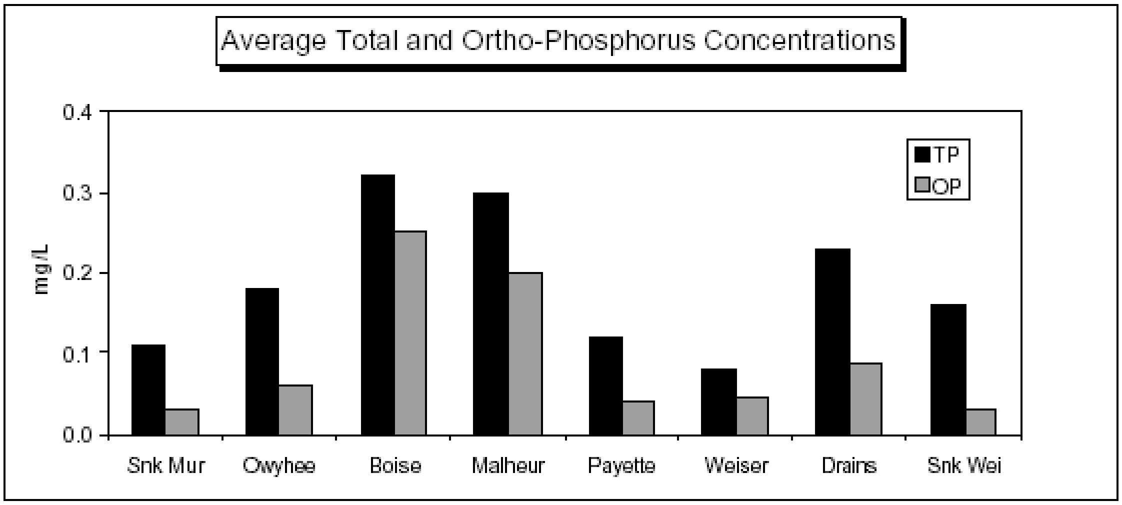


Figure 27. Total phosphorus (TP) and ortho-phosphorus (OP) concentrations collected in tributaries within the lower Snake River segment from data collected between 1970 and 1999 (Figure 2.3.6 in IDEQ [2001]). *Snk Mur* represents the Snake River near Murphy, and *Snk Wei* represents the Snake River near Weiser.

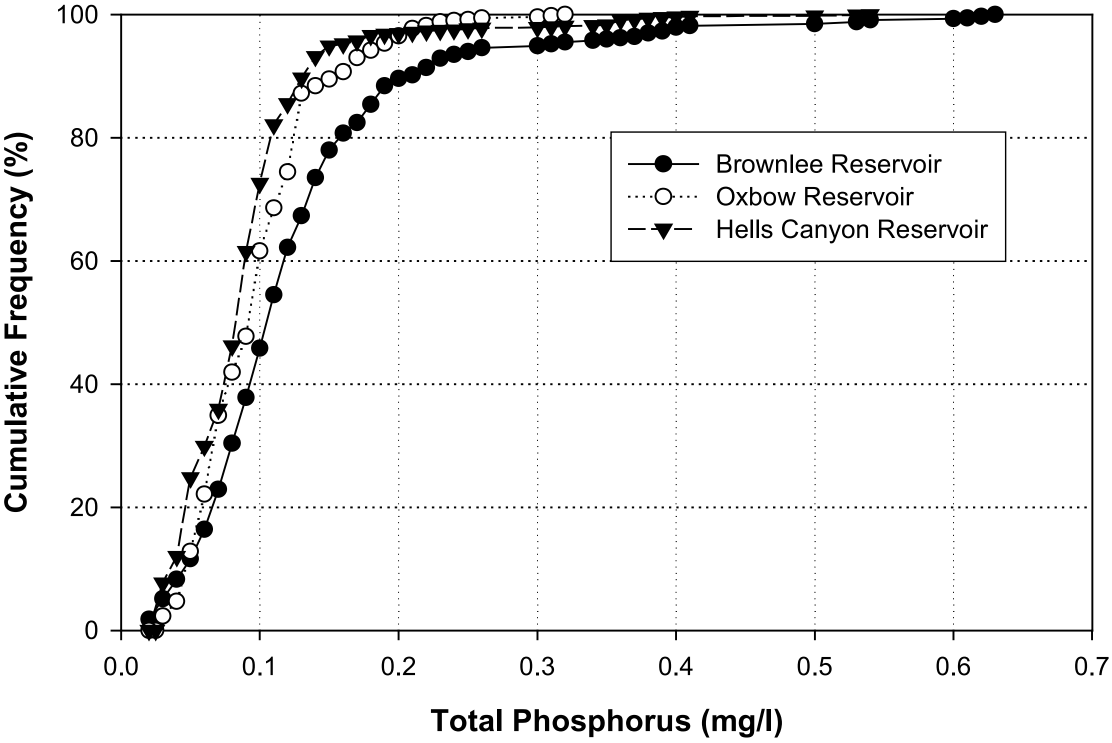


Figure 28. Frequency of exceedance curves for all total phosphorus levels measured in Brownlee, Oxbow, and Hells Canyon reservoirs from 1991 through 1998 (from Figure 24 in Myers and Pierce [1999]).

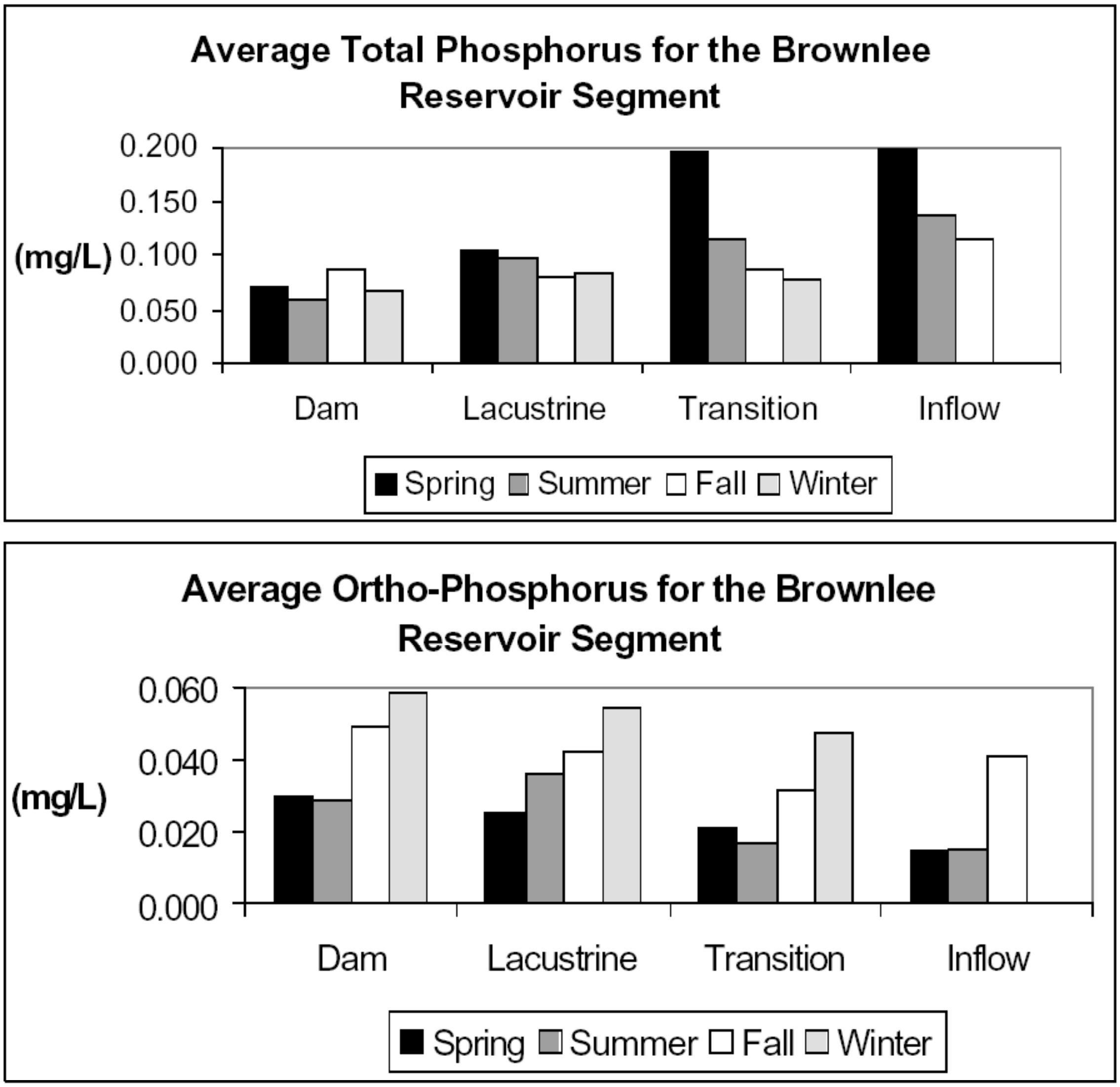


Figure 29. Average phosphorus (total and ortho) concentrations for Brownlee Reservoir in the lower Snake River segment (from Figure 2.3.16 in IDEQ [2001]).

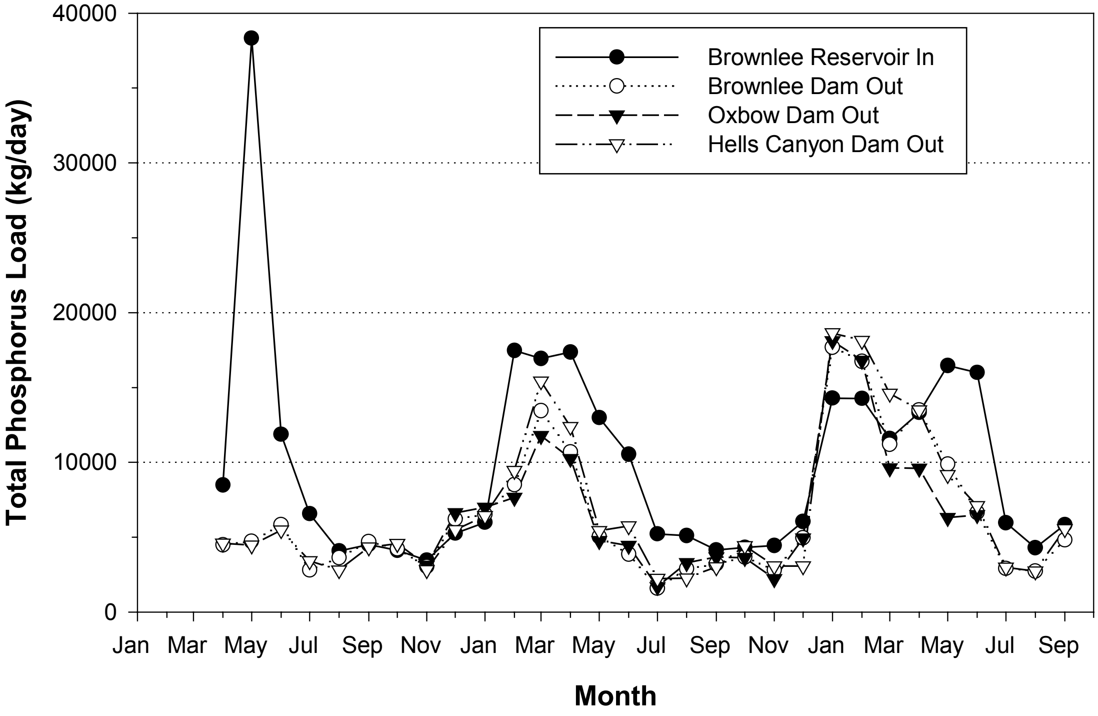


Figure 30. Plots comparing monthly average total phosphorus loads entering Brownlee Reservoir and discharging from Brownlee, Oxbow, and Hells Canyon dams during 1996 and 1997 (from Figure 27 in Myers and Pierce [1999]).

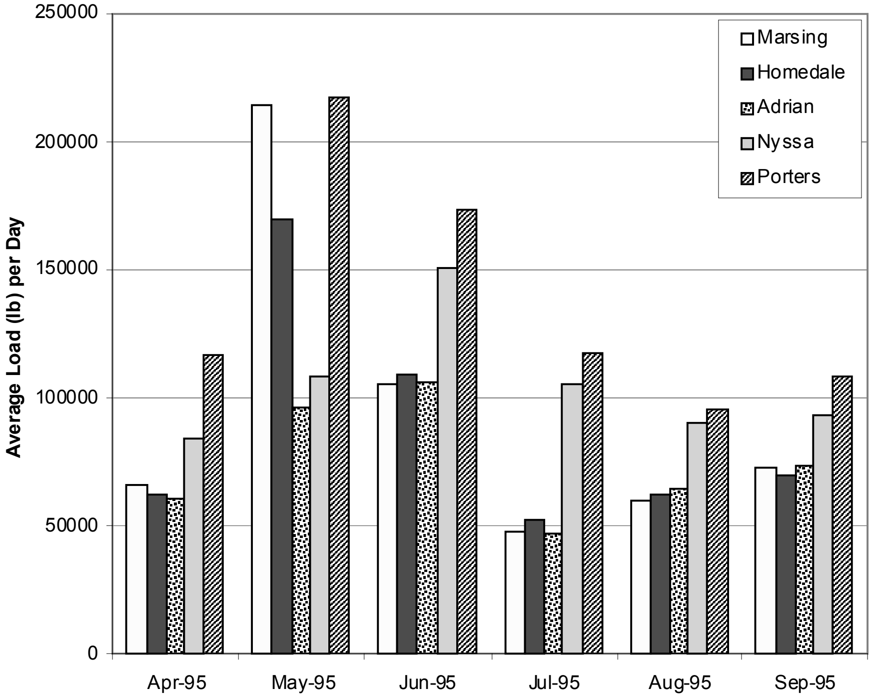


Figure 31. Mean total nitrogen loads from Marsing to Porters Flat for April through September 1995 (from Figures 4–10 in Harrison et al. [2000]).

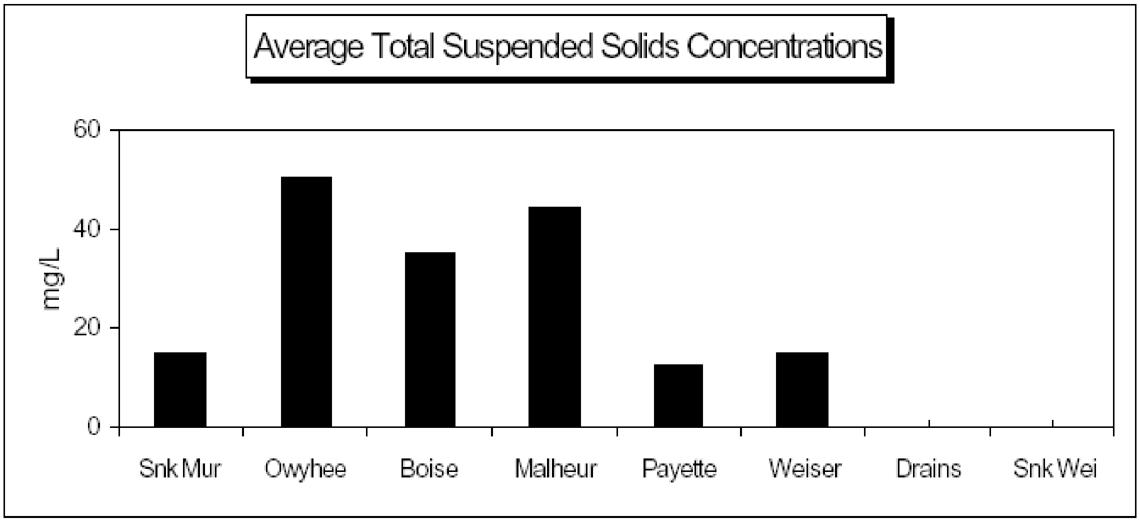


Figure 32. Average concentrations of total suspended solids for tributary and mainstem sites within the lower Snake River segment (Figure 2.3.10 in IDEQ [2001]). *Snk Mur* represents the Snake River near Murphy, and *Snk Wei* represents the Snake River near Weiser.

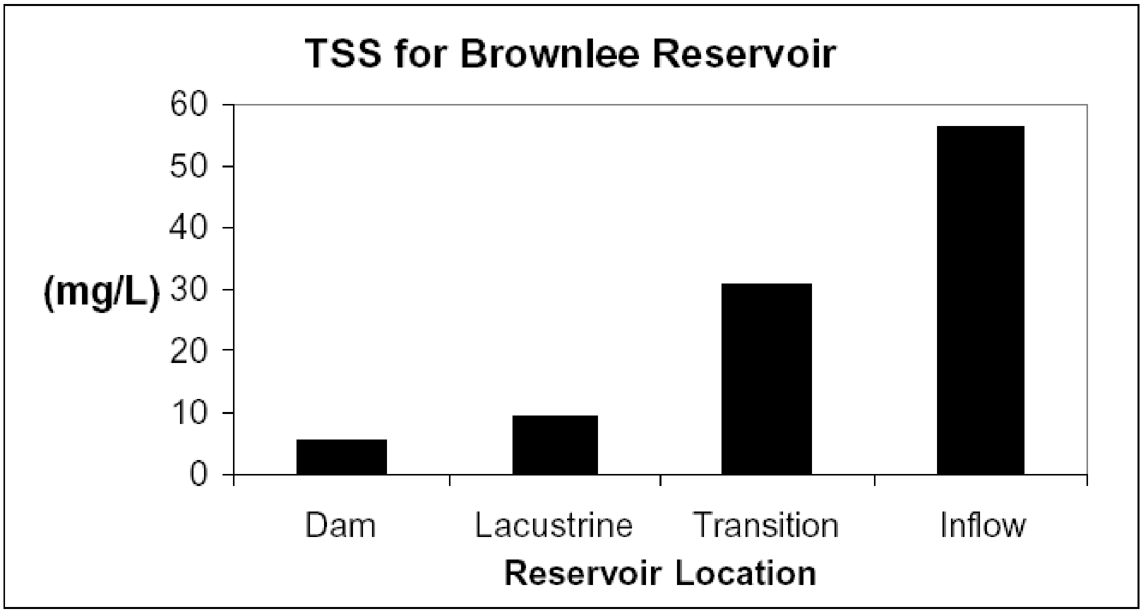
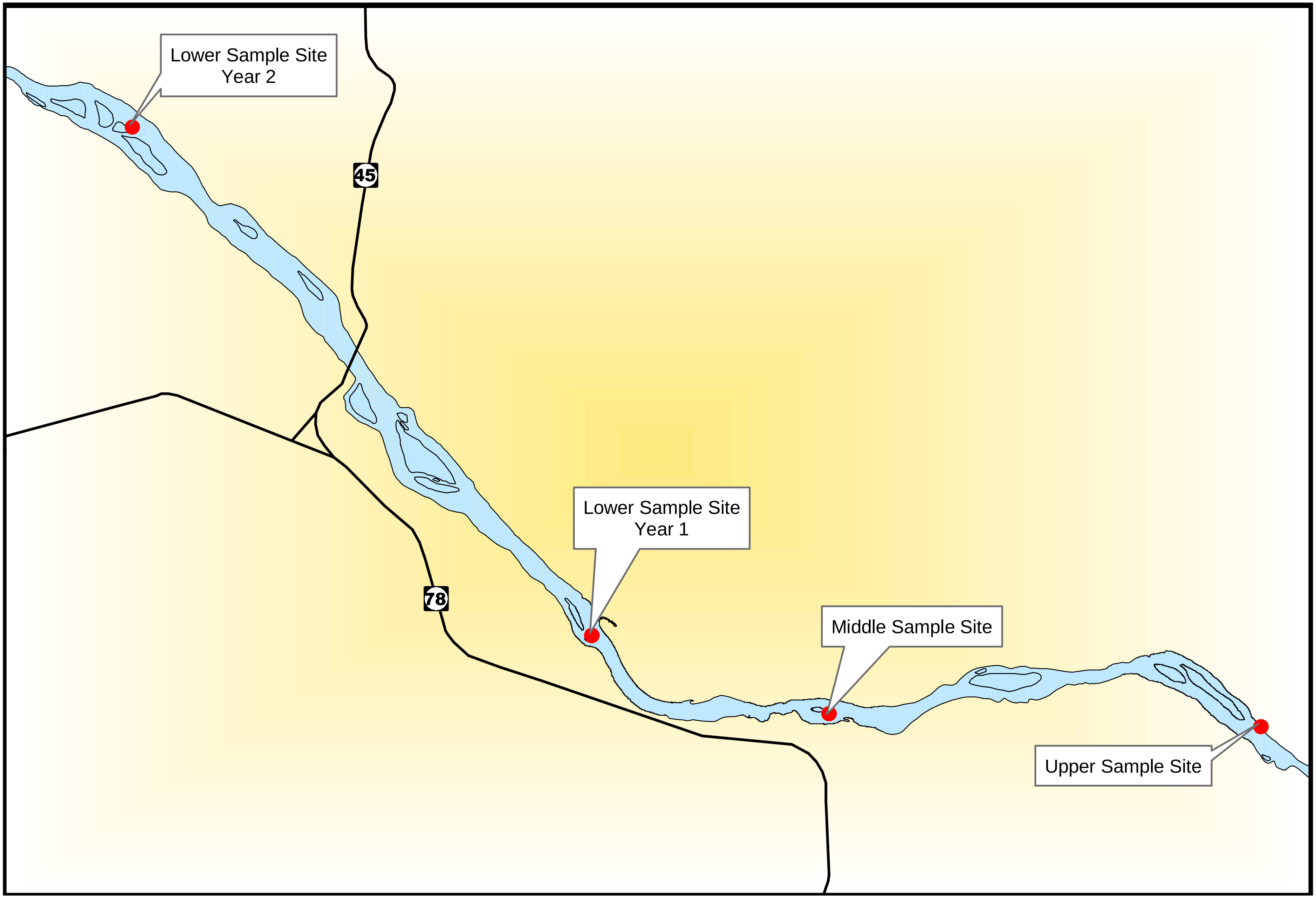
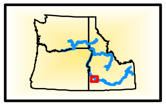


Figure 33. Average concentrations for total suspended solids (TSS) for Brownlee Reservoir in the lower Snake River segment (Figure 2.3.22 in IDEQ [2001]).




Vicinity Map

IDAHO POWER
An IDACORP Company

Legend

● Artificial Redd Site

🟦 Snake River

N E S W

Hells Canyon Project - FERC No. 1971

Tech. Report E.3.1-2 Chapter 5 Figure 34

Historic spawninig site locations used in sediment permeability and artificial redd evaluations.

Scale 1:51,146

0.4 0.2 0 0.4 0.8 1.2 1.6 Miles

This page left blank intentionally.

Figure 35. Upper sediment permeability and artificial redd site, looking upstream.

Figure 36. Middle sediment permeability and artificial redd site, looking downstream.

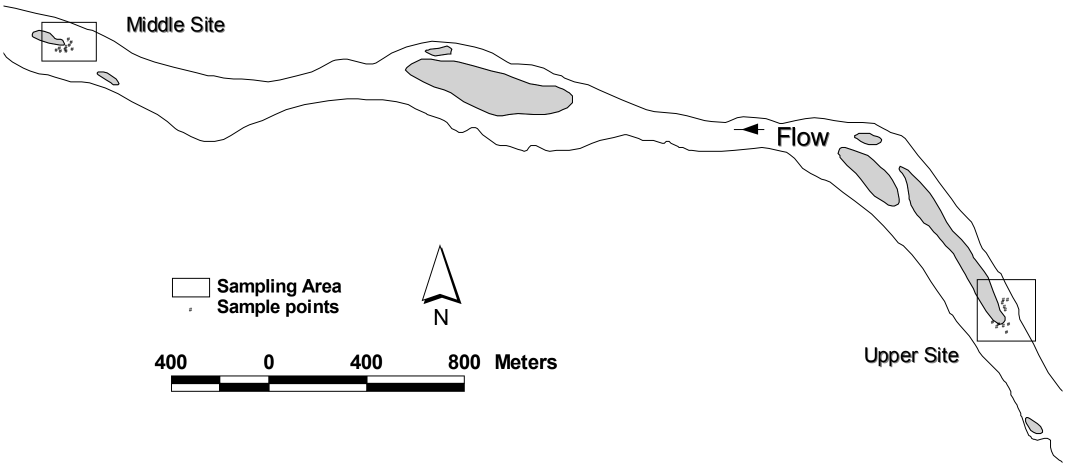


Figure 37. Upper and middle study site locations.

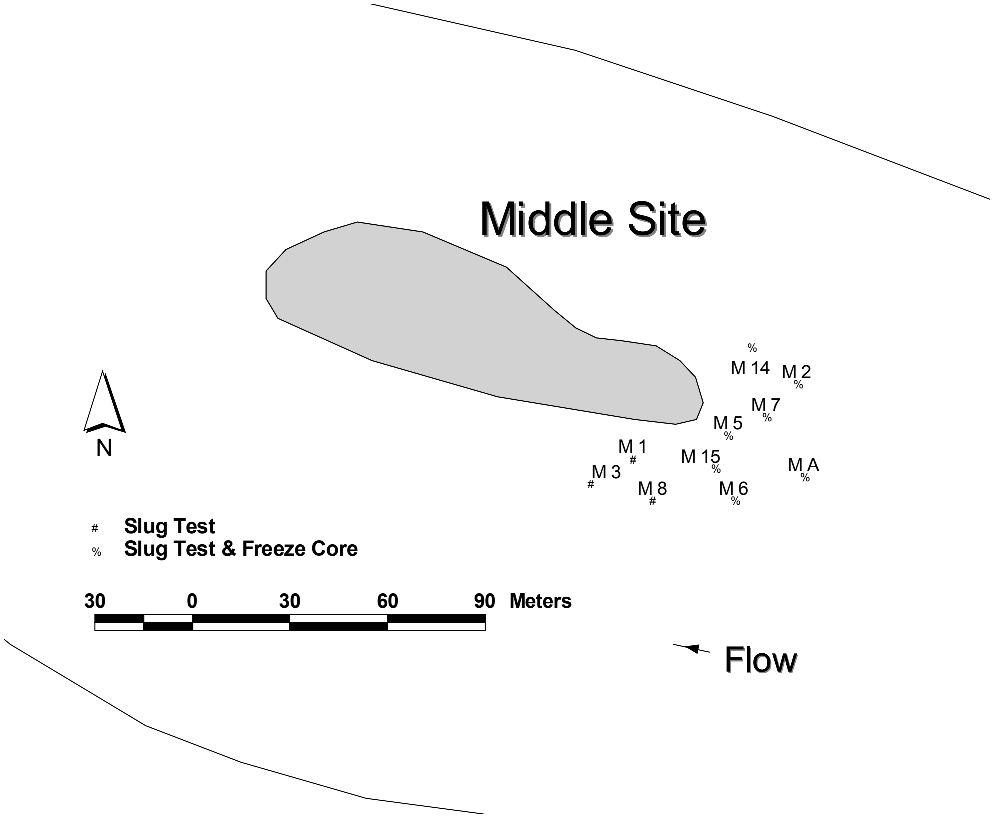


Figure 38. Middle site sampling locations.

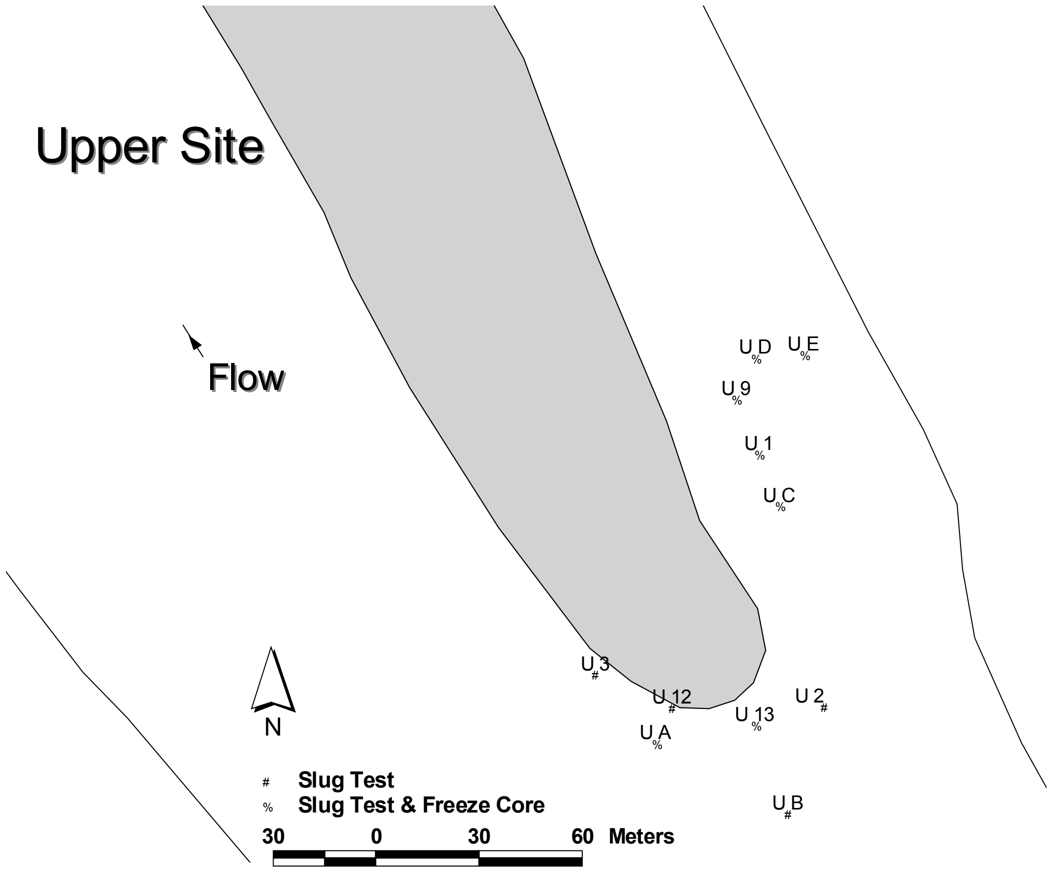


Figure 39. Upper site sampling locations.

Figure 40. Tri-tube assembly, tripod, and chain hoist used for extracting freeze cores. Liquid nitrogen is poured down into the tubes through the funnels to freeze the bed.

Figure 41. Thawing the freeze core over an aluminum sample collection box with a portable propane heater.

Figure 42. The surface layer of the sediment core is lost due to thawing. The triangular plate at left was at the riverbed surface.

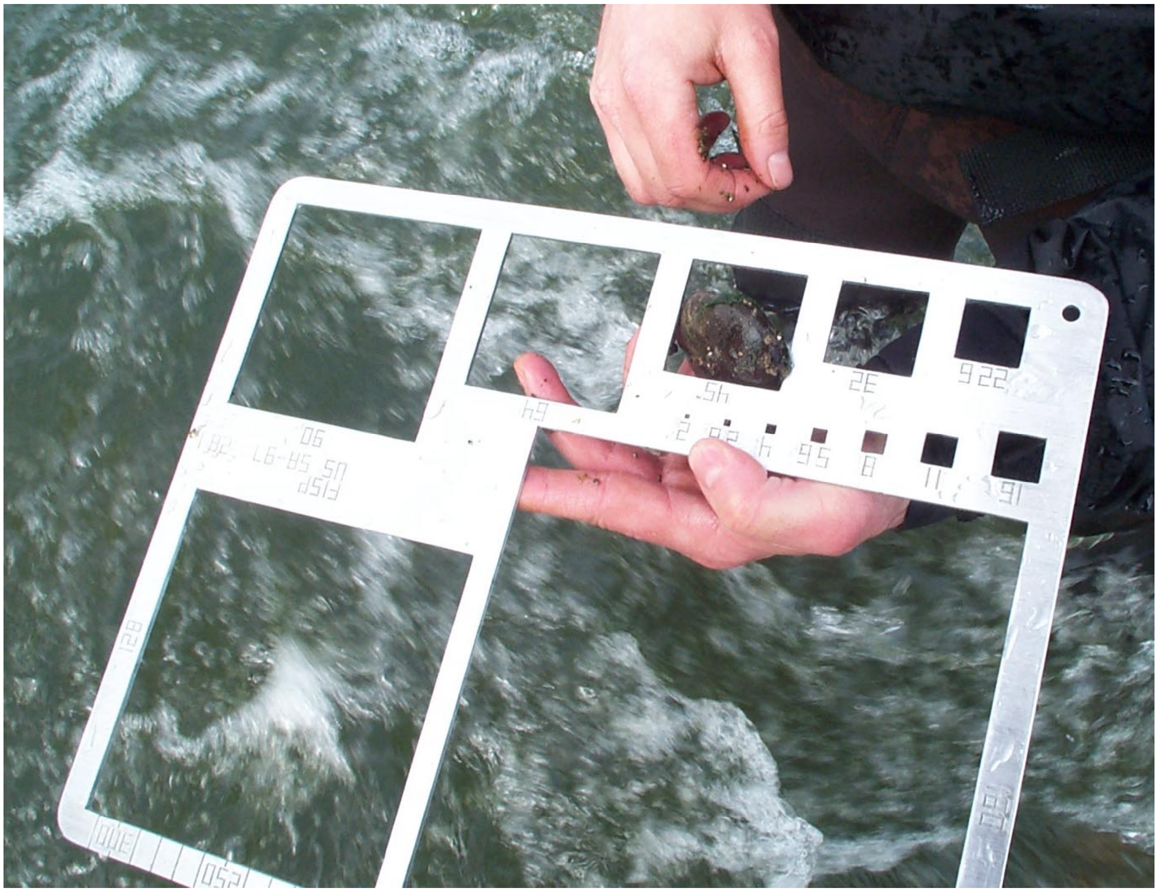


Figure 43. The sampling template used in the pebble count method.

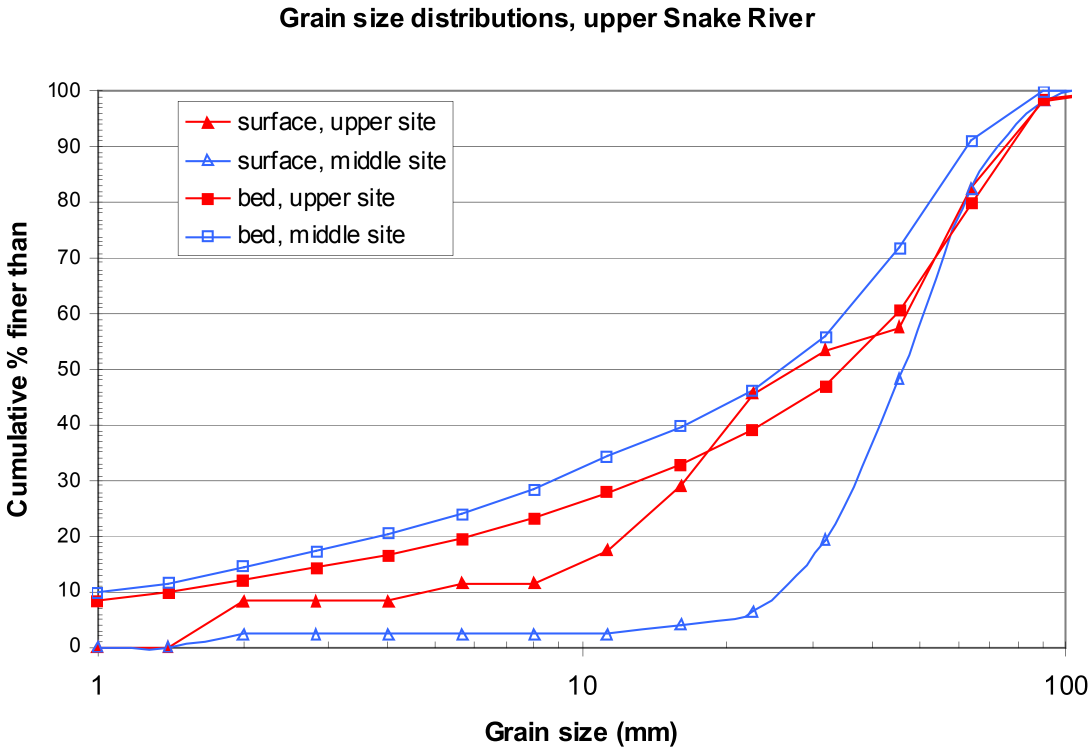


Figure 44. Grain size distributions at the upper and middle sites. *Surface* values were determined from pebble counts, while *Bed* values were determined from freeze cores.

Figure 45. The data logger is inserted into the piezometer through the pressure-regulating device.

Figure 46. The piezometer is outfitted with a pressure-regulating ball valve device and a small electric air compressor.

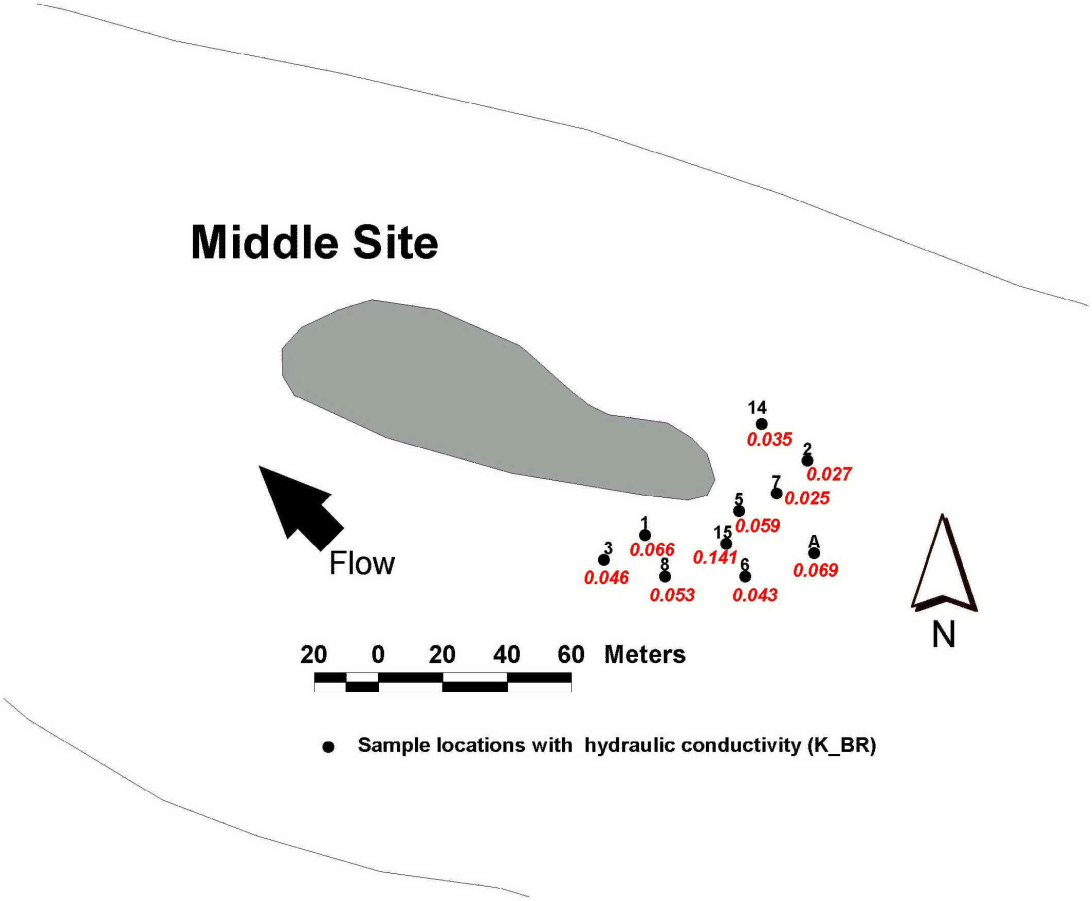


Figure 47. Hydraulic conductivity estimated with the Bouwer and Rice method (*K_BR*) at the middle site.

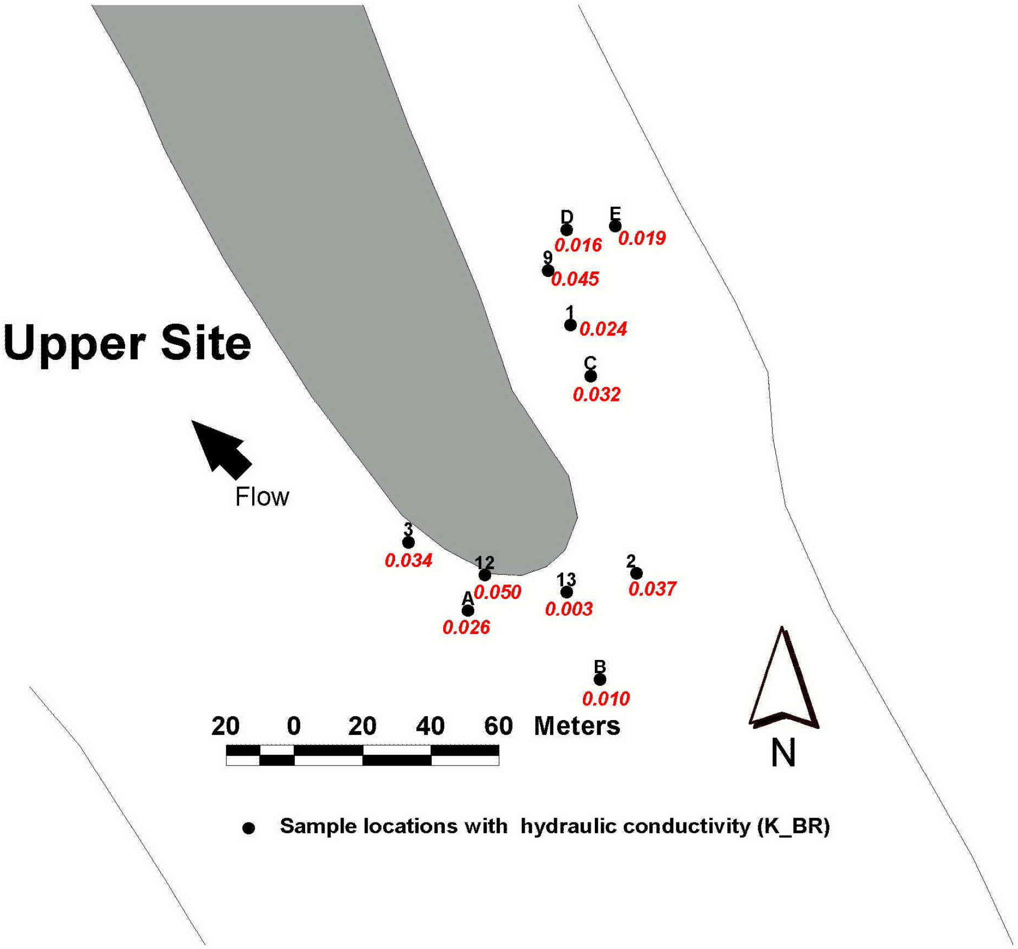


Figure 48. Hydraulic conductivity estimated with the Bouwer and Rice method (*K_BR*) at the upper site.

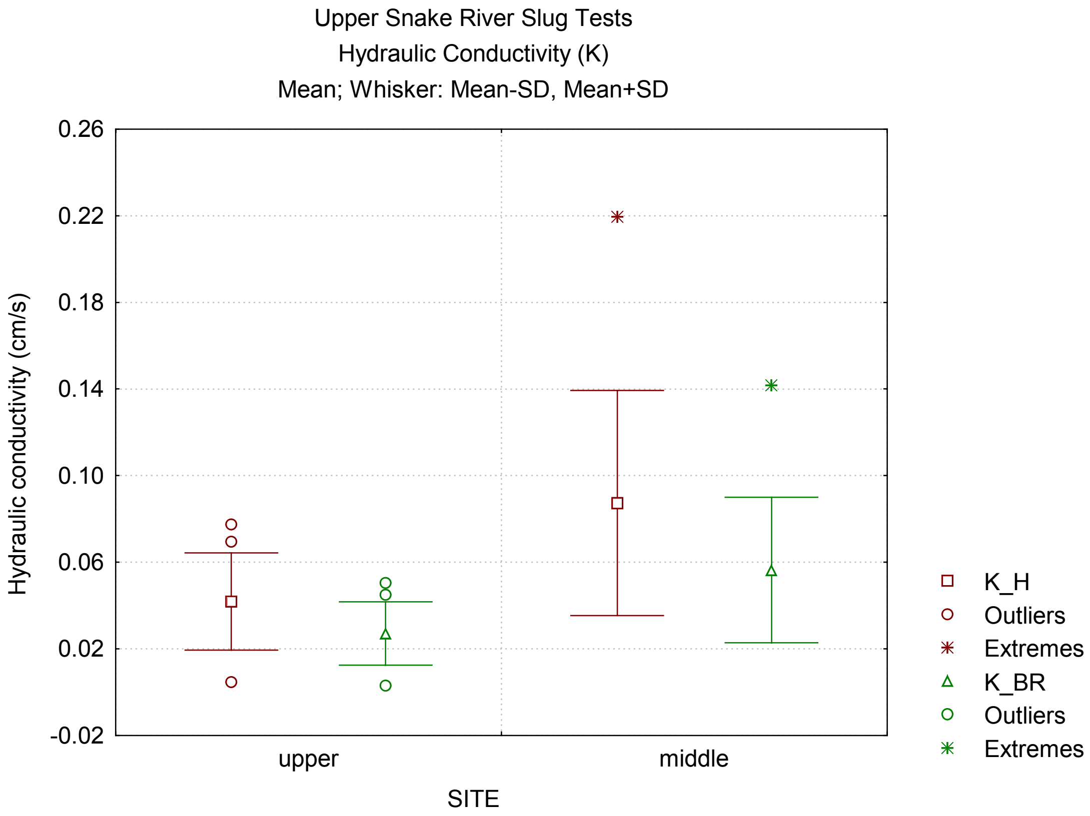


Figure 49. Mean hydraulic conductivity values at the middle and upper sites. (*K_H* represents use of the Hvorslev method and *K_BR* represents use of the Bouwer and Rice method.)

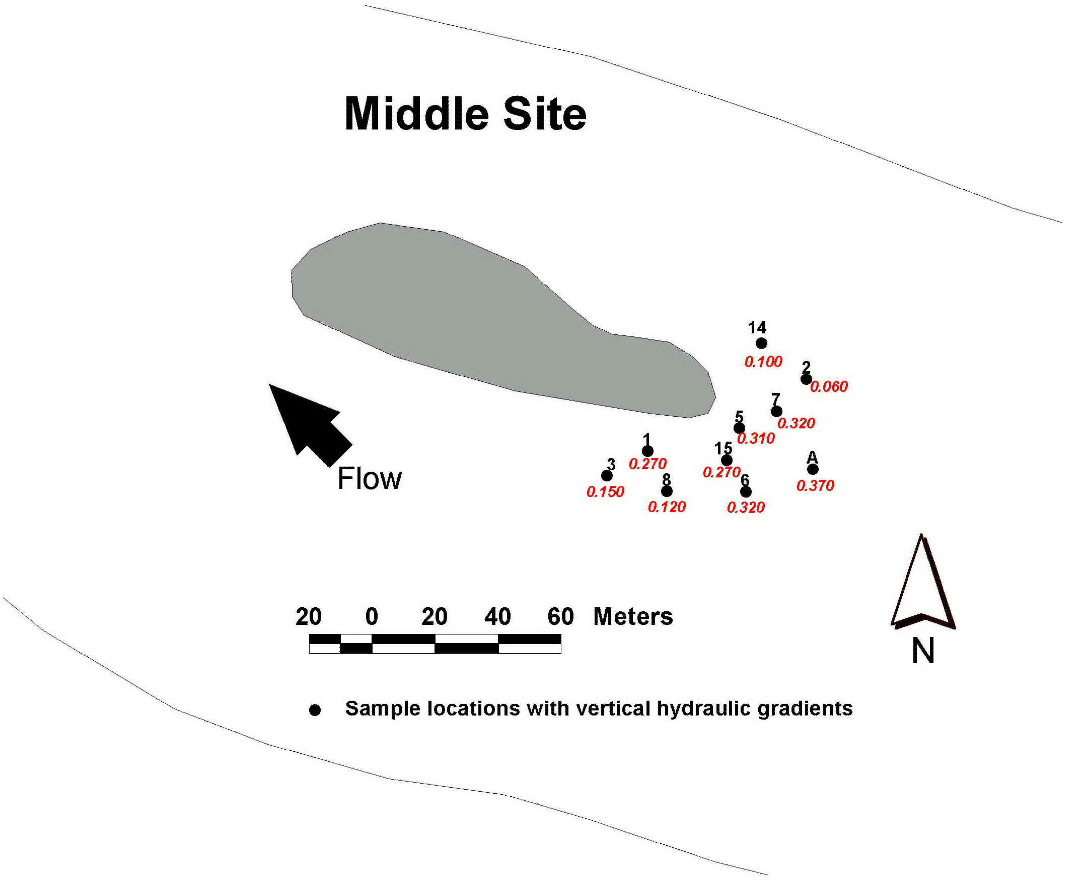


Figure 50. Estimates of vertical hydraulic gradient (VHG) at the middle site.

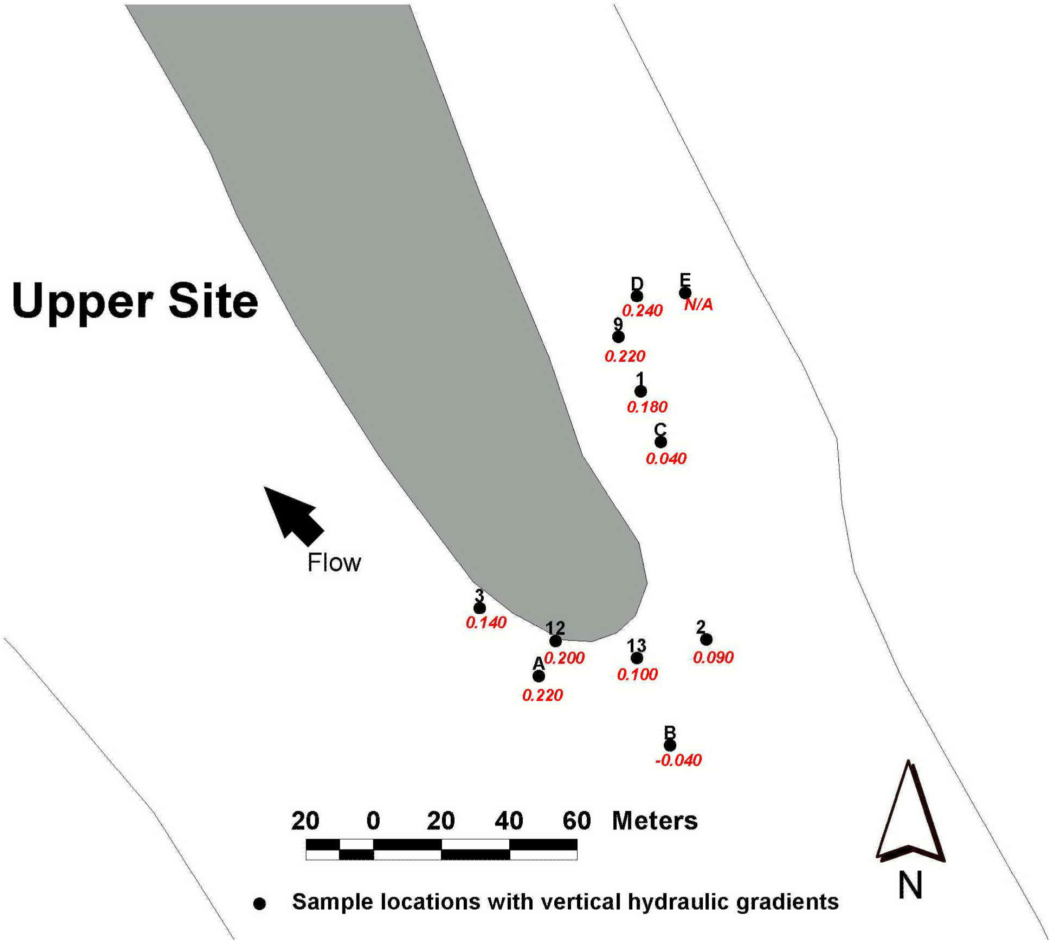


Figure 51. Estimates of vertical hydraulic gradient (VHG) at the upper site.

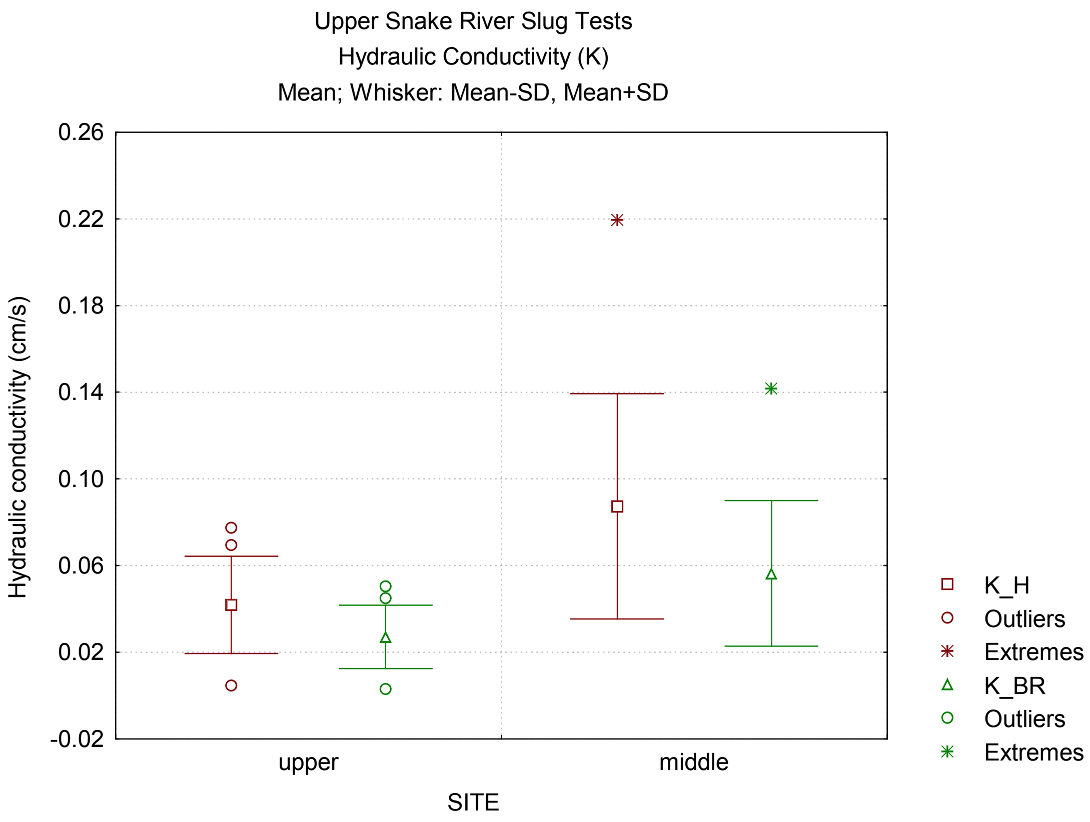


Figure 52. Mean hydraulic conductivity values at the middle and upper sites.

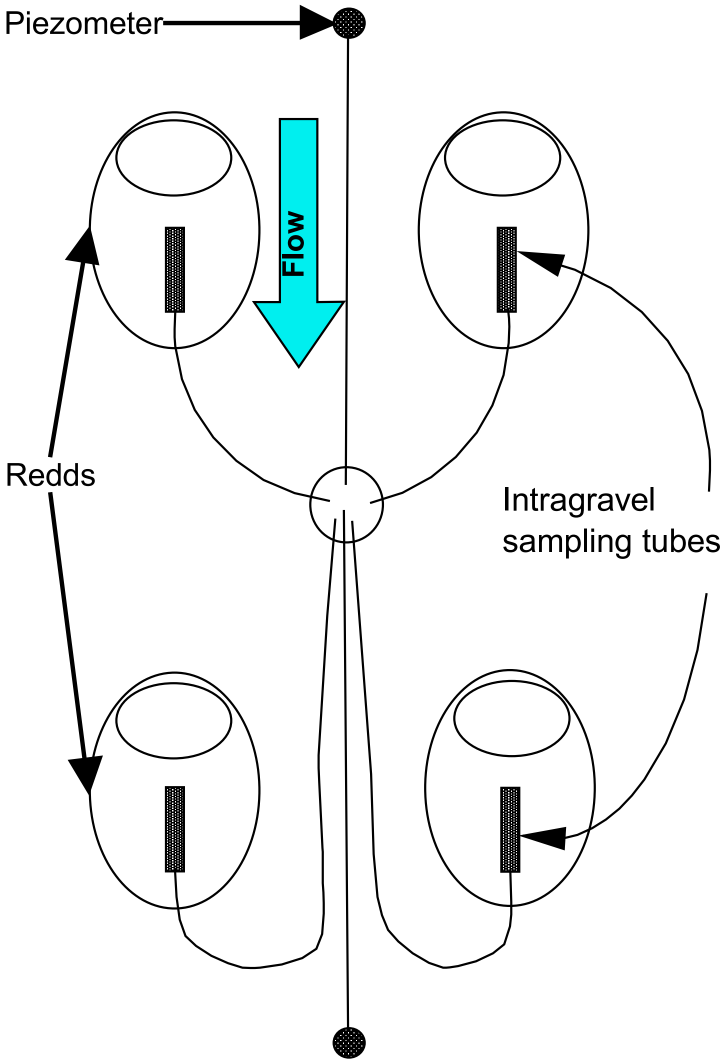


Figure 53. Surface view of layout of one cluster of artificial redds showing locations of redds and piezometers relative to a central sample collection site.

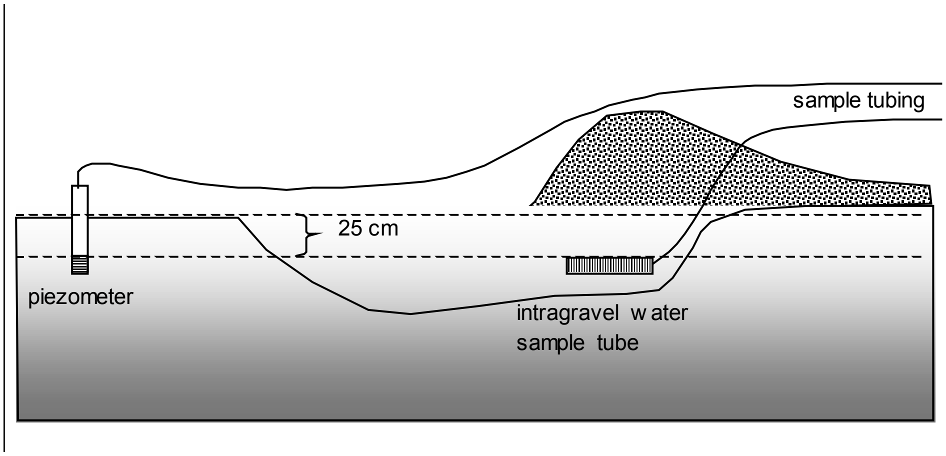


Figure 54. Side profile of layout of artificial redd and intragravel sampling tube and piezometer depths.

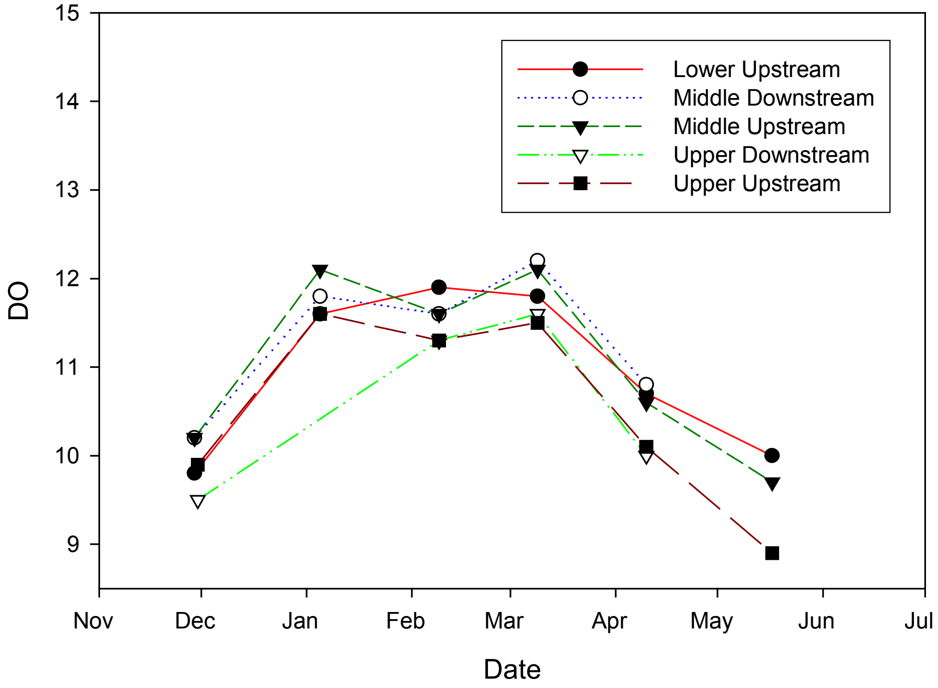


Figure 55. Water column dissolved oxygen (DO; mg/l) levels measured in year 1 (1999–2000).

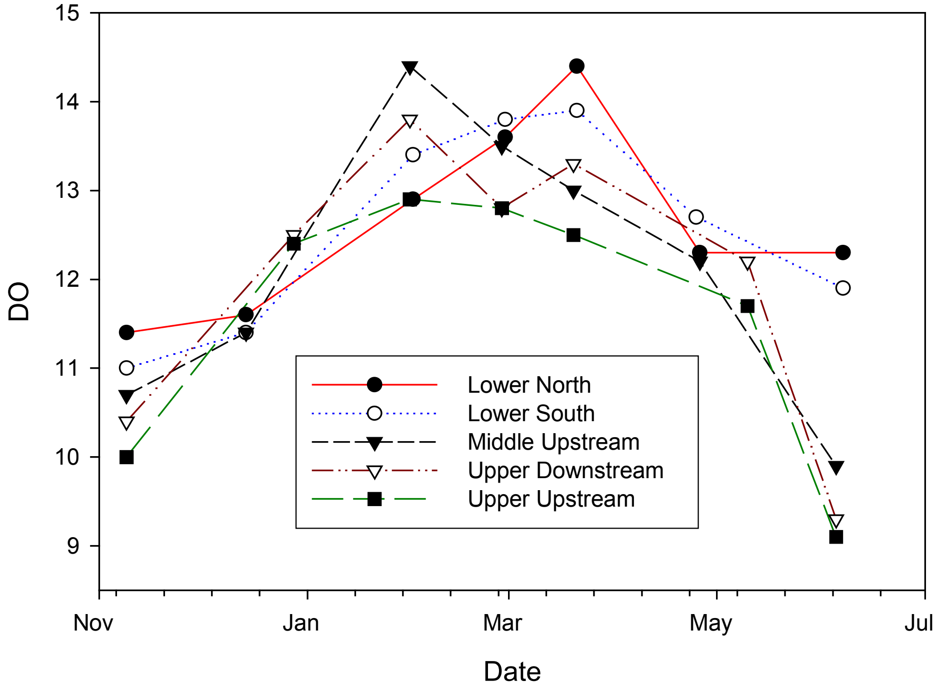


Figure 56. Water column dissolved oxygen (DO; mg/l) levels measured in year 2 (2000–2001).

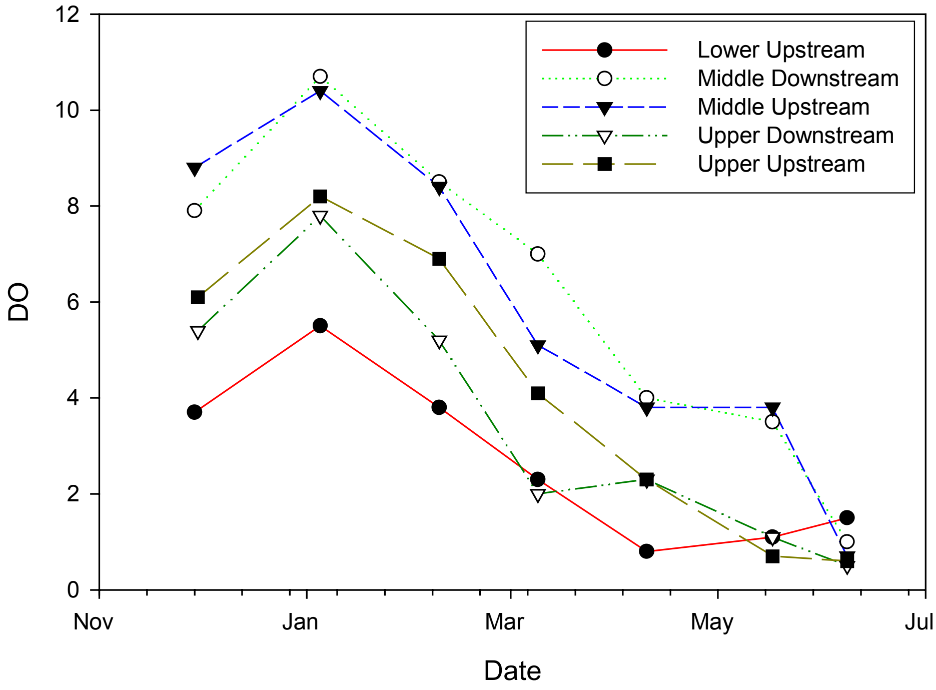


Figure 57. Piezometer dissolved oxygen (DO; mg/l) levels measured in year 1 (1999−2000).

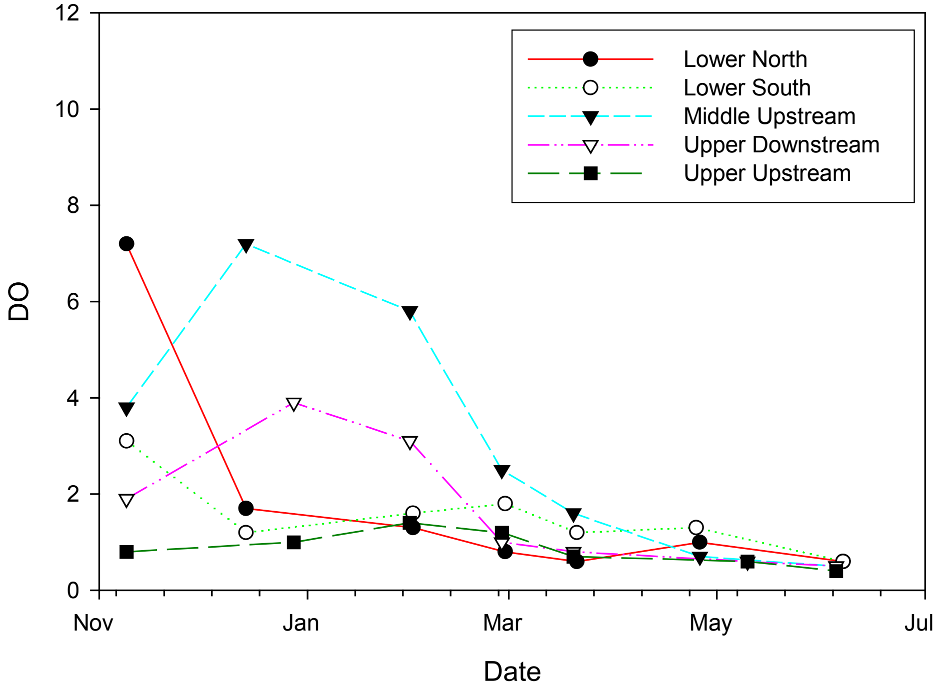


Figure 58. Piezometer dissolved oxygen (DO; mg/l) levels measured in year 2 (2000−2001).

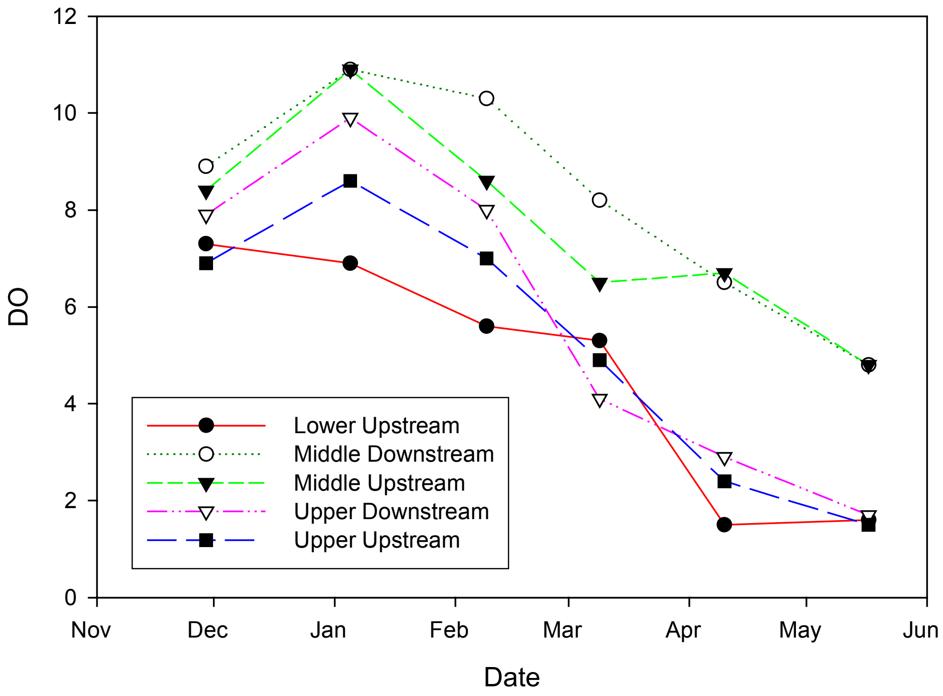


Figure 59. Artificial redd dissolved oxygen (DO; mg/l) levels measured in year 1 (1999−2000).

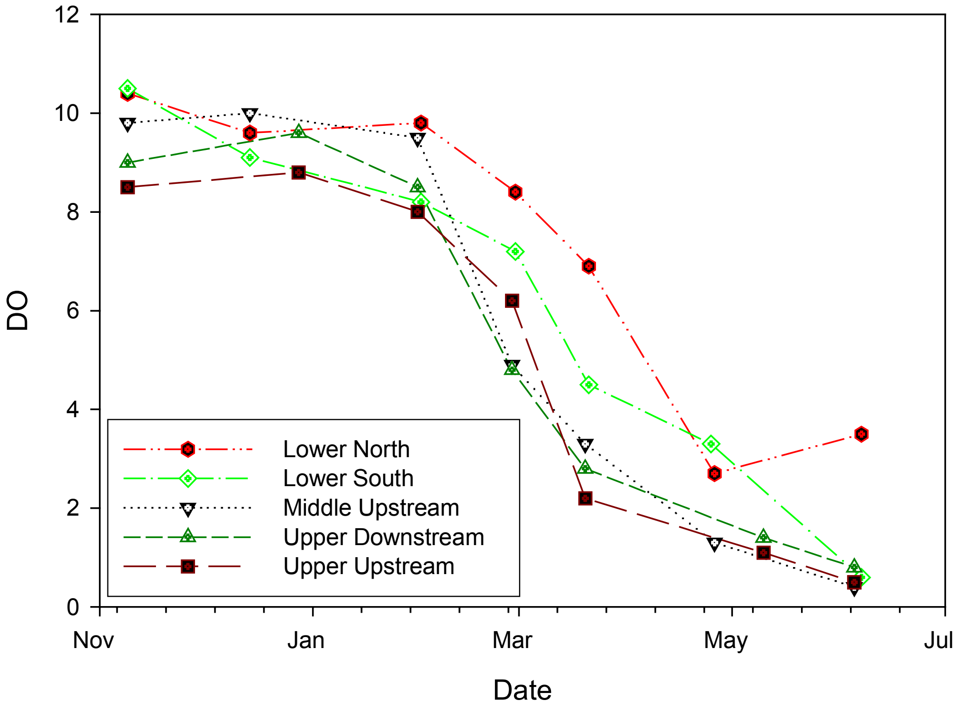


Figure 60. Artificial redd dissolved oxygen (DO; mg/l) levels measured in year 2 (2000–2001).

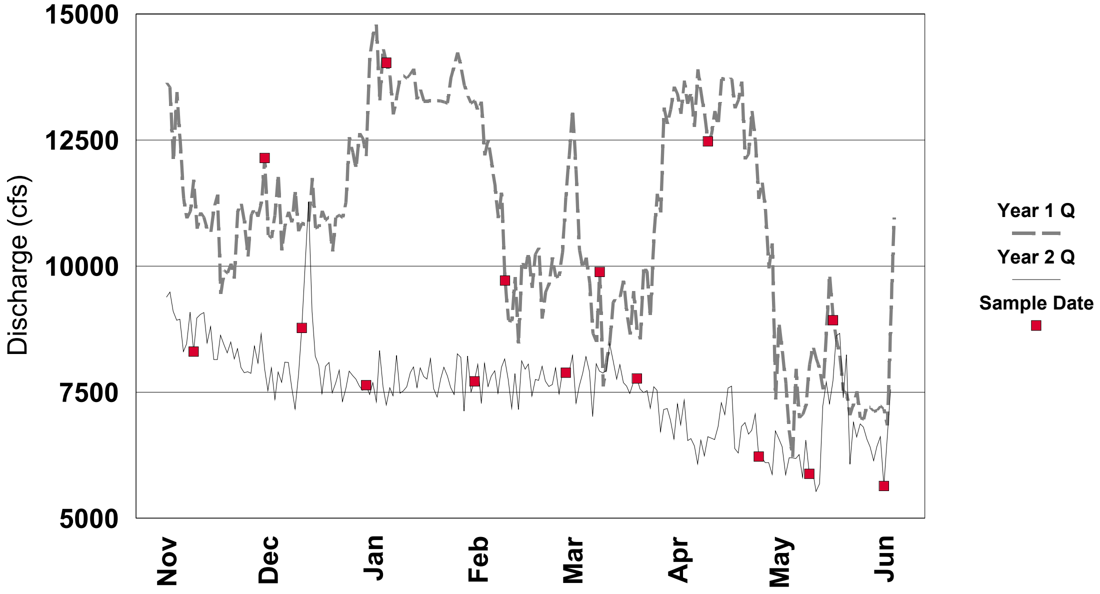


Figure 61. Discharge (Q; cfs) of the Snake River recorded at Murphy gauge during the sampling period of years 1 and 2 artificial redd surveys. Squares on the lines represent individual sampling dates.

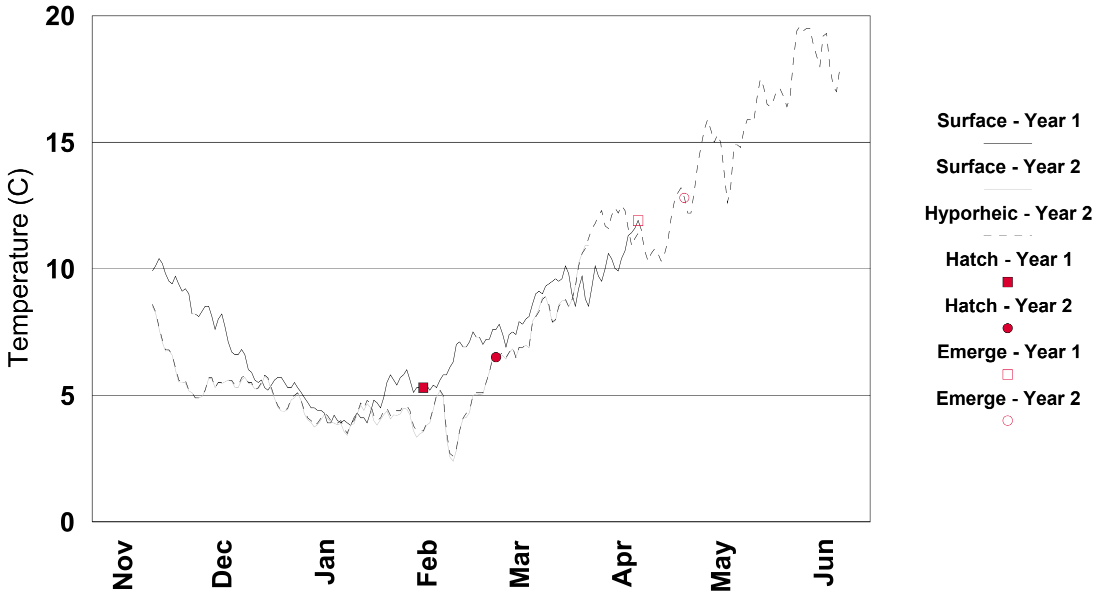


Figure 62. Surface temperatures in degrees Celsius (ºC) for years 1 and 2 and hyporheic temperature during year 2 for the artificial redd surveys. The solid square represents estimated hatch date (500 cumulative thermal units [ctu]), and the open square represents estimated emergence dates (1,000 ctu +5 days) for year 1. Circles represent year 2 hatch and emergence dates.