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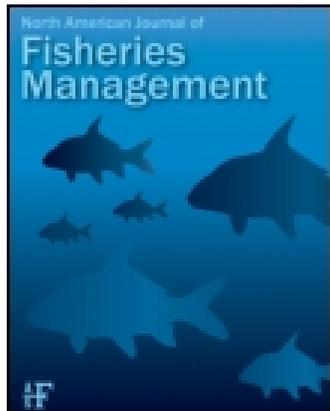
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Physicochemical Characteristics of the Hyporheic Zone Affect Redd Site Selection by Chum Salmon and Fall Chinook Salmon in the Columbia River

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Abstract.—Chum salmon *Oncorhynchus keta* and fall chinook salmon *O. tshawytscha* spawned at separate locations in a side channel near Ives Island, Washington, in the Columbia River downstream of Bonneville Dam. We hypothesized that measurements of water depth, substrate size, and water velocity would not sufficiently explain the separation in spawning areas and began a 2-year investigation of physicochemical characteristics of the hyporheic zone. We found that chum salmon spawned in upwelling water that was significantly warmer than the surrounding river water. In contrast, fall chinook salmon constructed redds at downwelling sites, where there was no difference in temperature between the river and its bed. An understanding of the specific factors affecting chum salmon and fall chinook salmon redd site selection at Ives Island will be useful to resource managers attempting to maximize available salmonid spawning habitat within the constraints imposed by other water resource needs.

Approximately 10–16 million anadromous salmonids returned to the mouth of the Columbia River at the turn of the 19th century; today, only about 2.5 million salmon make the same journey (NWPPC 1986). Historically, chum salmon *Oncorhynchus keta* were the most abundant species of Columbia River salmon, contributing as much as 50% of the total biomass of all salmon in the Pacific Ocean prior to the 1940s (Neave 1961). Chinook salmon *O. tshawytscha* made up the majority of the Columbia River commercial harvest in the late 1800s (Van Hyning 1973). However, by the 1950s, run sizes of chum salmon and fall chinook salmon returning to the Columbia River dropped dramatically, and local populations of both species were listed under the Endangered Species Act (ESA) in the 1990s (NMFS 1999; Battelle's Pacific Northwest Division and U.S. Geological Survey 2000). Habitat degradation, water diversions, harvest, and artificial propagation are the major human-related factors that have contributed to the species' decline (NMFS 1998).

Columbia River chum salmon spawn exclusively in the lower river below Bonneville Dam, whereas fall chinook salmon spawn in main-stem habitats throughout the basin. Both species spawn in a side channel to the Columbia River near Ives Island, downstream of Bonneville Dam. The Ives Island chum salmon are listed as threatened under

the ESA (NMFS 1999). Fall chinook salmon that spawn at Ives Island are not listed under the ESA, but are closely related to runs of listed fall chinook salmon in other parts of the basin, including Snake River fall chinook salmon.

Spawning surveys conducted at Ives Island over the last several years (1998–2001) showed that chum salmon and fall chinook salmon spawned in clusters in separate locations (U.S. Fish and Wildlife Service and Oregon Department of Fish and Wildlife, unpublished data). The presence of redd clusters suggested that fish were selecting specific habitat features within the study area (Geist and Dauble 1998). An understanding of the specific features of these spawning areas would allow quantification of the amount of habitat available to each species, so that minimum flows can be set to protect fish and maintain habitat.

Chum salmon and fall chinook salmon spawn over a wide range of habitat conditions (reviewed in Salo [1991] and Healey [1991]). In general, chum salmon spawn more frequently in low-velocity (10–30 cm/s), shallow streams and side channels and over a wider range of substrates than do other salmon species, particularly fall chinook salmon. Preliminary measurements of water depth, substrate, and velocity at the two species' spawning areas at Ives Island (U.S. Fish and Wildlife Service, unpublished data) fall within the wide range of criteria noted in other chum salmon and fall chinook salmon spawning areas. Thus, it is unlikely that these characteristics alone would ex-

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plain the clustering behavior (Geist and Dauble 1998).

Interchange between groundwater and surface water appears to be important in the selection of redd sites by chum salmon and fall chinook salmon throughout most of their geographic range. Chum salmon in the Kamchatka River, Russia, used temperature to locate spawning sites near groundwater discharge composed of both surface water and groundwater (Leman 1993). Observations of chum salmon spawning areas in the Columbia River system also showed that groundwater upwelling was a common feature of spawning areas (D. Rawding, Washington Department of Fish and Wildlife, personal communication). In addition, fall chinook salmon in the Hanford Reach of the Columbia River selected upwelling areas in preference to non-upwelling areas (Geist 2000). The upwelling of groundwater into potential redd sites presumably provides physical (e.g., temperature and flow) and chemical (e.g., inorganic or organic constituents) cues that salmon species use to locate spawning areas.

Additional information on the interchange of groundwater and surface water at Columbia River chum salmon spawning sites is needed to better define critical habitat (NMFS 1999). We hypothesized that the physical and chemical features of the groundwater–surface water interaction zone (i.e., the hyporheic zone) within salmonid spawning areas at Ives Island would explain species-specific differences in redd site selection between chum salmon and fall chinook salmon. We present the results of a two-year study that was conducted to test this hypothesis.

Study Site

The study area was a side channel between Pierce and Ives islands, located approximately 230 river kilometers (rkm) from the mouth of the Columbia River and 3.5 rkm downstream of Bonneville Dam. Physicochemical characteristics of the hyporheic zone were measured within a 565-m-long and 60-m-wide area (Figure 1). Water surface elevation within the study area was a function of main-stem Columbia River discharge, ocean tides, and the stage of the Willamette River (rkm 162), a Columbia River tributary. Hamilton Creek is a surface tributary that enters the study area but does not appreciably affect surface water elevations there. During the annual study period (mid-October through mid-December), daily average water depths, as recorded on a stage gauge on the north side of Ives Island, were 1.2 m in 1999 (range

= 0.6–2.9 m) and 0.4 m in 2000 (range = 0–1.4 m). Alluvial outwash from Hamilton Creek overlays the study area.

Methods

Spawning surveys.—Fall chinook salmon spawn at the Ives Island study site from mid-October to early December, whereas chum salmon typically spawn from early November to mid-December. Redd locations for both species were provided to us by the Oregon Department of Fish and Wildlife (ODFW). In 1999 and 2000, ODFW personnel conducted twice-weekly surveys within the study area during the fall chinook salmon and chum salmon spawning periods. The position of each new redd was recorded with a global positioning system (GPS) unit (Corvallis Microtechnology, March II). Spawning areas for both species appeared to be relatively constant between the two years.

Piezometer installation and monitoring.—Physicochemical characteristics of the hyporheic zone were measured with piezometers. During October 1999, 13 piezometers were installed within the study site. Each piezometer was constructed of a galvanized steel pipe (4.2-cm outside diameter, 3.5-cm inside diameter) that was screened with 31 cm of Johnson Screen (0.038-cm slot size). The screen was welded on one end to a 12-cm drive point and welded on the other end to a variable length (47, 77, or 108 cm) section of pipe, such that the overall length of each piezometer was either 90, 120, or 151 cm.

Piezometers were placed within the river channel in five clusters of two to six instruments (Figure 1). The river depth at sites where piezometers were installed was usually 1 m or less. Individual piezometers were placed in the riverbed by inserting a solid steel drive rod into the piezometer and manually pounding the piezometer to the desired depth below the riverbed surface (Geist et al. 1998). We attempted to place the top of the piezometer screen at a depth between 30 and 150 cm below the riverbed, which usually resulted in the top of the piezometer protruding above the substrate approximately 3–10 cm. Once the piezometer was in place, the internal drive rod was removed, a standpipe was added to extend the piezometer above the river's surface, and the piezometer was activated by removing fine substrate (<1.0 mm) with a hand pump. The standpipe was removed between sampling periods, and a polyvinyl chloride cap was placed over the top of the piezometer to prevent the entry of sediment. The

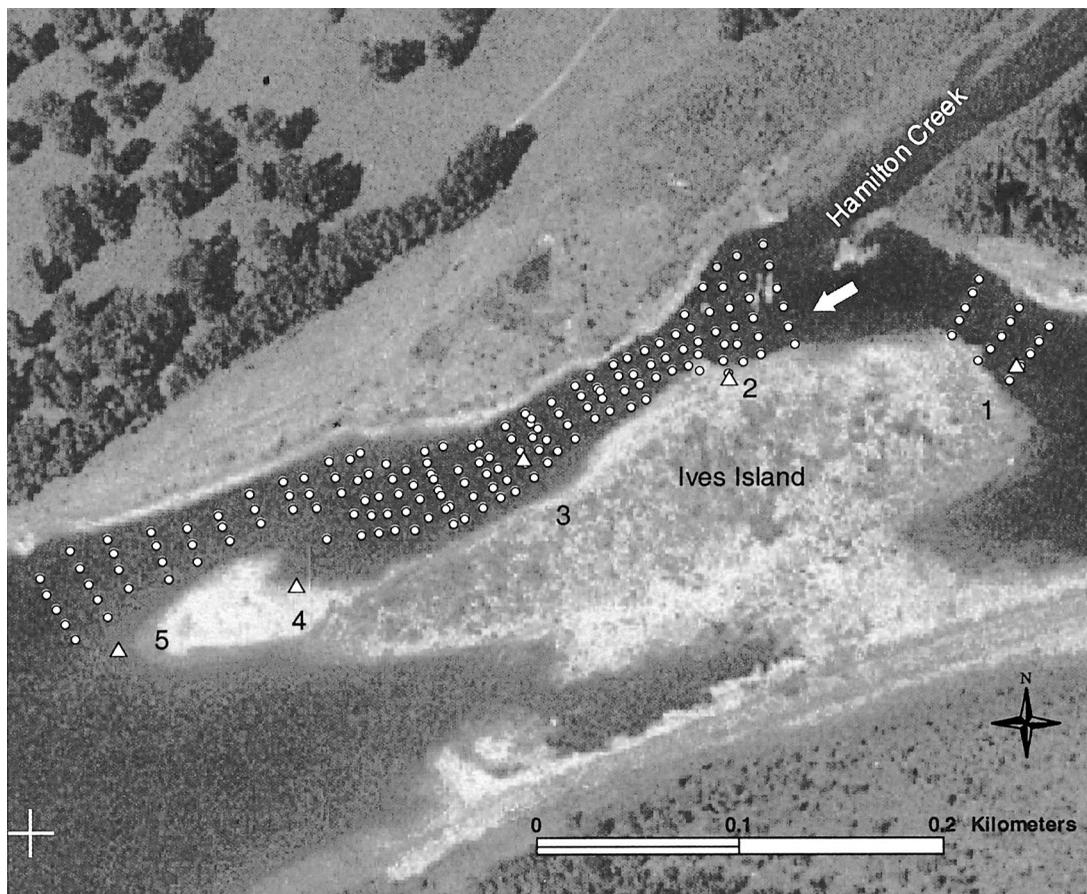


FIGURE 1.—An aerial view of the Ives Island study area in the Columbia River, Washington, showing the 171 temperature measurements (circles) and the five piezometer clusters (triangles). The white arrow indicates the direction of river flow.

horizontal position (resolution < 1 m) of the piezometer was recorded with a GPS (Trimble model Pro-XR).

To collect a sample, we relocated the piezometer with a GPS, uncapped the piezometer, and fitted it with a standpipe to elevate its top above the river surface. The piezometer was purged of at least three volumes of water prior to sampling. Specific conductance ($\mu\text{S}/\text{cm}$ at 25°C), hydraulic head (cm), dissolved oxygen (DO; mg/L), and water temperature ($^\circ\text{C}$) were sampled from the hyporheic water in the piezometer. The physicochemical parameters were also measured on a river sample taken in the area contiguous to the piezometer. The differences in temperature, dissolved oxygen, and hydraulic head were based on the piezometer reading minus the reading from its contiguous river sample. Piezometer clusters were sampled three times during October and November 1999, but

some individual piezometers were sampled only once. Water temperature and specific conductance were measured with a temperature and conductivity meter (Yellow Springs Instruments [YSI] model 30), and dissolved oxygen was sampled with a DO meter (YSI model 95). Hydraulic head measurements were taken from the top of the piezometer with an electrical interface measuring tape (Solinst). The hydraulic head measurements were used to calculate the vertical hydraulic gradient (VHG) for each piezometer, as

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

where Δh is the hydraulic head inside the piezometer minus the hydraulic head of the river (cm), and L (cm) is the distance below the riverbed to the top of the piezometer perforations. The VHG

is a unitless index, with positive values indicating an energy gradient sufficient to produce upwelling (i.e., hyporheic discharge zones) and negative values indicating a gradient sufficient to produce downwelling (i.e., hyporheic recharge zones; Freeze and Cherry 1979; Dahm and Valett 1996).

River and riverbed temperature.—Water temperatures of the river and riverbed were mapped over 4 d in December 2000. A total of 37 transects were spaced 10–20 m apart throughout the study site (Figure 1), for a total of 171 sampling locations. At points spaced approximately every 10 m along each transect, a post pounder was used to drive a customized temperature probe 10 cm into the riverbed. Each probe consisted of a length (125 or 155 cm) of GeoProbe drive rod (2.5-cm outside diameter, 1.8-cm inside diameter) with a threaded drive point attached to the bottom and a slotted drive cap attached to the top. The bottom 20 cm of the drive rod was perforated with approximately 30 holes (3-mm diameter), which allowed water to enter the rod and contact a thermistor (Omega). The thermistor was soldered to copper extension wire encased within polyethylene tubing (0.5-cm inside diameter). The slotted drive cap allowed the extension wire to exit the rod and attach to the temperature indicator (Omega model 450 ATH). Both the thermistor and temperature indicator had a stated accuracy of 0.15°C. Once the thermistor equilibrated (2–4 min), the water temperature of the riverbed was recorded. The rod was then extracted from the riverbed, and a measurement of river temperature was taken. Finally, a real-time GPS was used to acquire the universal transverse mercator coordinates of each measurement point.

Data analysis.—Physicochemical data collected from the piezometers in 1999 were plotted and inspected for normality and equal variances. Differences in physicochemical data of the hyporheic and surface waters were tested with analysis of variance and regression ($\alpha = 0.05$).

Ordinary kriging (Isaaks and Srivastava 1989) was used to interpolate the temperature probe data collected in 2000 (from the river and 10 cm below the surface of the riverbed) onto a regular grid. A geostatistical method based on a generalized form of linear regression, ordinary kriging allows one to incorporate an explicit model of a variable's spatial variability in the interpolation process. Variogram analysis (Isaaks and Srivastava 1989) provides a method for estimating and fitting a model to the spatial variability of random variables. Because of the directionality of the spatial variability of both riverbed and river temperature data found

during the variogram modeling, we applied an elliptical search pattern with radii of approximately 80 m along the river and approximately 40 m across the river in the kriging interpolation.

Cumulative distribution functions (CDFs) were calculated separately for the global temperature data of the river and riverbed. Because the sampled temperature measurements were taken on a regular grid throughout the study area, they provided unbiased estimates of the global CDFs of the river and riverbed temperatures. The temperatures at the redd locations of chum salmon and fall chinook salmon were obtained from the nearest nodes in the temperature grids estimated from kriging, and in all cases, the nearest grid nodes were less than 2 m from individual redds. The differences between the CDFs for the redd temperatures of the two species and the CDFs for the global temperature measurements were tested with two-sample Kolmogorov–Smirnov (K–S) tests (Zar 1999). The K–S statistic tests whether two sample distributions come from the same distribution, by comparing the size of the maximum difference between two CDFs.

Results

1999 Piezometer Data

No differences in specific conductance of the river and the riverbed were found for any of the piezometer clusters ($P = 0.36$; Table 1). Dissolved oxygen concentration of the river was significantly higher than that of the riverbed ($P < 0.001$) at all piezometer clusters, with the DO concentrations in the riverbed steadily decreasing from cluster 1 (10.8 mg/L) to cluster 5 (0.9 mg/L). **The most significant downwelling (i.e., negative VHGs) occurred at piezometer cluster 1 (Table 1), which was located in the vicinity of the spawning area occupied by fall chinook salmon in 1999 and 2000. In contrast, the upwelling was most pronounced (i.e., positive VHGs) at piezometer cluster 3, which was located near the spawning area occupied by chum salmon during both years.** The VHGs at all other clusters were essentially near zero. Water temperature of the riverbed was significantly different than the river ($P = 0.01$), based on measurements from the piezometers in 1999. The riverbed temperature averaged almost 7°C warmer than the river at cluster 3, but was cooler than the river at all other clusters (Table 1).

2000 Temperature Probe Data

Temperature mapping in 2000 showed that the riverbed temperature tended to be significantly

TABLE 1.—Mean values (SEs in parentheses) of specific conductance, temperature, dissolved oxygen, and water level data collected from the river and piezometer clusters (riverbed) at the Ives Island study site in the Columbia River during October and November 1999. Piezometers were installed 48.1 cm (SE = 12.1 cm) below the riverbed at cluster 1, 56.8 cm (SE = 17.2 cm) at cluster 2, 70.2 cm (SE = 9.9 cm) at cluster 3, 56.1 cm (SE = 17.2 cm) at cluster 4, and 72.6 cm (SE = 14.0 cm) at cluster 5.

Variable	Piezometer cluster				
	1	2	3	4	5
Number of times sampled	4	2	6	2	3
Specific conductance ($\mu\text{S}/\text{cm}$)					
River	144.2 (4.3)	151.9 (6.1)	141.6 (3.5)	152.4 (6.1)	150.8 (5.0)
Riverbed	146.7 (3.6)	144.0 (5.1)	131.5 (3.0)	135.3 (5.1)	163.9 (4.2)
Riverbed–river	2.6 (4.9)	–7.9 (6.9)	–0.1 (4.0)	–17.1 (6.9)	13.1 (5.6)
Temperature ($^{\circ}\text{C}$)					
River	11.8 (0.3)	11.7 (0.4)	11.1 (0.2)	11.8 (0.4)	11.8 (0.3)
Riverbed	11.6 (0.2)	10.9 (0.3)	17.8 (0.2)	11.6 (0.3)	11.1 (0.2)
Riverbed–river	–0.2 (0.4)	–0.9 (0.6)	6.7 (0.3)	–0.3 (0.6)	–0.7 (0.5)
Dissolved oxygen (mg/L)					
River	11.6 (0.4)	10.6 (0.6)	11.2 (0.4)	10.7 (0.6)	10.3 (0.5)
Riverbed	10.8 (0.6)	8.9 (0.9)	5.7 (0.5)	4.0 (0.9)	0.9 (0.7)
Riverbed–river	–0.8 (0.5)	–1.7 (0.7)	–5.5 (0.4)	–6.7 (0.7)	–9.4 (0.6)
Water level					
Riverbed–river (cm)	–2.5 (0.6)	–1.0 (0.8)	1.0 (0.5)	0.1 (0.8)	0.2 (0.7)
Vertical hydraulic gradient (cm/cm)	–0.05 (0.01)	–0.01 (0.01)	0.02 (0.01)	0.002 (0.01)	–0.002 (0.01)

warmer and more variable than river temperatures ($P < 0.001$), with a mean riverbed temperature of 8.7°C (SD = 2.2°C) and a mean river temperature of 5.7°C (SD = 0.5°C). The river and riverbed temperatures for the 109 chum salmon and 51 chinook salmon redds were estimated from the temperature of the nearest grid node in the kriging grids. The distribution of river temperatures at the locations of the chum salmon redds did not differ from the global distribution of river temperatures (K–S = 0.135; $P = 0.18$; Figure 2a). In contrast, chinook salmon redds were located in places where river temperatures were significantly warmer than the global distribution (K–S = 0.526; $P < 0.001$), with 80% of the redds associated with river temperatures between 6°C and 6.5°C (Figures 2a, 3a). Chum salmon constructed redds at sites where the distribution of riverbed temperatures was significantly warmer than the distribution of global riverbed temperatures (K–S = 0.445; $P < 0.001$), whereas the distribution of riverbed temperatures at locations of chinook salmon redds was significantly cooler than the global distribution (K–S = 0.539; $P < 0.001$; Figures 2b, 3b). Chum salmon situated their redds in areas where the riverbed temperatures were warmer than the river temperatures, whereas chinook salmon redds were located in areas where the riverbed temperatures were cooler than the river temperatures (Figure 2c, 3c). In both cases, the cumulative distribution of the difference between the riverbed and river temperatures (delta temperatures) associated with the

redds was significantly different from the sample delta temperatures (K–S = 0.560 for chinook salmon, 0.445 for chum salmon; $P < 0.001$ for both).

Discussion

Consistent with observations in previous years, chum salmon and chinook salmon spawned in separate locations near Ives Island in 1999 and 2000. The physicochemical characteristics of the hyporheic zone measured in 1999 were significantly different between the spawning areas of the two species. Chum salmon spawned in areas where relatively warm water from the hyporheic zone upwelled into the river. This was indicated by the predominance of redds at sites where VHGs between the riverbed and river were positive, and riverbed temperatures were $7\text{--}11^{\circ}\text{C}$ warmer than the river temperatures. In contrast, chinook salmon spawned in areas where river water downwelled into the bed, as indicated by negative VHGs between the riverbed and river, and similar DO concentrations and temperatures between the riverbed and river.

Our measurements of specific conductance were very similar between the river and the riverbed, suggesting that the water within the hyporheic zone at Ives Island originated predominantly from the river. Water originating solely from upland (i.e., phreatic) locations would have had elevated specific conductance relative to the river due to extended contact with inorganic constituents of the

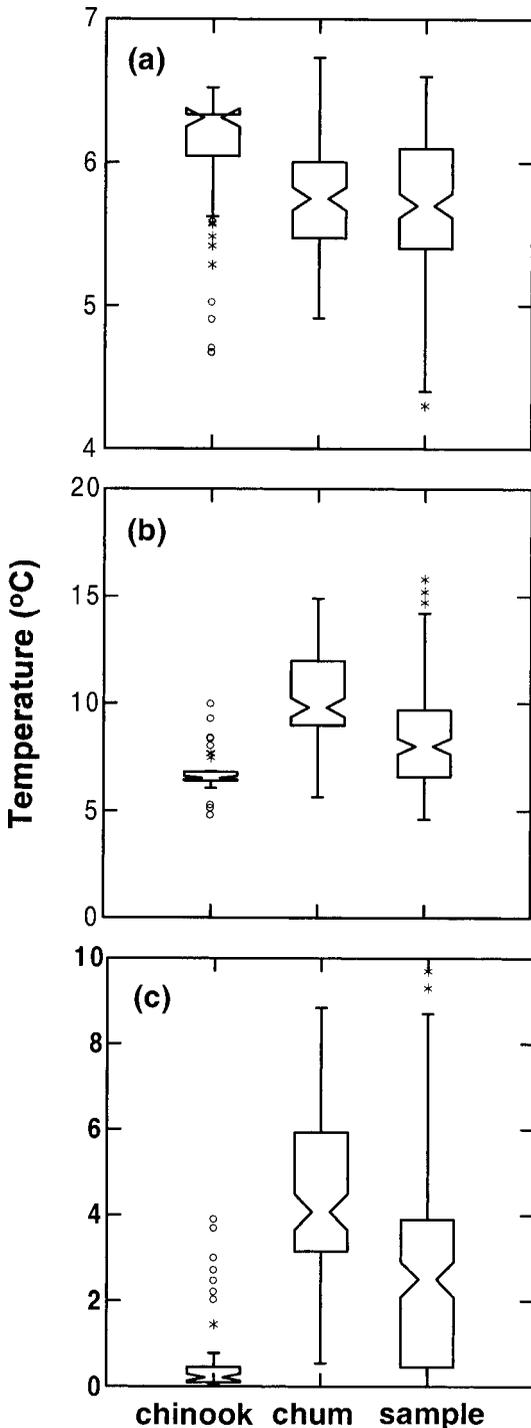


FIGURE 2.—Box plots of sample temperatures and estimated temperatures at the locations of chinook salmon and chum salmon redds: (a) river temperature, (b) riverbed temperature, and (c) delta temperature (riverbed less river). The medians of the distributions are shown as the centers of the notches and the lower and upper

soil (Freeze and Cherry 1979). Longitudinal variation in VHGs and DO levels within the study site suggested that geomorphic riverbed features of the channel (e.g., islands, gravel bars, and riffles) created hydraulic gradients sufficient to direct surface water into the riverbed at the upstream end of the study area, only to reemerge near cluster 3 (Vaux 1962, 1968; White 1993). However, downwelling and upwelling at the spatial scale of the study site would likely not explain the differences in temperatures we observed between the riverbed and the river.

We theorize that most of the water within the floodplain aquifer at Ives Island originated from the pool behind Bonneville Dam. This would explain the similar specific conductance values between the river and the hyporheic zone, and allow the water enough residence time to be affected by the heat sink of the groundwater system (Freeze and Cherry 1979). Small-scale differences in sediment structure (i.e., bedrock or impermeable layers), geothermal springs, preferential flow pathways, and the presence of Hamilton Creek likely affected how and where this warm groundwater was expressed within the study site. For example, the negative hydraulic head near the upstream end of the study area (cluster 1) could have been due to a riffle created by the alluvial outwash from Hamilton Creek and may have prevented the warm groundwater from entering the riverbed, thereby maintaining riverbed temperatures at or near surface water temperatures. Conversely, the lack of hydraulic head in the pool downstream of the riffle (cluster 3) created a groundwater convergence zone and allowed the warmer groundwater to upwell to the river channel.

The significant difference between the riverbed and delta temperatures associated with chum salmon and chinook salmon redds surveyed in 2000 and the global distribution of temperatures suggests that both species were preferentially selecting their spawning sites over other available locations. Physical or chemical cues arising from the interaction of groundwater and surface water were apparently used by both species to select spawning locations. This result is not surprising, because

quartiles are illustrated as the hinges of the box plots. Asterisks and circles represent outlier data points at 1.5 and 3.0 times the interquartile range, respectively. The notches represent an approximate 95% confidence interval around the median (McGill et al. 1978).

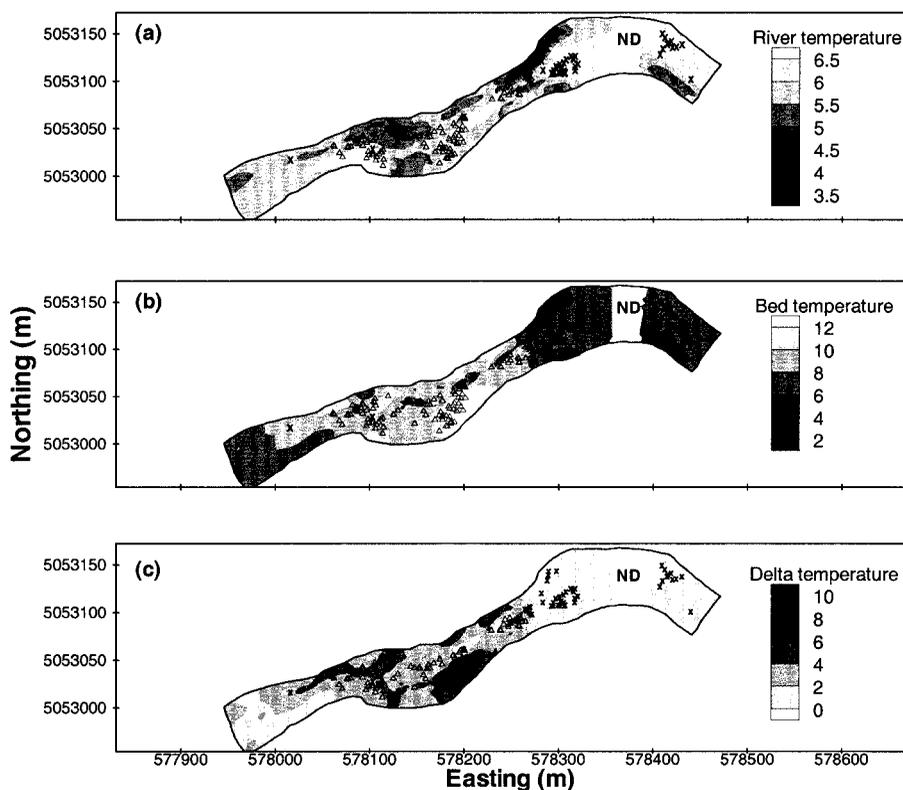


FIGURE 3.—Ordinary kriging estimates of the (a) river temperature, (b) riverbed temperature, and (c) delta temperature (riverbed less river). The chinook salmon redd locations in 2000 ($n = 51$) are shown as crosses and the chum salmon redds ($n = 106$) as triangles. Temperatures in the blank areas of the maps (labeled ND) were not estimated due to insufficient original data. For reference, Hamilton Creek enters the study area from the north at the location labeled ND (see Figure 1).

chum salmon have previously been observed spawning near upwelling sites in areas of low velocity (reviewed in Hale et al. [1985] and Salo [1991]). Other species have also been observed to preferentially select upwelling areas for spawning. Brook trout *Salvelinus fontinalis* preferentially spawned in sandy and silty substrate sites where upwelling was present, rather than using clean gravel in areas where upwelling was absent (Webster and Eiriksdottir 1976; Carline 1980; Witzel and MacCrimmon 1983; Curry and Noakes 1995). Upwelling was found in nearly 60% of the spawning sites of sockeye salmon *O. nerka* in a glacial river where spawning habitat was limited by siltation and substrate compaction (Lorenz and Eiler 1989).

Fall chinook salmon selected upwelling sites in preference to nonupwelling sites in the Hanford Reach (Geist 2000). However, in other locations, fall chinook salmon have preferred to spawn in downwelling areas located at the heads of riffles

(Healey 1991). The conflicting results imply that redd site selection may be based more on water quality characteristics, such as temperature and dissolved oxygen, than on the strength or direction of intergravel flow. **Indeed, fall chinook salmon at Ives Island and the Hanford Reach selected redd sites containing the highest DO concentrations in the river and riverbed, consistent with the high DO requirements for incubating relatively large eggs (Healey 1991).**

Another explanation for the conflicting results might be that redd site selection of fall chinook salmon varies as a function of whether they spawn in sympatry or allopatry with other species. In areas like Ives Island, where two species are sympatric within a small geographic area over an extended length of time, separation of spawning sites is necessary to avoid overlap. If the earlier-arriving fall chinook salmon selected upwelling sites that were also used by the later-arriving chum salmon, they would risk disturbance of their eggs by chum

spawning. The dislodgement of eggs from the protective environment of the redd would result in reduced incubation success of the fall chinook salmon embryos. However, in areas where fall chinook salmon do not spawn in sympatry with another species (e.g., Hanford Reach), the selection of spawning sites containing upwelling may be preferable.

The preference of either species to spawn in areas of upwelling potentially increases incubation success. Warm hyporheic discharge provides benefits to developing embryos by protecting the eggs from freezing and hastening incubation (Curry et al. 1995). Earlier emergence may be beneficial if food is limited later in the season, when more competition from other species is higher or when river flows are higher. Thus, a selective advantage may exist for chum salmon that spawn in hyporheic discharge areas. The temperature gradient observed during the chum salmon spawning period in 1999 and 2000 has also been observed during other times of the year (Pacific Northwest National Laboratory, unpublished data).

Increased understanding of the specific features of salmon spawning sites is critical for providing management agencies with the information they need to develop recovery plans for ESA-listed species. The selection of upwelling sites by spawning chum salmon will likely affect the discharge patterns and minimum flow requirements established for the Ives Island study area. The incorporation of measures of groundwater–surface water interactions into current habitat-use models would provide managers with a better definition of chum salmon and fall chinook salmon spawning habitat, thus yielding better predictions of recovery potential and more efficient use of limited recovery funding.

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