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PHYSICOCHEMICAL CHARACTERISTICS OF THE HYPORHEIC ZONE AFFECT REDD SITE SELECTION OF CHUM AND FALL CHINOOK SALMON COLUMBIA RIVER, 2001

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Physicochemical characteristics of the hyporheic zone affect redd site selection of chum and fall chinook salmon, Columbia River.

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Introduction

Chum salmon (*Oncorhynchus keta*) may historically have been 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 1940's (Neave 1961). By the 1950's, however, run sizes to the Columbia River dropped dramatically and in 1999 the National Marine Fisheries Service (NMFS) listed Columbia River chum salmon as threatened under the Endangered Species Act (ESA; NMFS 1999). Habitat degradation, water diversions, harvest, and artificial propagation are the major human-induced factors that have contributed to the species decline (NMFS 1998).

Columbia River chum salmon spawn exclusively in the lower river below Bonneville Dam, including an area near Ives Island. The Ives Island chum salmon are part of the Columbia River evolutionary significant unit (ESU) for this species, and are included in the ESA listing. In addition to chum salmon, fall chinook salmon (*O. tshawytscha*) also spawn at Ives Island. Spawning surveys conducted at Ives Island over the last several years show that chum and fall chinook salmon spawned in clusters in different locations (US Fish and Wildlife Service and Washington Department of Fish and Wildlife, unpublished data).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). Understanding the specific features of these spawning areas is needed to quantify the amount of habitat available to each species so that minimum flows can be set to protect fish and maintain high quality habitat.

Chum and fall chinook salmon spawn over a wide range of habitat conditions (reviewed in Salo 1991 and Healey 1991). In general, chum spawn more frequently in

low velocity (10 to 30 cm/s) shallow streams and side channels over a wider range of substrates than do other salmon species, especially fall chinook. Preliminary measurements of water depth, substrate, and velocity at the two species' spawning areas at Ives Island (US Fish and Wildlife Service, unpublished data) fall within the wide range of criteria noted in other chum and fall chinook salmon spawning areas. Thus, it is unlikely that these characteristics alone would explain the clustering behavior (Geist and Dauble 1998).

Interchange between ground water and surface water appears to be important in the selection of redd sites by chum and fall chinook salmon throughout most of their geographic range. Chum salmon in the Kamatcha River, Russia, used temperature to locate spawning sites near ground-water discharge composed of both surface and ground water (Leman 1993). Observations of chum salmon spawning areas in the Columbia River system also showed that groundwater upwelling was a common feature in spawning areas (Dan 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 over non upwelling areas (Geist 2000). Upwelling into potential redd sites presumably provides physical (e.g., temperature, flow) and chemical (e.g., inorganic or organic constituents) cues that salmon species use to locate spawning locations.

Additional information on the presence of the interchange of ground water 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 ground water – surface water interaction zone (i.e., hyporheic zone) within the

areas where chum and fall chinook salmon spawned at Ives Island would explain species-specific differences in redd site selection. The purpose of this paper is to present the results of a two year study that was carried out to test this hypothesis. Our findings suggest that chum salmon spawned in upwelling water that was significantly warmer than the surrounding river water. In contrast, fall chinook salmon constructed redds at down-welling sites where there was no difference in temperature between the river and its bed. Understanding the specific features that are important for chum and fall chinook salmon redd site selection at Ives Island will be useful to resource managers attempting to maximize available spawning habitat for these species within the constraints imposed by other water resource needs.

Study site

This study was conducted in a side channel of the Columbia River located between Pierce and Ives islands approximately 3.5 km downstream of Bonneville Dam (Rkm 233.5). Physicochemical characteristics of the hyporheic zone were measured within an area approximately 565 m long and 60 m wide (Figure 1). Water surface elevation within the study area was a function of the discharge in the main Columbia River, ocean tides, and the river flow (stage) of the Willamette River, a tributary to the Columbia River downstream of the study area (Rkm 162). Hamilton Creek is a surface water tributary to the study area but does not appreciably affect surface water elevations within the study area. During the annual study period (mid October through mid December), daily average water depths of the study area as recorded on a stage gage on the north side of Ives Island were 1.2 m in 1999 (range 0.6 to 2.9 m) and 0.4 m in 2000 (range 0 to 1.4 m). The study area is overlain by alluvial outwash from Hamilton Creek.

Fall chinook salmon spawn at the Ives Island study site from mid October to early December, while 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 Department (ODFW). ODFW staff conducted twice-weekly surveys within the study area during the fall chinook salmon spawning period (October 16 to December 4, 2000) and chum salmon spawning period (November 6 to December 18, 2000). The position of each new redd was recorded using a Global Positioning System (GPS) unit (Corvallis Microtechnology, March II).

Methods

Piezometer installation and monitoring

Physicochemical characteristics of the hyporheic zone were measured with the use of piezometers. During October, 1999, 13 piezometers were installed within the study site. Each piezometer was constructed of a galvanized steel pipe (4.2 cm o.d., 3.5 cm i.d.) that was screened with a 31 cm length of Johnson Screen^{TM} (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 the piezometers was either 90, 120, or 151 cm.

Piezometers were placed within the river channel in five clusters of two to six (Figure 1). The water depth of the river where piezometers were installed was usually $\leq$ 1 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). We attempted to place the

top of the piezometer screen at depths between 30 and 150 cm below the riverbed. This usually resulted in the top of the piezometer protruding above the substrate approximately 3 to 10 cm. Once the piezometer was in place, the internal drive-rod was removed, a standpipe was added to extend the piezometer above the water surface of the river, and the piezometer was developed by removing fines (<1.0 mm) with a hand pump. The standpipe was removed between sampling periods and a PVC cap was placed over the top of the piezometer to prevent the entry of sediment. The horizontal position (resolution less than 1 m) of the piezometer was recorded using a GPS (Trimble model Pro-XR).

In order to collect a sample, the piezometer was relocated using a GPS, uncapped, and fitted with a standpipe to elevate the piezometer top above the river level. Piezometers were purged of at least three volumes of water prior to sampling. The piezometers were used to sample specific conductance ($\mu S\ cm^{-1}$ at 25 °C), hydraulic head (h, cm), dissolved oxygen (DO, mg L^{-1}), and water temperature (T, °C) of the hyporheic water. These parameters were also measured on a river sample taken contiguous to the piezometer. The differences in temperature, dissolved oxygen, and hydraulic head were based on the piezometer reading (hyporheic water) minus the reading from its contiguous river sample. Piezometer clusters were sampled 3 times during October and November, 1999, but not all piezometers were sampled more than once. Measurements of water temperature and specific conductance were made with a temperature/conductivity meter (YSI model 30) and DO was sampled with a DO meter (YSI model 95). Hydraulic head measurements were taken from the top of the piezometer using an electrical interface measuring tape (Solinst). The hydraulic head measurements were used to calculate the vertical hydraulic gradient (VHG) for each piezometer:

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

where Δh was the hydraulic head inside the piezometer minus the hydraulic head of the river (cm), and L (cm) was the distance below the river bed to the top of the piezometer perforations. The VHG is a unit-less index with positive values indicative of an energy gradient sufficient to produce upwelling (i.e., hyporheic discharge zones) and negative values indicative of a gradient sufficient to produce down welling (i.e., hyporheic recharge zones) (Freeze and Cherry 1979; Dahm and Valett 1996).

River and bed temperature

Temperatures of the river and bed were mapped over a four day period in December, 2000. A total of 37 transects were spaced 10 to 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 bed. Each probe consisted of a length (125 or 155 cm) of GeoProbe drive rod (2.5 cm o.d., 1.8 cm i.d.) that had a threaded drive point attached to the bottom and a slotted drive cap attached to the top. The bottom 20 cm of the rod was perforated with approximately 30 holes (3 mm dia.) 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 cmi.d). 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 have a stated accuracy of $\pm$ 0.15 C. Once the thermistor equilibrated (2 to 4 minutes), the temperature

of the bed was recorded. The rod was then extracted from the bed and a measurement of river temperature taken. Finally, a real-time GPS was used to acquire the Universal Transverse Mercator (UTM) 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 statistically with analysis of variance (ANOVA) and regression ($\alpha = 0.05$).

Variogram analysis (Isaaks and Srivastava 1989) and geostatistical mapping were used to evaluate the spatial distribution of temperature data (river and 10 cm below the surface of the bed) collected in 2000. To account for curvature of the study area, a commercial software package (Gridgen®) was used to generate orthogonal grids. Temperature measurements were associated with the nearest grid nodes and the variogram modeling was performed on the temperature data using the corresponding orthogonal grid indices as the coordinates. Ordinary kriging (Isaaks and Srivastava 1989) was used to estimate the river and bed temperature throughout the study area on a regular grid in the orthogonal system. The temperature data and variogram models described above were input to the program KT3D of the GSLIB geostatistical subroutine library (Deutsch and Journel 1998) for the kriging estimation. Because of the directionality of the spatial continuity of both bed and river temperature data found during the variogram modeling, we applied an elliptical search pattern with a radius of 20 units along the river (~ 80 m) and 10 units across the river (~ 40 m) in the kriging estimation.

Cumulative distribution functions (CDF's) of the river and bed temperature data were calculated separately for the global temperature data of the river and bed. Because the sampled temperature measurements were taken on a regular grid throughout the study area, they provide unbiased estimates of the global CDFs of the temperature of the river and the bed. The temperatures at the locations of the two species of salmon redds were obtained from the nearest nodes in the orthogonal temperature grids estimated from kriging, and in all cases the nearest grid nodes were less than 2 m from the redd locations. The differences between the CDF's for the two species of redds and for the global CDF for the temperature measurements were tested using 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 CDF's.

Results

Piezometers

There was no difference in specific conductance of the river and the river bed for all piezometer clusters ($p = 0.36$). However, there were significant differences in temperature ($p = 0.01$) and dissolved oxygen ($p < 0.001$) between the bed and river. Water temperature of the river bed averaged almost 7 C warmer than the river at cluster 3, but was cooler than the river at all other clusters (Table 1, Figure 1). Dissolved oxygen concentration of the river was always higher than the river bed, with the concentrations in the bed steadily decreasing from cluster 1 (10.8 mg L^{-1}) to cluster 5 (0.9 mg L^{-1}). VHG was the most negative at piezometer cluster 1 and most positive at piezometer cluster 3 (Table 1, Figure 1). VHG at all other clusters was essentially near zero.

River and bed temperature

There were 171 sample measurements of the river and bed temperature that were evenly distributed across the study area (Figure 1), so that the data provides estimates of the global distributions of those temperatures in the study area. The variability of river temperature data was much less than that of bed temperature (Figure 2a-b). The river temperature ranged from 4.3 to 7.3 C with a standard deviation of 0.5 C, while bed temperature ranged from 4.6 to 15.8 C and had a standard deviation of 2.2 C. Overall, the bed temperature tended to be significantly warmer than river temperatures ($p < 0.001$), with a mean bed temperature of 8.3 C and a mean river temperature of 5.7 C.

Variogram analyses of the temperature data showed that the range of spatial continuity perpendicular to the length of the river was 7.5 and 9 units for river and bed temperatures, respectively. This equated to approximately 30 and 36 m, respectively, in the original coordinates (Figure 3). The range in the direction parallel to the centerline of the river was 16 units for river and bed temperature, or approximately 64 m in the original coordinates. The resulting variogram models were used to design an elliptical search pattern that was employed for the ordinary kriging of the temperature data and as the spatial continuity models input for the kriging itself. Consistent with the variogram models, kriging estimates indicated greater continuity of the bed and river temperatures parallel to the centerline of the river than they were perpendicular to it (Figure 4).

The river and bed temperatures for the 109 chum and 51 chinook salmon redds were estimated from the relevant temperature of the nearest grid node in the kriging grids. The cumulative distribution of river temperatures at the locations of the chum redds was no different than that of the global distribution of river temperatures (KS =

0.135; p = 0.18; Figure 2a). In contrast, chinook redds were located in places where river temperatures were significantly warmer than the global distribution (KS = 0.526; p < 0.001) with 80% of the redds located where river temperatures were between 6 and 6.5 degrees (Figure 2a and 4a). Chum salmon placed redds at sites where the distribution of bed temperatures was significantly warmer than the distribution of global bed temperatures (KS = 0.445; p < 0.001), whereas the distribution of bed temperatures at locations of chinook redds was significantly cooler than the global distribution (KS = 0.539; p < 0.001; Figure 2b and 4b). Chum salmon also placed their redds in areas where the bed temperatures were warmer than the river while chinook salmon redds were located where the bed temperatures were cooler than the river (Figure 2c and 4c). In both cases the cumulative distribution of the delta temperatures (bed – river) associated with the redds was significantly different from the sample delta temperatures (KS = 0.560 and 0.445 for chinook and chum, respectively; p < 0.001 for both).

Discussion

Consistent with previous years, chum and chinook salmon spawned in distinct and separate locations at Ives Island in 2000. The physicochemical characteristics of the hyporheic zone were significantly different between spawning areas for 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 vertical gradients between the bed and river were positive, and bed temperatures were 7 to 11 C warmer than the river. In contrast, chinook salmon spawned in areas where river water downwelled into the bed as indicated by negative vertical gradients between the

bed and river, and similar dissolved oxygen concentrations and temperatures of the bed and river.

Our measurements of specific conductance were very similar between the river and the bed, suggesting that the water within the hyporheic zone at Ives Island originated predominantly from the river. Had the water originated solely from upland (i.e., phreatic) locations, the specific conductance would have been elevated relative to the river due to its extended contact time with inorganic constituents within the soil (Freeze and Cherry 1979). That the vertical gradients and dissolved oxygen levels within the study site varied longitudinally suggested that geomorphic bed features of the channel (e.g., islands, gravel bars, riffles) created hydraulic gradients sufficient to direct surface water into the bed at the upstream end of the study area only to re-emerge near cluster three (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 bed and the river.

We theorize that the majority of water within the floodplain aquifer at Ives Island originated from the pool behind Bonneville Dam 3.5 km upstream. 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 ground water system (Freeze and Cherry 1979). Small scale differences in sediment structure (i.e., bedrock, impermeable layers), geothermal springs, preferential flow pathways, and 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 riffle created by the alluvial outwash

from Hamilton Creek and may have prevented the warm groundwater from entering into the bed, thereby maintaining bed temperatures at or near the temperature of the surface water. 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.

That the bed and delta (bed – river) temperatures associated with both species redds were significantly different than the global distribution of temperatures suggested that chum and chinook were preferentially selecting their spawning sites over other available locations. It appears physical and/or chemical cues arising from the interaction of groundwater and surface water were used by both species to select spawning locations. This is not surprising because 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 also have been observed to preferentially select upwelling areas for spawning. Brook trout (*Salvelinus fontinalis*) will preferentially spawn in sandy and silty substrate sites where upwelling is present, rather than use clean gravel in areas where upwelling is 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 (*O. nerka*) of a glacial river where spawning habitat was limited because of siltation and substrate compaction (Lorenz and Eiler 1989).

Fall chinook salmon selected upwelling sites over non upwelling sites in the Hanford Reach (Geist 2000). However, in other locations fall chinook salmon have shown a preference for spawning in down-welling areas located at the head of riffles (Healey 1991). These observations are consistent with our results, indicating that these

fish may be selecting redd sites based on hydraulic and associated water quality characteristics such as temperature and dissolved oxygen. Indeed, fall chinook salmon selected redd sites containing the highest dissolved oxygen concentrations in the river and the bed, and is consistent with the high dissolved oxygen requirements for incubating their relatively large eggs (Healey 1991).

Warm hyporheic discharge provides benefits to developing embryos by protecting the eggs from freezing, and optimizing incubation and emergence periods (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, there could be a selective advantage for chum to spawn in hyporheic discharge areas. The temperature gradient observed during the chum 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 to provide management agencies the information they need to develop recovery plans for species listed under the ESA. The discharge patterns and minimum flow requirements established for the Ives Island study area will likely be affected by whether chum salmon spawn near upwelling sites. The incorporation of measures of ground water – surface water interactions into current habitat-use models would provide managers a better definition of chum and fall chinook salmon spawning habitat which will likely result in better predictions of recovery potential and more efficient use of limited recovery dollars.

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Table 1. Average values (± standard error in parentheses) of physicochemical data collected from the river and piezometer clusters (bed) installed at Ives Island study site during October through November, 1999.

	Piezometer cluster				
Parameter	1	2	3	4	5
Meas. depth below bed (cm)	48.1 (12.1)	56.8 (17.2)	70.2 (9.9)	56.1 (17.2)	72.6 (14.0)
Sample number	4	2	6	2	3
Specific conductance (uS/cm)					
River	144.2 (4.3)	151.9 (6.1)	141.6 (3.5)	152.4 (6.1)	150.8 (5.0)
Bed	146.7 (3.6)	144.0 (5.1)	131.5 (3.0)	135.3 (5.1)	163.9 (4.2)
Bed – river	2.6 (4.9)	-7.9 (6.9)	-10.1 (4.0)	-17.1 (6.9)	13.1 (5.6)
Temperature (C)					
River	11.8 (0.3)	11.7 (0.4)	11.1 (0.2)	11.8 (0.4)	11.8 (0.3)
Bed	11.6 (0.2)	10.9 (0.3)	17.8 (0.2)	11.6 (0.3)	11.1 (0.2)
Bed – 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)
Bed	10.8 (0.6)	8.9 (0.9)	5.7 (0.5)	4.0 (0.9)	0.9 (0.7)
Bed – river	-0.8 (0.5)	-1.7 (0.7)	-5.5 (0.4)	-6.7 (0.7)	-9.4 (0.6)
Water level					
Bed – river (cm)	-2.5 (0.6)	-1.0 (0.8)	1.0 (0.5)	0.1 (0.8)	0.2 (0.7)
VHG (cm/cm)	-0.05 (0.01)	-0.01 (0.01)	0.02 (0.01)	0.002 (0.01)	-0.002 (0.01)

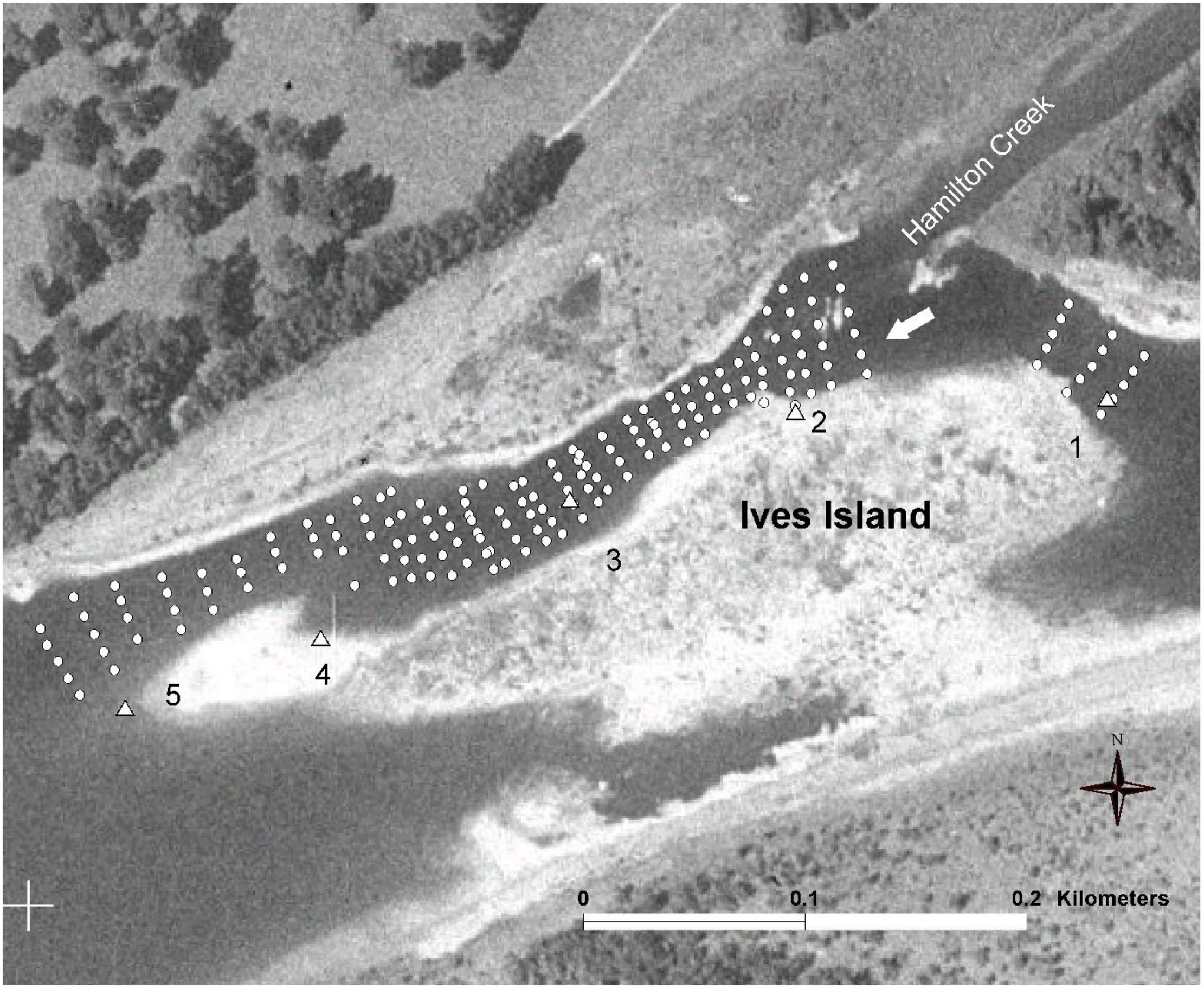
Figure captions

Figure 1: An aerial view of the Ives Island study area showing the locations of temperature measurements (circles) and the five piezometer clusters (triangles). Direction of river flow is indicated by the white arrow.

Figure 2: Box plots of sample temperature and estimated temperatures at the locations of chinook salmon and chum salmon redds: (a) river temperature, (b) bed temperature, and (c) delta temperature (bed-river). The medians of the distributions are shown as the center of the notches, and the lower and upper quartiles as the hinges of the box plots. The notches themselves represent an approximate 95% confidence interval around the median, so that if the notches for two box plots do not overlap, then the difference between the medians of the two samples is significant at the 95% confidence level (McGill et al. 1978). Asterisks and circles represent outlier data points at 1.5 and 3.0 times the inter-quartile range, respectively.

Figure 3: Variograms and models of measured temperatures of the (a) river and (b) bed. The variogram in the direction perpendicular to the river is plotted using a cross with the model shown by dash line, while the variogram parallel to the river is shown with diamonds with the model a solid line.

Figure 4: Ordinary kriging estimates of the temperature of the (a) river, (b) bed, and (c) delta (bed - river). The locations of chinook salmon redds (n=51) are shown with crosses and chum salmon redds (n=106) shown by triangles. The blank area in the temperature maps (labeled ND) was not estimated due to insufficient original data.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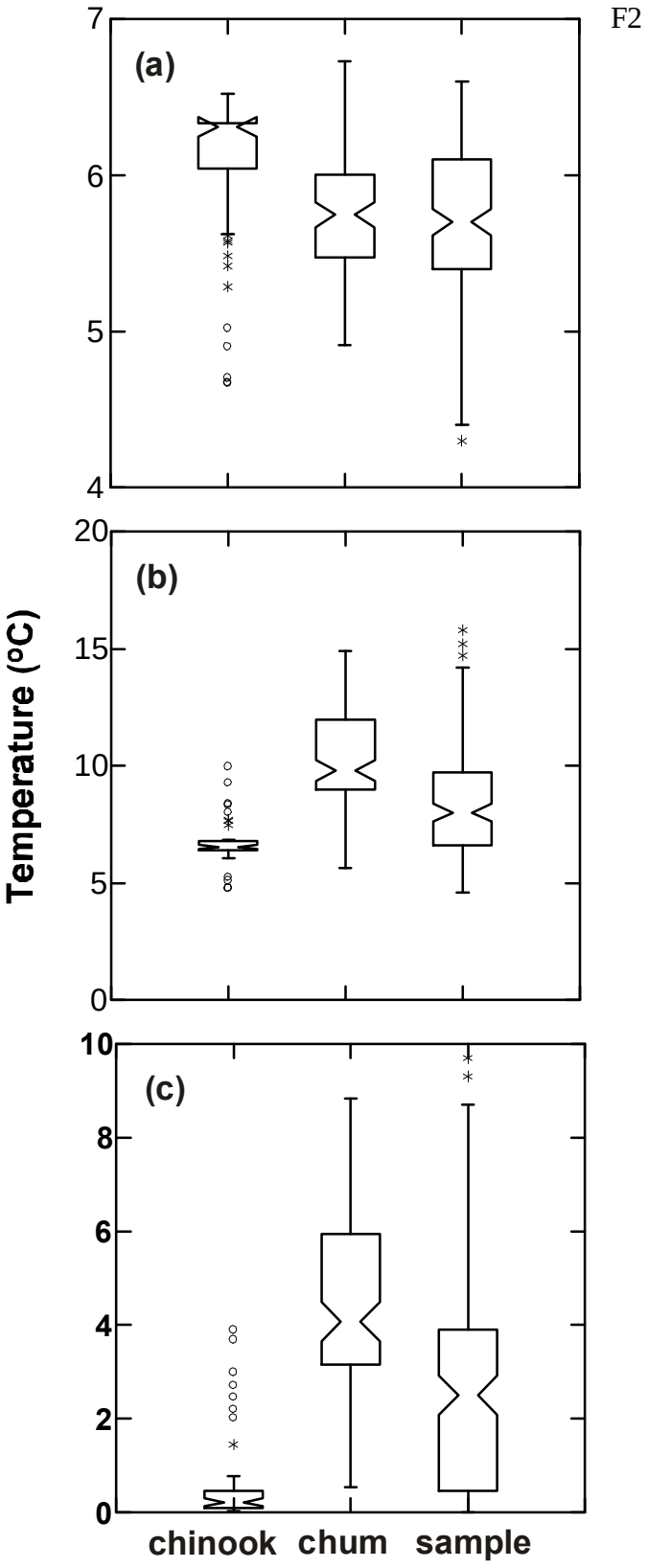
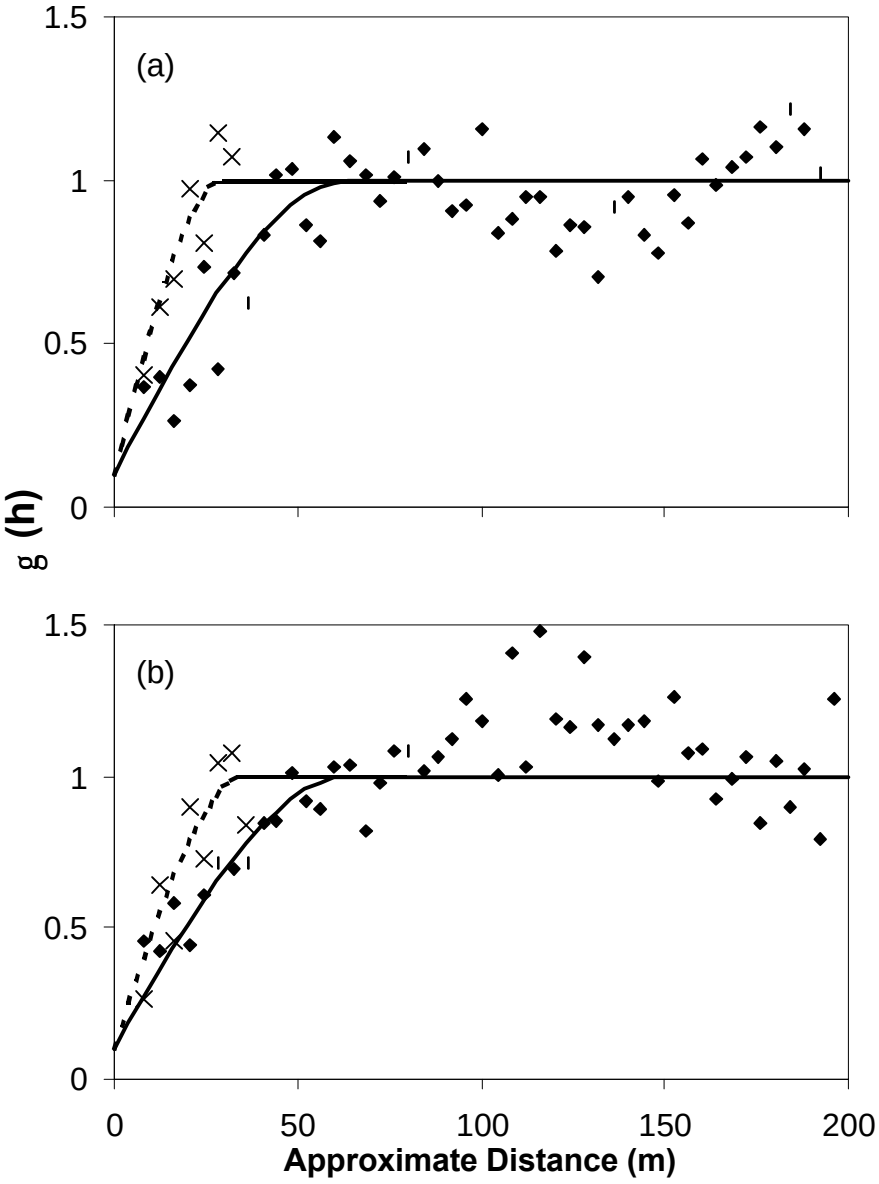
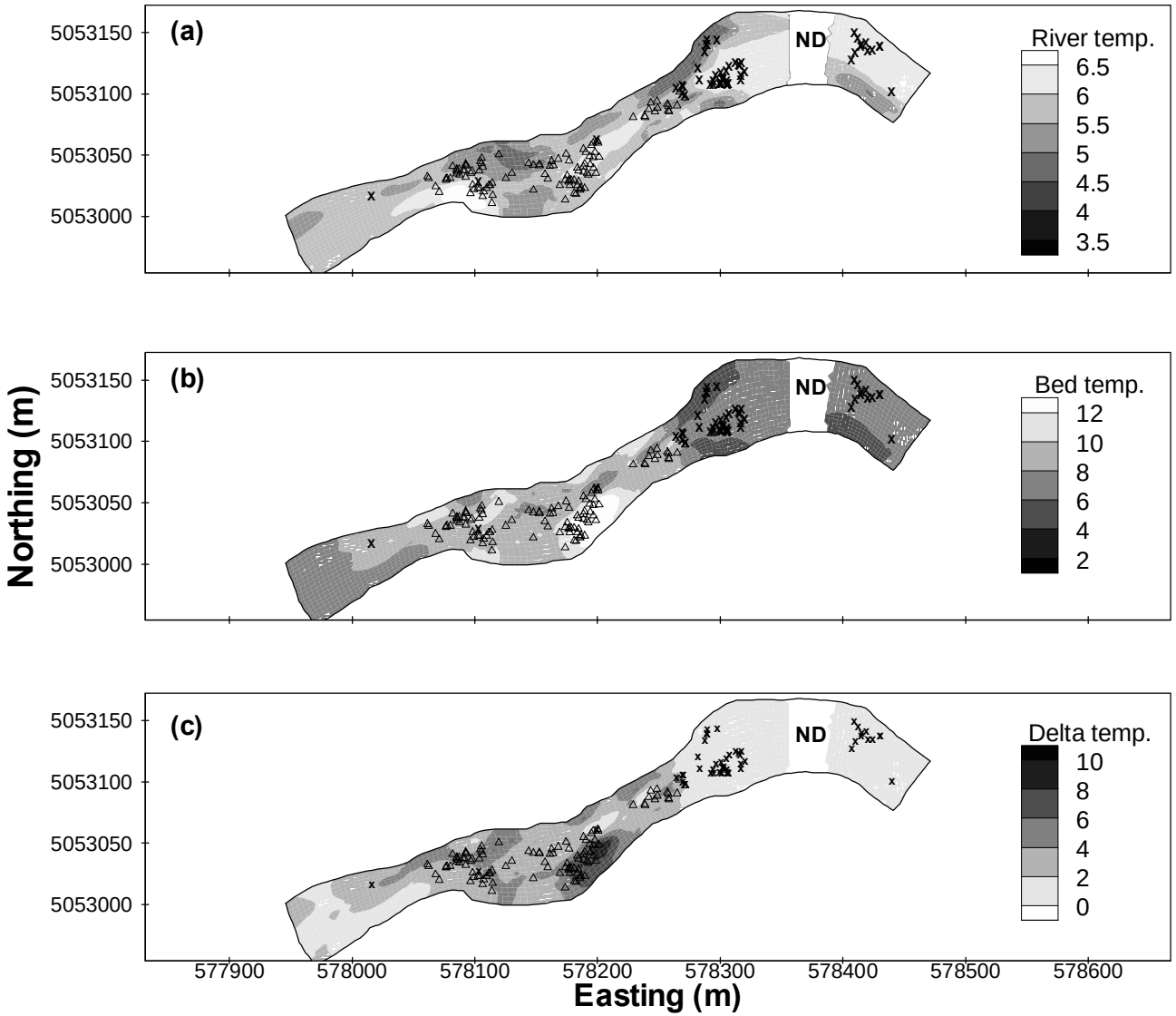
0.2 Kilometers

F2





F3


(a)
ND
River temp.
6.5
6
5.5
5
4.5
4
3.5
(b)
ND
Bed temp.
12
10
8
6
4
2
(c)
ND
Delta temp.
10
8
6
4
2
0
5053150
5053100
5053050
5053000
Northing (m)
577900
578000
578100
578200
578300
578400
578500
578600
Easting (m)

F4