Aerial redd count validation for improving fall Chinook salmon abundance estimates in the Deschutes River, Oregon

Final Report

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Abstract

Aerial and boat redd counts for fall Chinook in three Deschutes River reaches were compared with best estimates of true redd counts, considered a census. Fall Chinook census surveys recorded redd accumulation during the spawning period from mid-October 2007 through mid-January 2008. First fall Chinook redds were observed in mid-October 2007. All redds, except for two, were constructed by mid-December 2007. Increases in redds through the spawning period was associated with three-day minimum water temperature and two-day change in river discharge. On average, aerial counts at 64 km• h^{-1} were 14% of the true number of redds, while aerial counts at 32 km• h^{-1} were 27% of the true number of redds according to census counts in three reaches. On average, boat observers counted 55% of the true redds identified by census observers in the upper two reaches, Jackson and Smith. Effects, direction of bias, and magnitude of the errors are unknown but are being distributed in the fall Chinook escapement estimates (in basin, Columbia Basin, and ocean harvest). Authors advance recommendations to improve the accuracy of fall Chinook redd counts in the Deschutes River by: improving observer precision; measuring error so an adjustment can be developed; stratifying reaches according to physical obstacles to visibility (*e.g.*, turbidity, depth, turbulence, terrestrial/aquatic cover) to reduce variance; and evaluating the best method (aerial or boat counts) for calculating estimates by reach.

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Introduction

Fall Chinook (*Oncorhynchus tshawytscha)* redds have been counted by aerial survey since 1977 (Jason Seals, Assistant Fish Biologist, ODFW, pers. comm.) and are used, in part, for population estimates in the basin. Deschutes River fall Chinook salmon are harvested in sport and commercial fisheries in the ocean and Columbia River Basin (CRB), they are a popular non-tribal recreational fishery in the Deschutes River, and provide an important subsistence fishery for the Confederated Tribes of the Warm Springs Reservation of Oregon (CTWSRO). This salmon population is one of three escapement indicator stocks used by the United States Chinook Technical Committee (USCTC) to monitor effectiveness of the U.S. – Canada Treaty to set harvest limits on wild Columbia River upriver bright fall Chinook salmon. The CTWSRO and Oregon Department of Fish and Wildlife (ODFW) co-manage salmon populations in the Deschutes River.

Escapement of Deschutes River fall Chinook salmon is estimated using data from two sources: 1) aerial redd counts from the mouth to Sherars Falls and Sherars Falls to Pelton-Round Butte Hydroelectric Project at river kilometer [rkm] 161 and 2) fish marked at an adult fish trap at Sherars Falls (rkm 71) are recaptured through multiple types of second event samples. Fall Chinook that ascend Sherars Falls are recovered during carcass surveys at the end of the spawning season (November - January), during tribal and recreational harvest, and at the Pelton adult fish trap (rkm 161) from mid-October through January. Marked and unmarked fish are recorded and a population estimate is made for the 'upper river', above Sherars Falls. Spawner escapement below Sherars Falls is estimated by multiplying the number of Chinook above Shears Falls to the ratio of redds below to redds above the falls. The following formula is used by ODFW to estimate escapement of fall Chinook below Sherars Falls:

$$N_{\text{Below Sherars}} = N_{\text{Above Sherars}} \left(\frac{\text{Redds Below Sherars}}{\text{Redds Above Sherars}} \right)$$

An alternative method for this calculation, which yields the same result, is multiplying the estimated abundance of fall Chinook above Sherars Falls to the number of redds counted above Sherars Falls, yielding fall Chinook-per-redd above Sherars Falls. The number of fall Chinook-per-redd is then applied to the number of redds counted below Sherars Falls during the aerial survey, yielding the abundance of fall Chinook below Sherars Falls, referred to as the 'lower river'.

Spawner escapement above and below Sherars Falls, are added together to estimate total Deschutes River escapement. Estimated harvest from creel census is added to the spawner escapement estimate yielding a total run estimate to the Deschutes River. The fall Chinook escapement estimate is reported to the USCTC and Technical Advisory Committee (TAC) to the United States v. Oregon case. These estimates are then used to estimate run size and set harvest regulations in international waters and in the CRB.

There are important management implications for correctly assessing the number of fall Chinook redds in the Deschutes River. The concern with the current methodology is that the expansion factor, calculated in the upper river, used to estimate escapement in the lower river, is incorrect. This is due to the assumption that redds counted in aerial surveys represent the correct proportion of redds above and below Sherars Falls or alternatively, that fall Chinook-per-redd above Sherars Falls is equal to fall Chinook-per-redd below Sherars Falls. ODFW acknowledges the assumption that "redd counts are consistent throughout the 100 miles surveyed" (unpublished report) for which the authors interpret to mean all redds have an equal probability of detection. This is an important point because if redds do not have an equal probability of detection in the upper and lower river, due to water depth, turbulence, topography, or other factors, then the ratio may be erroneous and the population estimate incorrect. Management decisions based on faulty data may lead to overharvest.

Despite reliance on escapement estimates from redd counts by harvest managers, uncertainties in observed counts has not been documented bringing the validity of using redd counts for inferring population status into question. CTWSRO acknowledges accurate escapement estimates are needed to manage fall Chinook salmon in the Deschutes River effectively. However, observer error structure (*sensu* Muhlfeld et al. 2006) has not been explored and adjustments in counts have not been made to more accurately estimate the true number of redds. To begin to examine error, or to describe bias in aerial redd counts, we chose three index reaches and intensively surveyed fall Chinook redds through the spawning season, from October 2007 through mid-January 2008. Redds were observed by boat, walking the bank, or wading. This intensive redd survey is our best estimate of the true number of fall Chinook redds. We use these counts as a census from which we compare aerial redd counts and a less intensive redd count by boat at the end of the spawning season. We describe spatial and temporal distributions of fall Chinook in three index reaches in the Deschutes River and examine redd counts by reach and sub-reach in conjunction with habitat measurement. This information will be used to propose recommendations for improving the current method of conducting redd surveys and inferring population abundance of fall Chinook in the Deschutes River.

Study Site

The lower Deschutes River Subbasin (hydrologic unit code 17070306) is located in north-central Oregon, flowing northerly from Pelton-Round Butte Hydroelectric Project at rkm 161 to its confluence with the Columbia River (Figure 1). A series of hydroelectric dams begin at rkm 161. Currently, no fish passage is available at these facilities terminating fall Chinook distribution prematurely.

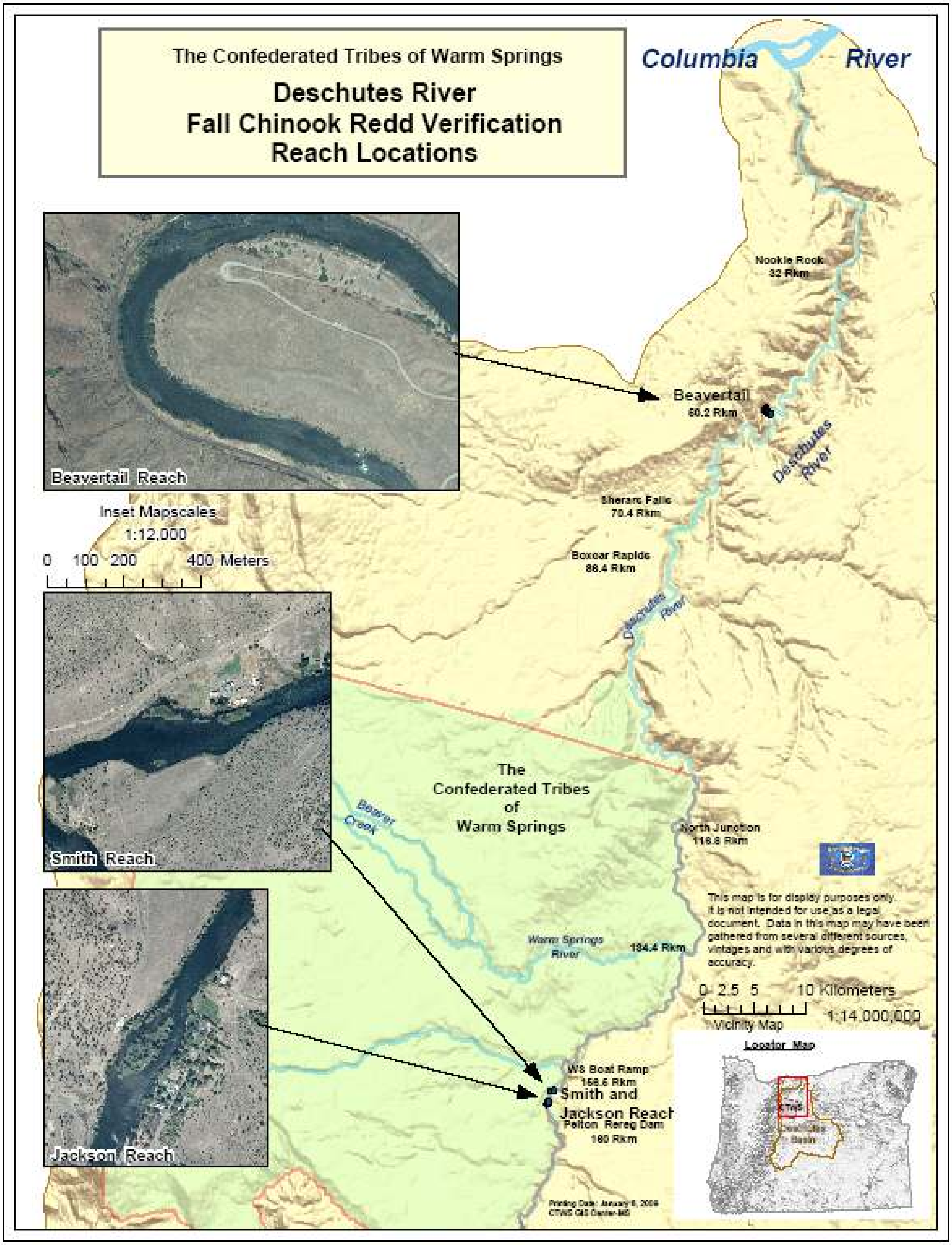


Figure 1. Vicinity map of the Deschutes River from the mouth to Pelton Dam.

The lower Deschutes River drains about 6,993 km^2, with 1,223 km of perennial streams and 2,317 km of intermittent streams. Most of headwaters within the basin are located on the eastern slope of the Cascade Mountain Range. West side tributaries to the lower Deschutes are largely spring-fed with stable base flows except during snowmelt. However, White River enters the Deschutes River at rkm 74.9 and is glacially fed. During periods of inclement weather, large amounts of glacial flour can be transported via White River and decrease visibility in the Deschutes River for periods ranging from hours to several days. Eastside tributaries drain the Ochoco Mountains, with flow dominated by snow melt and precipitation. Winter high flows are a result of rain-on-snow events and low levels of precipitation during summer months result in intermittent flows (O'Connor et al. 2003).

Index reach selection

Index reaches were selected based on past records of fall Chinook salmon redd densities, physical characteristics and logistics (given a short window of optimal visibility, can the reach be floated and allow observers to count all redds). We selected three index reaches for this study (rkm is upper extent): Jackson (rkm 160), Smith (rkm 159), and Beavertail (rkm 50.2) reaches (Figure 1). Within each reach, subsections were demarcated, based on morphology or similar lengths to facilitate counting redds.

Jackson and Smith reaches are upstream of Sherars Falls and are characterized by multiple islands and braided channels in an open floodplain. Side channels are narrow (~10 - 20 m) in the upper portions of both reaches with the main channel > 50 m. Beavertail reach, is constrained by rim-rock lined canyon walls and basalt cliffs. Is located downstream of Sherars Falls and the confluence with the White River (rkm75).

Methods

Accumulation of fall Chinook redds over the spawning season in three index reaches

Redd accumulation was tracked during the fall Chinook spawning season in three index reaches on the Deschutes River beginning mid-October 2007 and ending mid-January 2008. Counts from the redd accumulation study (census counts) were best estimates with error minimized by frequent observations of adult fall Chinook constructing and/or occupying redds (Dunham et al. 2001). Familiarity with channel features and redd development in each reach also allowed us an added level of confidence. Census counts are used for comparison with boat and aerial survey redd counts at the end of the spawning period.

A pre-spawning survey was conducted to map all old and false redds present at the beginning of the spawning season. To distinguish these features from newly constructed salmon redds for subsequent surveys during the study, maps included all completed redds and other redd-like features, which developed into a cumulative map of all redds (McGrath et al. 2007). When a redd, or redd-like feature was located, it was recorded on the map. All features from start to finish were recorded on every survey date. If a redd straddled two subsections, it was counted in the upstream subsection (McGrath et al. 2007).

Crews counted redds from a drift boat in the three index reaches every three to five days during the spawning season from October 18, 2007 through January 14, 2008. Surveys were conducted four days per week (twice at Beavertail and twice at Jackson and Smith reaches) weather permitting or barring equipment failure. Redd counts were conducted between 10 am and 3 pm. Census observers used a 4.9 m (16 foot) aluminum drift boat with a propeller-driven 15 hp motor. The boat was fitted with a custom-designed viewing platform on the bow. Four possible methods were employed to optimize visibility of redds: 1) walking the bank; 2) wading the river; 3) observing from the platform while the oarsman walked the boat down the river; and 4) observing from the platform while the oarsman either rowed the boat downstream or ran the motor, in a back-trolling fashion, slowly backing the boat downstream (McGrath et al. 2007). Polarized sunglasses were worn to improve redd visibility.

The same observers recorded redds together throughout the study. They had three and 25 years experience counting redds. Redds were counted by consensus between the two observers; once a potential redd was observed they would declare their opinion on its condition (true, false, in progress, test and redds from previous years), come to an agreement, then record the result and map the location (Appendix 1, McGrath et al. 2007). Any disagreement was noted. Surveys ended when no new redds were identified after three additional passes and fish were no longer present.

During each census survey, factors affecting visibility of individual redds were recorded including: color contrast (categorical variable between 4 [bright] to 1 [dull]), cover (terrestrial/aquatic vegetation, surface turbulence), and overlap (none, partial or total) with other redds. River discharge and turbidity were also recorded (McGrath et al. 2007). Discharge data from USGS gaging stations at Deschutes River near Madras, Oregon (14092500; rkm 160) for the Jackson and Smith reaches and Deschutes River at Moody Rapids near Biggs, Oregon gaging station (14103000; rkm 0.8) for the Beavertail reach was used . Turbidity was measured using a LaMotte 2020 portable turbidity meter (Chestertown, MD) at the start of each survey.

Assess variation in fall Chinook redd counts by boat and aerial survey compared with census observations

We evaluated observer error to determine under what circumstances a redd survey by boat or air is most accurate. Census counts were used as the true number of redds upon which aerial and boat based methods were compared. None of the observers that participated in boat and aerial comparisons had prior knowledge of redd locations in index reaches from census counts.

Boat observers were accompanied by census observers on December 26 and 27, 2007 in the upper two index reaches, Jackson and Smith. Observers had 1.5 and 7.5 years experience performing salmon redd surveys. Bearvertail was not wade-able and deemed unsafe to have observers on the viewing platform. Census observers took notes but did not share information with boat observers. We compared redds identified by observers to our census counts to assess the number of redds correctly identified, those that were missed (omissions), and those that were added because a feature of the riverbed was mistaken as a redd (false identifications).

Aerial counts were conducted on December 31, 2007 by two independent observers in a helicopter. These observers did not participate in the census or boat surveys. Aerial survey observers had five and 10 years experience counting salmon redds. Aerial redd observers reported total number of redds counted per reach. However, they were not evaluated by the census observer in the same manner as described for the boat surveyors. Study site boundaries and subsections within study sites were marked with buoys that were visible from the air. Observers recorded redd counts within each subsection of each index reach. Two flights, one at 64 km• h^{-1} (the standard protocol for Deschutes River aerial surveys) and the other at 32 km• h^{-1}, were done to assess the affect of air speed on the ability of the observers to see redds (R. Thurow, Fish Biologist, RMRS, Boise ID, pers. comm.). Counts were done at both speeds occurred consecutively. The helicopter flew approximately 30 to 90 m above the river.

To test for differences between percentages of redds per sub-reach correctly counted at 64 km• h^{-1} and 32 km• h^{-1}, we used the two-sample procedure in Statgraphics, version 15.0 (StatPoint Technologies, Inc., Warrenton VA). After confirming the standardized skewness and kurtosis were between the ranges of -2 to +2, indicating normality in the data, we used the t-test to compare the mean percentage correct between 64 km• h^{-1} and 32 km• h^{-1}. A p-value of the t-test less than 0.05 indicated a difference between the means at the 95.0% confidence level.

Habitat characteristics

Habitat variables were recorded October 22 and 23, 2007 to describe the index reaches and relate redd counts to environmental factors. Measurements were made along three representative transects per sub-reach, perpendicular to the flow, and spaced approximately ¼, ½ and ¾ along the length of the sub-reach (McGrath et al. 2007). These measurements included: wetted width (rangefinder); depth (¼, ½ and ¾ distance from bank); visual estimation of percent substrate by category (sand, gravel, cobble, boulder, and bedrock) in a 10 m wide band; dominant vegetation type of the left and right banks (grass, shrub, or tree); number of large woody debris (LWD – at least 10 cm in diameter) pieces; and visual estimation of cover type (terrestrial vegetation, aquatic vegetation, LWD, and white water) as a percentage of the transect length (Appendix 2, McGrath et al. 2007).

Water temperatures were recorded hourly with Hobo® loggers (Onset Computer Corporation, Pocasset, MA). One logger was just downstream of Jackson and Smith reaches in the Deschutes River immediately upstream of the Highway 26 Bridge (rkm 155.8). The other was located downstream from Beavertail reach near Pine Tree Campground (rkm 63.2). Temperature loggers were encased in a water-proof container and anchored to the substrate.

Relationship between increase in Chinook redds and environmental variables

Nonparametric multiplicative regression (NPMR in HyperNiche version 1.12, Mjm Software, Gleneden Beach, Oregon, (McCune and Mefford 2004) was used to examine the relationship between the increase in number of Chinook redds between survey dates and environmental factors. A Gaussian weighting function with a local mean estimator was used in a forward stepwise regression of increase in redds between survey dates (log ([number redds counted survey $time_2$ - number redds counted survey $time_1$]) + 1) against the predictor (environmental variables), then expressed fit as a cross-validated R^2, or xR^2 (Berryman and McCune 2006). The log transformed increase in redds between sample dates was the response variable used to fit the best model. Environmental or predictor variables included water temperature, river discharge, turbidity, lunar phase, and days from the beginning of survey to when redd was finished (Table 1).

Table 1. Quantitative and categorical variables used in the environmental matrix.

Water temperature
• Daily average water temperature (ºC) • Daily minimum water temperature (ºC) • Daily maximum water temperature (ºC) • 3-day average water temperature (ºC) • 3-day minimum water temperature (ºC) • 3-day maximum water temperature (ºC)
Discharge of the Deschutes River at the nearest USGS gage (m^3/s)
• Discharge on survey date • 2-day change in discharge prior to survey date
Turbidity
• Turbidity (NTU)
Categorical variables
• Lunar phase of survey date (full moon=15, new moon=0) • Day redd was finished (Oct 18 = day 1 to Jan 14 = day 89)

Model sensitivity is calculated from the average absolute values of the differences induced by nudging the predictors. Predictors are nudged one at a time by + or -5% of the range of the predictor, and HyperNiche accumulates statistics on the difference this makes in the response variables. A value of 1.0 means that on average, nudging a predictor results in a change in response of equal magnitude. Sensitivity with a value of zero means that nudging a predictor has no detectable effect on the response (McCune and Mefford 2004). The Monte Carlo procedure was used to test the null hypothesis that the fit of the selected model is no better than could be obtained by chance alone, given an equal number of predictor variables.

Correspondence between habitat characteristics and redd densities

If redd locations are related to habitat, and habitat measurements are representative of the sub-reaches, then the density of redds in sub-reaches should correspond with the grouping arrangement of the sub-reaches on the basis of habitat features. A cluster analysis of redd number or density by sub-reach should have a similar dendrogram structure as for the habitat analysis. We compared sub-reach group assignments from cluster analyses of habitat characteristics and redd densities for correspondence.

To examine similarities and differences among sub-reaches by habitat characteristics, we used a hierarchical agglomerative cluster analysis using Euclidean distance measure and Ward's method for group linkage in PC-ORD, version 5.06 (McCune and Mefford 2006). Quantitative and categorical (bank vegetation, plus whether the sub-reaches were in a side or main channel) habitat variables (Appendix 2) were organized into a matrix of 12 rows (sub-reaches) and 23 columns (of 17 habitat characteristics) for cluster analysis. Reach location or name was not included in the matrix upon which the cluster analysis was performed, but the groupings were made on the basis of the habitat characteristics alone. Reach length was excluded in the matrix since it has no biological significance on whether the habitat is suitable for a redd but is an artifact of study design. The resulting dendrogram was pruned such that the information retained would be at least 75% and not result in more than four groups. After pruning, group membership was assigned to the sub-reaches and groups were described in terms of common habitat features.

Categorical variables were transformed into a series of binary variables (0/1) for the analysis each with a value of '0' (no) or '1' (yes) and assigned to each sample unit (location/date of redd increase) according to the given trait. In the simple case where there are only two outcomes, only one column pertains to both conditions. For example, increase in redd counts from a reach that is a side channel or not (main channel). If a column in the environmental matrix was 'side-channel' then each row in that column will have a '1' if data from the sample unit corresponded to a reach that was a side-channel. If the data corresponded to a reach that was in the main stem, then the cell would be given a '0'. In the case of right and left bank vegetation, only one trait could receive a '1' but there could be more than one trait that could receive a '0'. For example, since there were four possible outcomes of dominant vegetation in the three transects per sub-reach (grass, shrub, tree or if each transect had one of each it was mixed) there were four columns for left bank and four for right bank. In the column left bank grass, a '1' was given if that was the dominant vegetation for that bank in that sub-reach and all other entries in the column were given a '0' if grass was not the dominant vegetation.

Results

Spatial and temporal distribution of fall Chinook redds in three index reaches

Fall Chinook spawning activity was observed during the first two surveys (October 18 and 19, 2007). Redds "in-progress" were recorded in all three index reaches. The first fully constructed redds were observed on October 26, 2007 in Jackson and Smith reaches and October 30, 2007 in Beavertail reach. Redd counts in Beavertail reached maximum counts (35 redds) prior to the upper two reaches, on December 18, 2007 (Figure 2). Smith reach had the greatest number of redds (89) among index reaches recorded January 14, 2008. Redd counts in Jackson peaked December 20, 2006 with 42 redds. Majority of redds were accumulated at Beavertail by November 7 (57%), Smith by December 10 (55%), and Jackson by December 5 (55%). Contrast between redds and substrate diminished through the spawning period to the extent that some redds constructed early in the season were imperceptible by the end of the season.

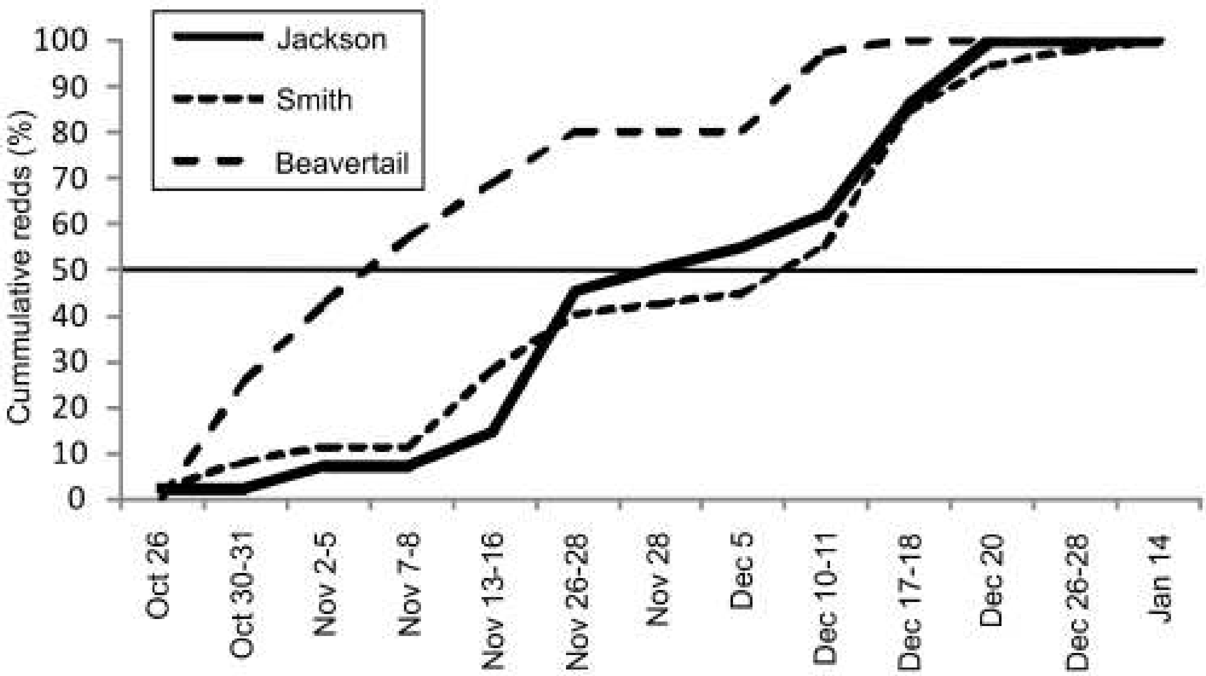


Figure 2. Cummulative fall Chinook redd counts in three Deschutes River index reaches during spawning season 2007-2008.

Redd number and density varied among sub-reaches (Figure 3, Appendix 3). Smith sub-reach 2, hereafter called Smith 2, had the highest density 32 redds/100 m and Beavertail 5 had the lowest with zero. Clustering of redds were observed in three sub-reaches: Jackson 2, Smith 1 and Smith 2. In Jackson 2, there was partial overlap of 58% (8/24) and total overlap of 8% (2/24) of redds. In Smith 1, there was partial overlap of 7% (2/28) and total overlap of 7% (2/28) of redds. In Smith 2, there was total overlap of 6% (3/48) of redds.

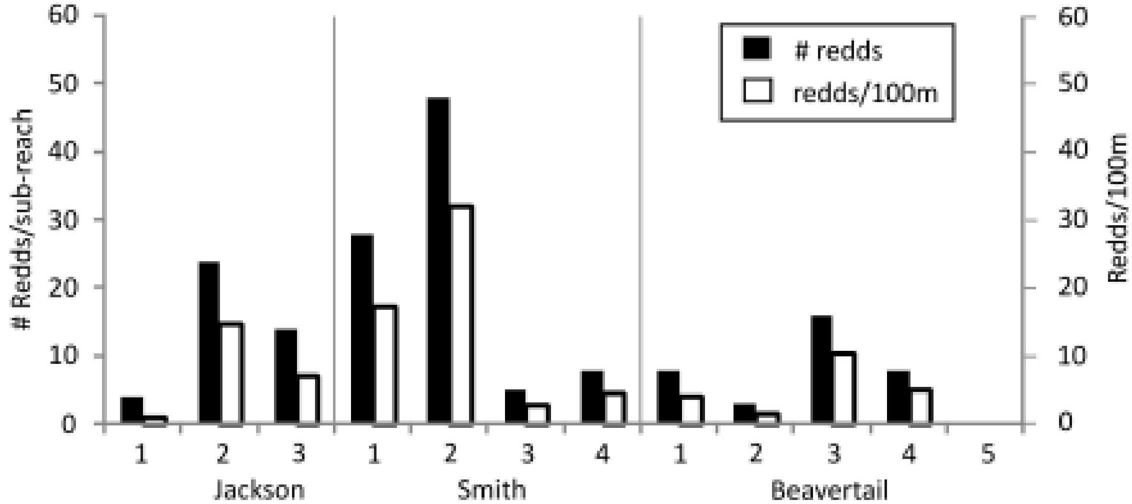
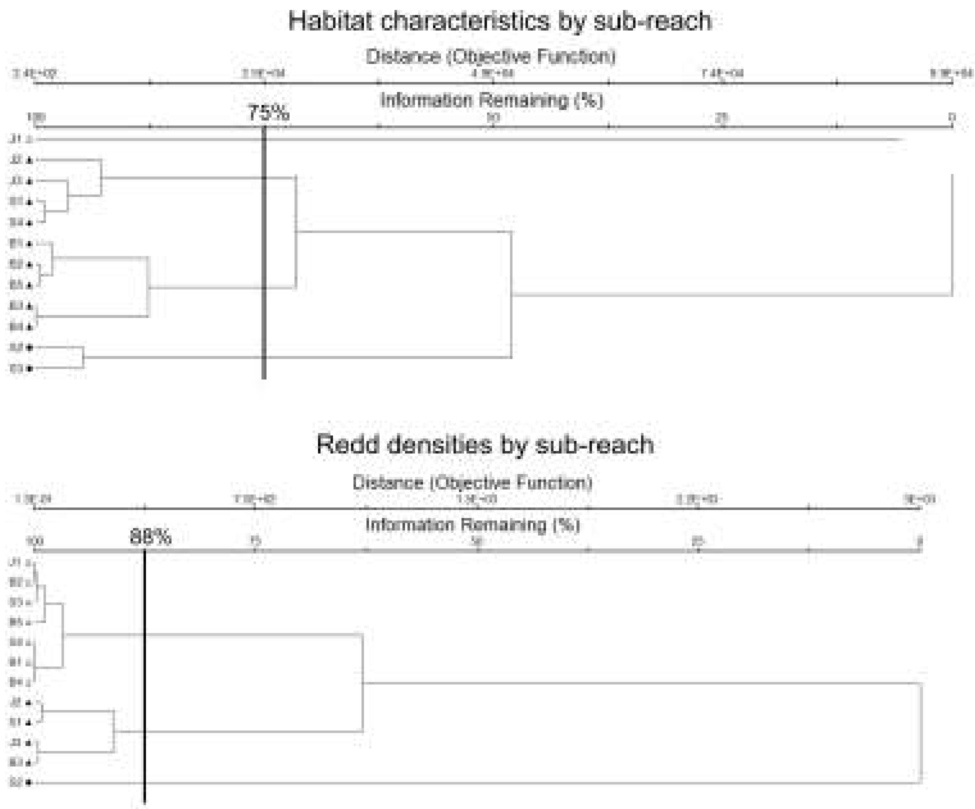


Figure 3. Total fall Chinook redd counts and redds/100 m by sub-reach, Deschutes River, Oregon, 2007 - 2008.

Cluster analysis of habitat characteristics by sub-reach resulted in a dendrogram with 9% chaining (Figure 4). The habitat dendrogram was split into three groups by considering which divisions would result in a practical number of groups in terms of shared habitat features. Habitat characteristics were assessed among the groups to discover common features. Information retained at this level was 75%. All sub-reaches in Beavertail were assigned the same group membership, as were main channel reaches in the upper two reaches, Jackson and Smith, and upper side-channel sub-reaches were grouped (Table 2).

Table 2. . Sub-reaches by habitat groups and associated characteristics.

Beavertail Group deep water, high % sand, low % gravel	Upper main stem high w:d, high % gravel, high white-water cover	Upper side-channel high large woody debris and terrestrial veg., high % gravel
Beavertail 1	Jackson 1	Smith 1
Beavertail 2	Smith 2	Smith 4
Beavertail 3	Smith 3	Jackson 2
Beavertail 4		Jackson 3
Beavertail 5		



Sub-reaches on the left: Jackson (J)1,2,3; Smith (S) 1,2,3, 4; and Beavertail (B) 1,2,3,4, 5.

Figure 4. Dendrograms of habitat characteristics and redd densities by sub-reach.

Cluster analysis of redd densities by sub-reach resulted in a dendrogram of 24% chaining (Figure 4). The dendrogram was split into three groups to compare with the three habitat groups. There was a high density group (32 redds/100 m), a medium density group (7 to 17.3 redds/100 m) and a low density group (0 to 5 redds/100 m). Information retained at this level was 88%.

The three redd-density groups do not completely correspond with groupings of sub-reaches by habitat characteristics (Table 3). Sub-reaches associated with the upper main stem were split between the high- and low-density redd groups. Upper side-channel sub-reaches were predominantly (75%) in the medium-density redd group. Beavertail sub-reaches were mostly (80%) assigned to the low-density redd group, except for one that was given group membership to the medium-density redd group. Conversely, the medium density group was mostly (75%) upper side channel and the low density group was mostly (57%) Beavertail sub-reaches.

Table 3. Sub-reaches by redd densities and comparison with habitat group membership (B=Beavertail, UMS=upper main stem, USC=upper side channel).

High density 32 redds/100m	Medium density 7 to 17.3 redds/100m	Low density 0 to 5 redds/100m
Smith 2 (UMS)	Jackson 2 (USC)	Jackson 1 (UMS)
	Jackson 3 (USC)	Smith 3 (UMS)
	Smith 1 (USC)	Smith 4 (USC)
	Beavertail 3 (B)	Beavertail 1 (B)
		Beavertail 2 (B)
		Beavertail 4 (B)
		Beavertail 5 (B)

Relating increases in fall Chinook redd counts to environmental factors

Three-day minimum water temperature and two-day change in river discharge and were included in the best model (highest cross-validated R^2 value among all models generated) for predicting the relationship between increase in redds between surveys and environmental factors in Jackson and Smith reaches (xR^2=0.3527, 31 sample units). According to sensitivity and tolerance, three-day minimum water temperature was the best predictor for increases in fall Chinook redds in Deschutes River study reaches (Table 4). The selected model resulted in an equal or better fit than randomized runs (HyperNiche Monte Carlo procedure, p=0.48). The greatest increase in fall Chinook redds between survey dates occurred when three-day minimum water temperatures were between 8º C and 10º C and an increase in discharge of 14 m^3/s in two days (Figure 5).

Table 4. Model predictors with sensitivity and tolerance values for an increase in redds in Jackson and Smith reaches.

Predictor	Sensitivity	Tolerance
3d minimum water temperature	0.9628	0.3562
2d change in Q	0.8501	132.3

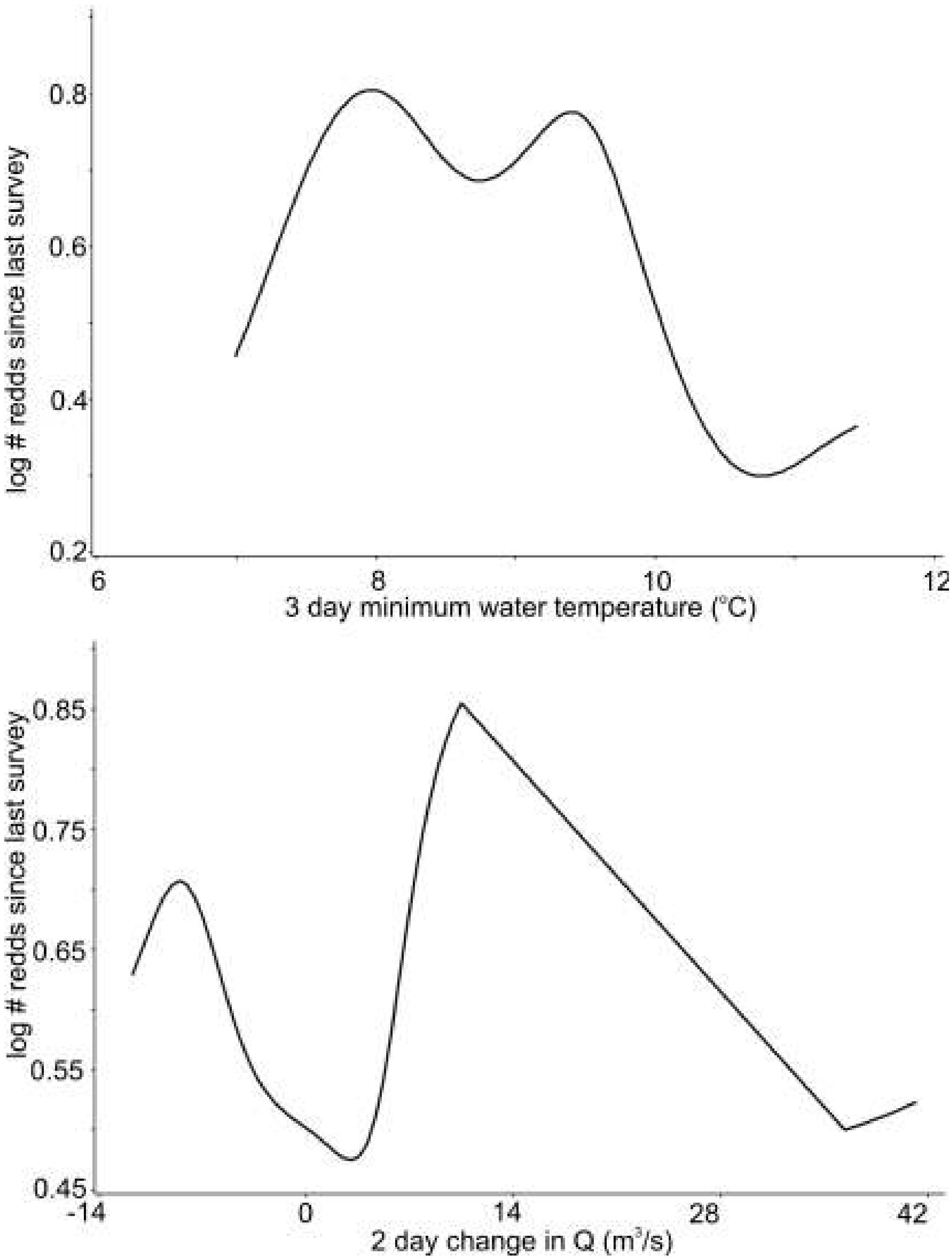


Figure 5. Response of increase in redds to environmental variables, Deschutes River, Oregon, 2007 - 2008.

Assess observer bias for aerial and boat redd counts

On average, boat observers counted 55% of the true redds identified by census observers in Jackson and Smith reaches (Figure 6). They were more accurate in their correct redd counts in Jackson reach than in Smith, 61% and 53%, respectively. Boat observers missed an average of 45% of true redds identified in the census counts in Jackson and Smith reaches. They missed an average of 16.5 redds (39% of total true redds in census) in Jackson and 40.5 redds (47% of total true redds in census) in Smith reach.

Boat observers were less likely to add redds to their counts as miss them; they added, or falsely identified an average of 11% of the total redds identified by census counts. Average false identifications between observers were 6 in Jackson and 8.5 in Smith reaches (14% and 10% of the total number of true redds in Jackson and Smith reaches, respectively).

Inter-observer error varied between boat observers. Observer 1 correctly identified more true redds than observer 2 (70% and 40% correct redds, respectively). Observer 1 also missed fewer redds (29%) compared to Observer 2 at 61%. Observer 2 had more false identifications (19) than observer 1 (10).

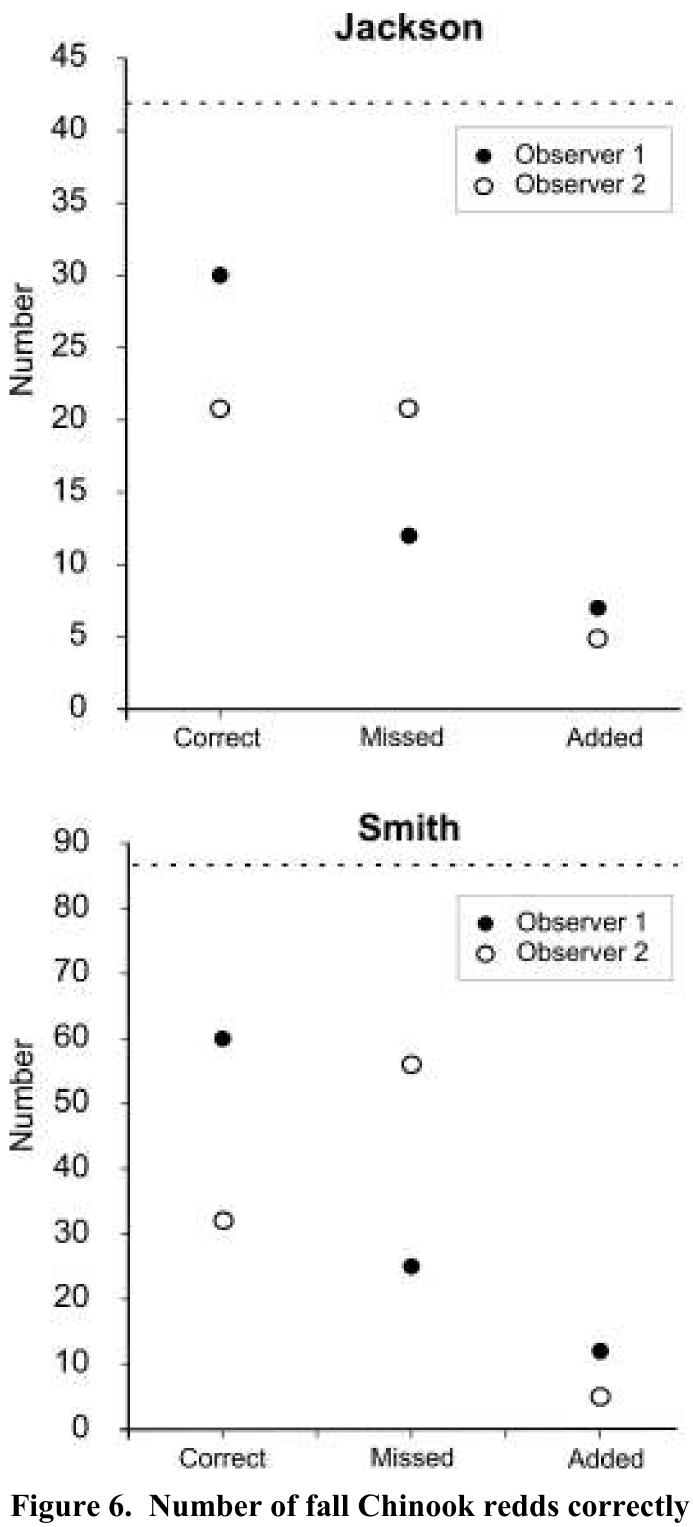


Figure 6. Number of fall Chinook redds correctly counted, missed (omissions), and added (false identifications) from boat survey in Jackson and Smith reaches, Deschutes River, Oregon, 2007 - 2008. Dashed horizontal lines refer to best estimates (census) of redd numbers.

On average, aerial counts at 64 km• h^{-1} were 14% of the true number of redds, while aerial counts at 32 km• h^{-1} were 27% according to census counts (Figure 7). At 64 km• h^{-1}, aerial observers counted, on average, 12.3 fewer redds per sub-reach in Jackson (undercounted by 88%), 17.6 fewer redds per sub-reach in Smith (undercounted by 81%), and 6.3 fewer redds per sub-reach in Beavertail (undercounted by 90%) than census counts. At 32 km• h^{-1}, aerial observers counted, on average, 12.0 less redds per sub-reach in Jackson (undercounted by 86%), 14.9 less redds per sub-reach in Smith (undercounted by 68%), and 4.9 less redds per sub-reach in Beavertail (undercounted by 70%) than census counts. Comparing mean redds counted by aerial surveyors as a percentage of the total census counts between 64 and 32 km• h^{-1}, the percentage of the true number of redds counted at 32 km• h^{-1} was significantly greater than that counted at 64 km• h-1 (excluding Beavertail sub-reach 5 for which both aerial and census observers counted zero, n=11, two-sided t-test, p=0.02).

Observer bias varied among reaches and air speeds. Observer 1, on average, was more accurate than observer 2 at both 64 km• h^{-1} (18% and 12% correct redd counts, respectively) and 32 km• h^{-1} (34% and 20% correct redd counts, respectively).

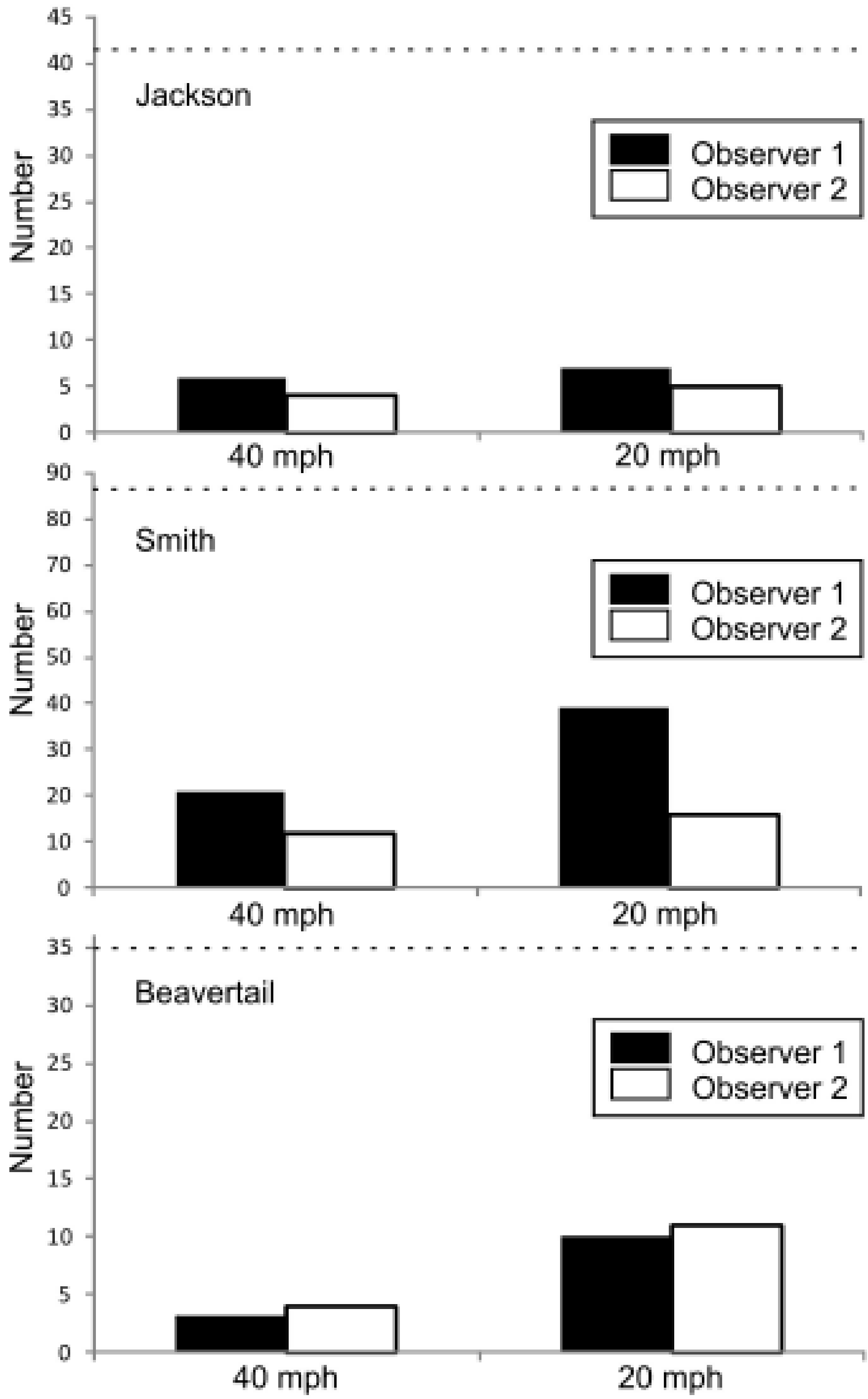


Figure 7. Number of fall Chinook redds counted during aerial survey compared with census counts (dashed lines) in Jackson, Smith and Beavertail reaches, Deschutes River, Oregon, 2007 - 2008.

Discussion

Comparison of survey methods: aerial vs. boat

In Deschutes River index reaches, Chinook redd counts by boat surveyors were more accurate than aerial surveyors, averaging 55% and 27% (at best) correct by sub-reach, respectively. Reducing airspeed from 64 to 32 km• h^{-1} improved the accuracy of redd counts for aerial surveys by a factor of two, from 14% to 27% correct number of redds counted. By aerial survey alone (at 64 km• h^{-1}), the current methodology for quantifying fall Chinook redds in the Deschutes River, a large proportion of redds (approximately 86%) are not counted, if these results are representative of previous surveys (unpublished, ODFW). A study validating aerial redd counts in the Middle Fork Salmon River (MFSR) reported aerial counts and "true" counts, based on more reliable ground surveys, were highly correlated (r=0.78, n=52 reaches; Isaak and Thurow 2006). Aerial counts on MFSR were conducted at airspeeds ranging between 20 and 40 km• h^{-1} and elevations ranging between 15 and 50m, compared to 30 to 60 km• h^{-1} and 30 to 90m elevation in this study. The same speed and elevation is not possible for much of the Deschutes River, especially in canyon reaches where winds can create difficulties for pilots. Isaak and Thurow (2006) also had consistency in observers from 1995 to 2003 which has not occurred in the Deschutes River.

Habitat characteristics and redd locations

Temporal characteristics of Chinook spawning dictates survey logistics. The study began in mid-October when redds were in progress but none had been completed. Frequent observations by census surveyors ensured most of the reproductive adults were represented in boat and aerial counts. In late December, when boat and aerial counts were conducted, all redds were constructed in Jackson and Beavertail reaches. Two additional redds (2% of total) were constructed after aerial and boat surveys were completed. Since migration timing for individual spawning populations of salmonids can vary among years due to physical and biological characteristics of the environment, Muhlfeld et al. (2006) suggest periodic surveys be part of any redd count protocol so most reproductive adults are counted.

In addition to determining when most spawning adults would be represented in redd counts, census observers in this study were able to determine when redd superimposition occurred. Redd superimposition is characterized by overlapping redd pits or tailspills and results from construction of multiple redds in the same area (Dunham et al. 2001). Census observers noted fall Chinook redd residency at 7 to 10 days. Typically, female Chinook remain in close proximity to their finished redd to guard against egg predation and the occurrence of subsequent redd superimposition (Neilson and Bradford 1983; Neilson and Geen 1981). When superimposition occurred, no redds were observed to have guarding females present and new spawners appeared fresh (less fungus, tail more intact, more silver than blushed in body color). In addition, the contrast between the second redd and riverbed was more distinct compared with that of the previous redd. Algae and awfuchs diminished the contrast of the first redd as the spawning season progressed. The likelihood for boat or aerial surveyors correctly counting superimposed redds at the end of the spawning season, in which total overlap occurs, would be low since they do not see changes through time as does census surveyors.

Redd distribution in index reaches was not uniform. Fall Chinook redds were clustered throughout the side channels in Jackson 2 and Smith 1 and 2 with superimposition occurring in 8%, 7% and 6% of redds, respectively. Superimposition may occur when there is a high density of spawners (Semenchenko 1988) and may result in the loss of previously deposited eggs (Burgner 1991) influencing reproductive success of salmon. In a study of spatial pattern analysis of fall Chinook spawning habitat use at Locke Island in the Hanford Reach, Geist et al. (2000) determined that individuals competed for space based on redd densities (16.1 redds/ha) and spatial pattern (redds occurred in clusters but within clusters redds were uniformly spaced). If redd density and pattern can be used as a guide, competition for space in Smith 2 likely occurred because redd density at Smith 2 was greater than that reported at Locke Island, 25.6 and 16.1 redds/ha, respectively, and redds occurred in clusters. Competition for space suggests habitat limitation. Ligon et al. (1995) described how lack of gravel recruitment below Cougar Dam on the McKenzie River, Oregon, limited spring Chinook spawning habitat; this resulted in saturation of spawning gravel by spawners, redd superimposition, and a limit to the number of eggs that could be seeded in the river. Pelton-Round Butte Hydroelectric Complex may be having a similar affect in the Deschutes River. Studies are currently underway to determine gravel movement and whether gravel is limiting fall Chinook spawning (Bob Spateholtz, PGE, pers. comm.). Limitation of suitable spawning habitat is not a prerequisite for redd superimposition to occur; a preference for prime habitat over less desirable, but suitable, habitat can also lead to redd superimposition (Essington et al. 1997). Superimposotion is minimized when females defend their redds after egg deposition (Burgner 1991).

In upper sub-reaches of Jackson and Smith reaches, dunes were observed. Mass spawning and repeated spawning can change riverbed characteristics leading to dune formation where dune heights may reach 0.75 to 1.5m (DeVries 1997). The most dramatic dune features were located in Smith 2, where a long band of dunes (50m), perpendicular to the flow, formed rows mid-channel, near the island located river-left and was a site of active spawning (Appendix 3).

The peak of fall Chinook spawning in three Deschutes River index reaches was between November 7 and December 10, 2007 when half of the total redds were counted. Episodic increase in redds counts between surveys were related to the three-day minimum water temperature (between 8ºC and 10ºC), similar to the ranges found by Bjornn (1971), Bjornn and Reiser (1991) and McCollough (1999). The recommended spawning temperature range for spring, summer and fall Chinook is 5.6ºC to 13.9ºC (Bjornn 1971; Bjornn and Reiser 1991). Declining water temperature also has been found to initiate spawning activity; fall Chinook spawn as temperatures decline from 13.4ºC to 5ºC (McCullough 1999). This is similar to what was found in the Deschutes River where daily average water temperatures decreased throughout the spawning season (from 12.5ºC to 7.2ºC below Jackson and Smith; from 12.3ºC to 6ºC below Beavertail, unpublished data).

In Deschutes River index reaches, a pattern of increased spawning activity with an increase in discharge (two-day increase of $14m^3/s$) was also found. Upstream migration of spawning adult Chinook in the Columbia River has been correlated with increased flows. Keefer et al. (2008) found flow was the best single predictor of spring Chinook migration timing (for both peak and median counts; April flow 1970 - 2006 time series) over Bonneville Dam (rkm 235). River discharge has been correlated with an increase in spawning activity of fall Chinook salmon in the tailrace of Wanapum Dam on the Columbia River between rkm 658.7 and 664 (McMichael et al. 2005). Highest rates of fall Chinook spawning activity in the tailrace of Wanapum Dam occurred at flows less than 2000 m^3/s and progressively less for flows from 2000 m^3/s to 4000 m^3/s. McMichael et al. (2005) found no apparent relationship in change of flows and spawning activity in tailrace index reaches as we did in Deschutes River index reaches, perhaps due to greater magnitude in flows. Discharge in Deschutes River index reaches ranged between 120 m^3/s to 169 m^3/s during the spawning season.

Characterizing spatial distribution of Chinook spawning activity and associating redds with habitat characteristics may be of interest to track inter-annual variation in spawning distribution and redd density, determine primary spawning locations, and identify habitat characteristics associated with areas of high and low redd densities (potentially important for future study design). Spatial distribution of Chinook redds varied among sub-reaches. One sub-reach had distinctly greater redd density than others (32 redds/100 m), Smith 2. Upper main stem reaches were characterized by high width to depth ratios (average w:d ratios 126 to 178.4) and high proportions of gravel substrate (0.2 to 6.4 cm). However, other upper main channel reaches had both low (Jackson 1 and Smith 3, 0 to 5 redds/100 m) densities of redds, despite apparent similarities in habitat characteristics. Upper side channel reaches were mostly in the medium density group (7 to 17.3 redds/100m), except for Smith 4 in the low density group. Upper side channel sub-reaches were characterized by large woody debris and terrestrial vegetation cover and high proportion of gravel substrate. Both upper main channel and side channel groups had high proportions of gravel. Beavertail sub-reaches were in the low density redd group, except for Beaver 3 in the medium density group, and were characterized by deeper water (1.4 m average), high proportions of sand, and low proportion of gravel. The lack of correspondence between sub-reach classifications by habitat and redd density indicates that variables measured during the survey did not fully capture those important to location selection by Chinook to construct redds and that the scale of the sub-reaches, however defined, is larger than that of individual redds or redd clusters. Chinook salmon redds are typically distributed in a patchy fashion and are located in areas of suitable depth (0.5-7 m), velocity (0.5-2 m/s), substrate (2.5 – 15.2 cm dia.; gravel and cobble in this study), bed slope (0-5%), lateral slope of the river bottom (<4%) and are often spatially correlated to channel bar formations and areas of upwelling (Geist et al. 2008; Geist and Dauble 1997; Geist et al. 2000; Hanrahan et al. 2004).

Management Recommendations

Implications of the status quo

Under the currently methodology for counting fall Chinook redds in the Deschutes River, aerial surveys at 64 km• h^{-1}, undercounts redds by 86%. Applying an inflated number of Chinook per redd ratio above Sherars Falls to the number of redds counted below Sherars Falls may overestimate the escapement of fall Chinook in the Deschutes River if redd counts in the lower river are near the true value. Alternatively, it may have little effect if redd counts in the lower river are also underestimated by the same proportion. The reach from the mouth to Sherars Falls is 44% of fall Chinook spawning distribution in the Deschutes River but 69% of fall Chinook redds were counted in the lower river by aerial survey (10-year average, 1997-2006, unpublished data). This demonstrates the scale at which an incorrect inference in Chinook abundance may have on the escapement estimate.

It is likely that the probability of redd detection in the lower river is not equal to the upper river. Flights typically begin in the upper river in the morning and end in the lower river in the afternoon. Therefore, in the relatively unconstrained upper river, aerial observers may have better visibility than the lower river, characterized by steep canyon walls that cast shade except for a brief period mid-day. Counting redds in canyon reaches is particularly challenging for observers because water is typically deeper when the river is more confined, shadows are cast in the morning and afternoon reducing visibility and when the sun is directly overhead so there are no shadows, glare from the water surface also reduces visibility.

Errors are being distributed in the fall Chinook escapement estimates (in basin, Columbia Basin, and ocean harvest) and the effects and magnitude of the errors is unknown. Because Deschutes River fall Chinook is one of three escapement indicator stocks used by the Chinook Technical Committee (CTC) to monitor effectiveness of the U.S. – Canada Treaty to set harvest limits on wild Columbia River upriver bright fall Chinook salmon, accuracy is important. The CTC calculates ocean abundance of a fish stock from the estimate of its escapement using a stock-recruit model such as Ricker model. If the escapement estimate has a large error, the resultant estimate of ocean abundance will also have a large error. This may lead to overharvest if the escapement estimate is inflated as quotas would be set higher than if the correct escapement number was reported.

Recommendations to improve fall Chinook redd surveys on the Deschutes River

To improve accuracy of total number of fall Chinook redds counts in the Deschutes River, observer precision must be improved and accuracy must be adjusted by calculating a correction factor based on observer error. Errors in observer precision may be categorized by visibility and perception of redds. Visibility of redds is related to physical obstacles such as turbidity, depth, turbulence, vegetation, and degree of shading. Perception of redds is related to the observers ability to decipher redds from other channel features and is largely a matter of training but individuals also inherently differ in their ability to train their eyes to see patterns. After improving observer precision, accuracy can be adjusted for bias correction and construction of confidence intervals. Corrections and confidence intervals may be applied to past aerial redd survey data, given sufficient quality, for trend analyses.

In both boat and aerial surveys in Deschutes River index reaches, there were differences in redd counts between observers. In this study, observer experience ranged broadly from 1.5 to 25 years (mean=8.6 years), and a brief in-the-field orientation on redd identification was given for boat surveyors. Brief verbal instruction was provided for aerial observers. Inter-observer variability should be minimized to reduce error and increase precision. If there is low variability in observer precision, accuracy can be corrected. In bull trout redd counts, Dunham et al. (2001) used novice observers but received a 1 h presentation and discussion of redd counting and identification followed by a 1 - 2 h training session in the field, which included actual bull trout redds, while Muhlfeld et al. (2006) used experienced observers with 10 to 26 years experience. Dunham et al. (2001) reported a high degree of inter-observer variability and that the most experienced observers were not always the most accurate. Muhlfeld et al. (2006) reported low variation in observer counts but that observers made both errors of omission and false identification, which often offset each other. Dunham et al. (2001) suggests that further training beyond their protocol is needed to improve counts or accept high inter-observer variability is unavoidable. Specifically, training should test the observer's ability to count redds until the observer attains relatively consistent counts with minimal error and that training should focus on factors that create counting errors, realizing that the influence of redd and habitat characteristics on observer error may differ among observers and streams (Dunham et al. 2001).

To assess observer error and increase the validity of using redd counts for inferring true number of redds in the Deschutes River, multiple observers (enough for statistical validity) must be scored on correct number of redds counted, redds missed and false identifications (redds added) within strata. Stream reaches should be defined within strata and a proportion randomly selected for scoring. Corrections would then be applied on a per-strata basis. Muhlfeld et al. (2006) modeled observed redd counts as the sum of two, independent discrete random variables: the number of redds detected plus the number of false identifications. The assumptions are 1) true redds have an independent and equal chance of detection (binomial distribution) and 2) false identifications occur with uniform probability along the stream (each small increment of stream length has an equal and independent probability of holding false identifications – Poisson distribution). The parameter of interest is T (true number of redds) for which there are data on R (counted number of redds) in which there is a probablility (p) of detecting a true redd. Muhlfeld et al. (2006) modeled observed redd counts as

$$R = A + F,$$

A follows the binomial distribution (T, p), and F follows the Poisson distribution (λd), λ being the rate of false counts per kilometer and d the distance sampled (km). Under the dual error structure, the expected value of an observed redd count is $Tp + \lambda d$ and its associated variance is $Tp(1-p) + \lambda d$. We can calculate mean estimates of p and λ from scoring observers in a future study and can measure d. The parameter that we will estimate is T', the mean number of redds given an observed count, which is equal to $(R-\lambda d)/p$ and its associated variance is $[T'p(1-p) + \lambda]/p^2$ (Muhlfeld et al. 2006).

At least in part, strata may need to be based on redd density because the dual error structure in redd counts leads to a change in redd count bias depending on the frequency of the true redds in the sampled reach. The number of redds missed in a redd count is a function of the actual number of true redds present in the stream and false counts are dependent on the reach length (Muhlfeld et al. 2006). At certain redd frequencies, the number of true redds missed will equal the number of false redds added. At low redd frequencies, relatively few redds will be missed relative to the expected number of false counts because false counts are only dependent on reach length. Conversely, when redd frequencies are high, observed redd counts are expected to be lower than true redd numbers. In addition to redd densities, stratification may be based on physical obstacles to visibility (turbidity, depth, turbulence, terrestrial/aquatic cover) to reduce variance. Reach stratification can be worked out based on prior redd, carcass and habitat surveys.

Although boat observers were more accurate than aerial observers in this study, it is not practical to survey the entire 161 km of fall Chinook spawning distribution in the Deschutes River by boat. Boat access is limited in some areas and large rapids in some reaches pose safety issues. It is also not practical to have a dozen surveyors participate in an aerial survey due to cost, safety, ability to score them not only on number of redds counted but also individual redds correctly counted, missed and added, plus there would be increased error due to environmental variability from multiple flights at different days and time of day. A potential approach is to use geo-referenced videography to capture redd numbers and locations in the entire 161 rkm of the Deschutes River. A gyro-stabilized camera with a polarized lens fitted to the helicopter, equipped with a digital video recorder (Red Hen Systems SDVR, Fort Collins, Colorado) can be used to capture video along with geospatial information the entire spawning length of the Deschutes River, and the geo-referenced video can be assessed and used within the ArcGIS environment (GeoVideo is an extension tool for ArcGIS developed by Red Hen Systems). Sections of the river where redd visibility from aircraft is poor may be surveyed using a jet boat fitted with a viewing platform. The jet boat would be an improvement over the drift boat because of greater stability and more power from the motor would allow the boat to hover so areas of high redd density can be thoroughly counted. Both methods would require validation from census survey using index reaches.

The geo-referenced aerial video can be evaluated by a census observer to ensures that redds that exist in the river are indeed visible on the video. The census observer could then score multiple video observers on redd counts whose results could be used to calculate error, correction factors, and construct confidence intervals on a per strata basis. Video observers could review the aerial flight at their desired speed and environmental conditions would be consistent among observers.

In the optimal study design, three geo-referenced aerial videography flights would occur. A pre-spawning period video would document redds from previous spawning seasons. A mid-spawning season flight would document early redds from the spawning period before becoming re-colonized by algae and also to track redds in high frequency areas to help sort out superimposition. Visibility of Chinook redds in the Deschutes River was affected by algal re-colonization as contrast between redds and river substrate decreased with time. Redds dug early in the season may be missed or mistaken for redds from previous spawning periods. Redd superimposition, in which redds become indistinguishable in space, also decreased visibility in this study.

Depending on budget and other logistics, it may be possible to time geo-referenced aerial videography flights to minimize environmental variation among reaches. If completed over a short time interval, multiple flights can record video so that daylight and other environmental conditions are optimized for more constant environmental conditions among reaches. Through census surveys, optimal visibility with respect to river discharge, turbidity (*e.g.* glacial flour from White River), and time of day in various reaches (*e.g.* canyon walls, open floodplains) can be determined. Survey timing cannot improve visibility due to cover (terrestrial or aquatic vegetation), river depth or turbulence so reach stratification on the basis of obstacles to visibility may distribute error more evenly within strata reducing variance.

After experimentation with reach stratification, and counting redds via aerial videography and jet boat a standard protocol for fall Chinook redd surveys in the Deschutes River should be developed. This would ensure continuity of procedures over time as personnel may change and lead to improved accuracy of redd counts.

The alternative to a visually based escapement estimate is to use a mark and detection system. Redd surveys to assess escapement estimates of fall Chinook salmon in the Deschutes River may become needless in the future if fish marked with PIT tags can be detected by PIT tag interrogators at the mouth of the Deschutes River and at Sherars Falls. There is a PIT tag detection system at Sherars Falls in the Deschutes River. Installation of a PIT tag interrogator is planned for the mouth of the Deschutes River in late 2010. If the plan proceeds, this site could be used to estimate escapement to the upper Deschutes River. Estimates of the total Deschutes River escapement would be the sum of this improved estimate of the upper Deschutes River and lower Deschutes River escapement measured using current methods.

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Appendices

Appendix 1. Information recorded during fall Chinook redd census.

The following information was recorded for each feature (protocol provided by C. McGrath and R. Thurow, USDA Forest Service, Rocky Mountain Research Station, Boise, ID, McGrath et al. 2007).

1. For each feature, the following classification was recorded: redd, in-progress redd, false redd, test redd, or old (previous year) redd. Redds had a completed, three-dimensional, pit-and-tailspill morphology of a redd and the female was no longer actively constructing the redd, although the female could still be guarding the redd. Females were actively constructing in-progress redds. False redds were geomorphic bed features that could be mistaken for a redd and were possibly caused by activity of other animals (e.g., beavers) or hydrologic scour. Test redds were areas where a salmon began redd construction (typically a small oval depression) but abandoned the site before redd completion and spawning. Old redds were redds constructed by either spring-spawning steelhead prior year Chinook salmon.
2. No longer visible features: Features may become obscured due to superimposition, substrate scour, disturbance by animals, periphyton growth, sediment deposition, or water turbidity. The observers referred to their maps to recall where features occurred previously, and if a feature was no longer visible, it was re-classified as "no longer visible" and the reason was noted. If a previously-recorded feature was not recorded on a new survey date, it was implied that the feature was no longer visible.
3. Each feature was given a unique identification number. During subsequent surveys, the number initially assigned to an individual feature remained constant, even if that feature was eventually reclassified. In this manner, each census contained a record of the cumulative total of redds and other features observed to that date.
4. Color contrast between gravels inside and outside of redds was visually estimated as 1=none, 2=low, 3=medium, 4=high, or 5=extreme.
5. Cover that might decrease visibility included woody debris, surface turbulence, overhanging terrestrial vegetation, aquatic macrophytes, or undercut banks. The degree to which cover obscured each feature was recorded as no cover, partial cover, or total cover.
6. The degree to which a redd overlapped with another was recorded as no overlap, partial overlap, or total overlap.
7. Comments relevant to each feature were recorded and could include descriptions of redd visibility, details on size or location, presence of adult fish, and distance from other features.
8. Features were drawn on sub-reach maps during each survey and were identified with their feature IDs. The Map ID on the data form was the observer's first and last initials, date, subsection: e.g., MF071015-1 (Matt Fox, 2007-Oct15, Subsection1). Previous maps were brought into the field for reference in subsequent surveys. When redds were clustered, more detailed maps were drawn in the field notebook and referenced the page number on the subsection maps. Care was taken to draw the spatial arrangement of redds and redd-like features relative to other landmarks (boulders, snags, etc) and the stream banks, with distances between features and landmarks recorded. This level of map detail is critical for tracking individual features over time.

The following groups defined substrate composition: sand and silt (<2mm), gravel (2-64mm), cobble (64-250mm), boulder (250-4000mm), bedrock (>4000mm).

Appendix 2. Habitat characteristics measured over three transects per sub-reach and averaged.
Jackson and Smith measured Oct. 23, 2007, Q=5020cfs at USGS 14092500. Beavertail measured 10/22/2007, Q=5980cfs at USGS 14103000.

Reach	Channel Dimensions				Channel Substrate (%)[1]					Cover[2]				
	av. wid. (m)	av. dep. (m)	W:D	len. (m)	sand	gravel	cobble	boulder	bedrock	# LWD[3]	% terrestrial vegetation	% aquatic veg.	% LWD	% WW[4]
Jackson														
1	66	0.37	178.4	365	0	70	30	0	0	0	5	35	1	20
2	30	0.46	65.2	163	5	68	25	0	0	19	17	22	12	10
3	32	0.59	54.2	200[5]	38	50	10	0	0	17	30	5	12	5
Smith														
1	15	0.68	22.0	162	21	66	9	0	0	11	25	0	6	2
2	125	0.78	160.2	150	13	73	13	0	0	7	5	0	3	25
3	97	0.77	126.0	180	28	68	3	0	0	6	5	0	3	35
4	22	0.53	41.5	178	23	72	3	0	0	8	40	0	4	5
Beavertail														
1	78	1.49	52.3	201	85	0	3	10	0	3	2	0	0	30
2	77	1.48	52.0	205	63	5	5	10	0	2	2	1	0	0
3	77	1.39	55.4	152	38	43	12	6	0	1	2	0	0	5
4	75	1.49	50.3	161	50	41	4	0	0	8	10	0	2	2
5	80	1.22	65.6	194	73	12	15	0	0	11	13	0	5	2

[1]Values do not add to 100% across rows because they were averaged from three transects.
[2] Cover as a % of the transect length, averaged over three transects.
[3] large woody debris; [4] white water; [5] combined lengths of both braided channel sections

Bank characteristics (G=grass, S=shrub, T=tree) of all three transects per sub-reaches.

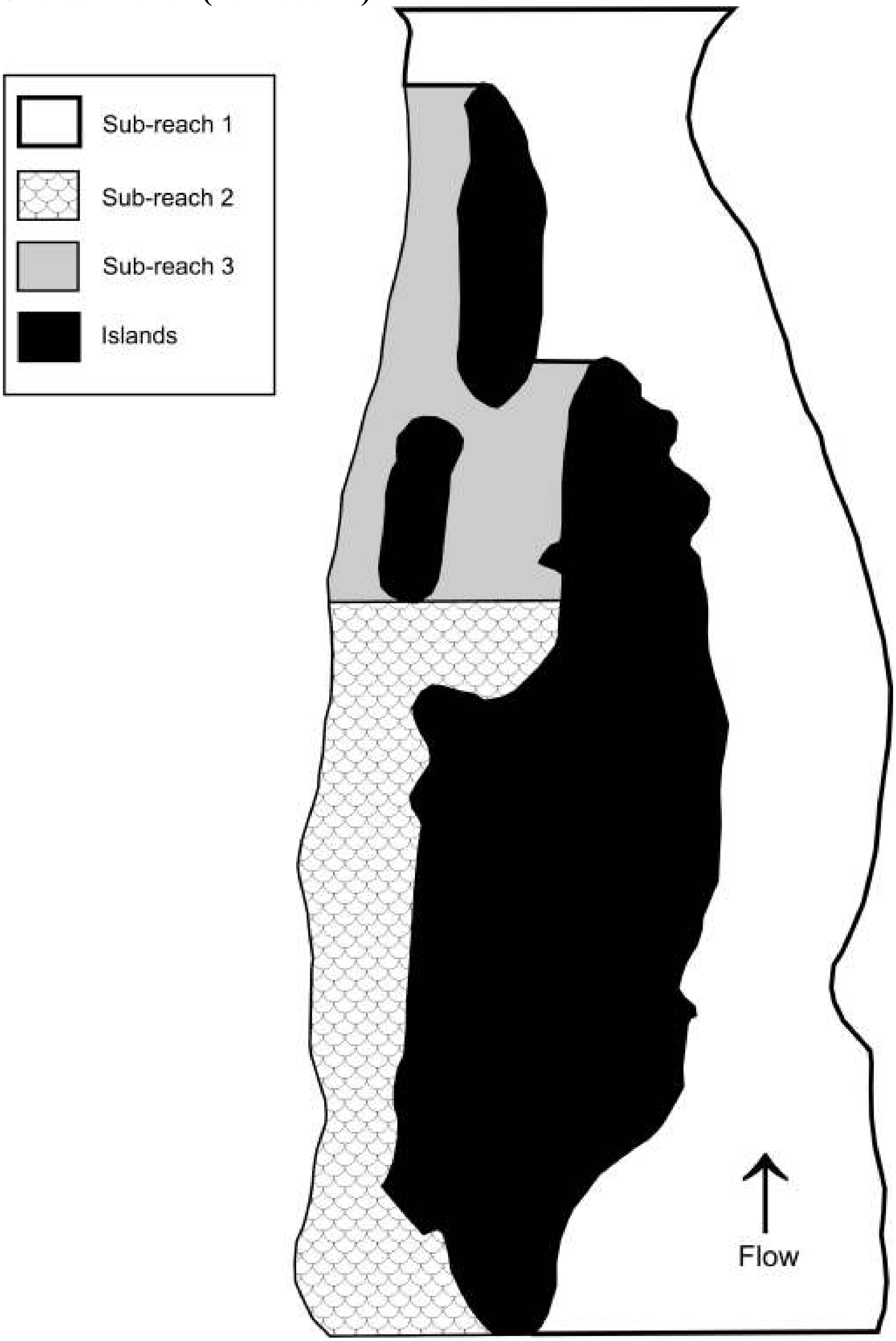
Reach/Sub	left bank	right bank
Jackson 1	S	G
Jackson 2	STS	SSG
Jackson 3	TGG	SS

Reach/Sub	left bank	right bank
Smith 1	GST	STS
Smith 2	GSS	GTS
Smith 3	TTT	GGT
Smith 4	TTT	TTT

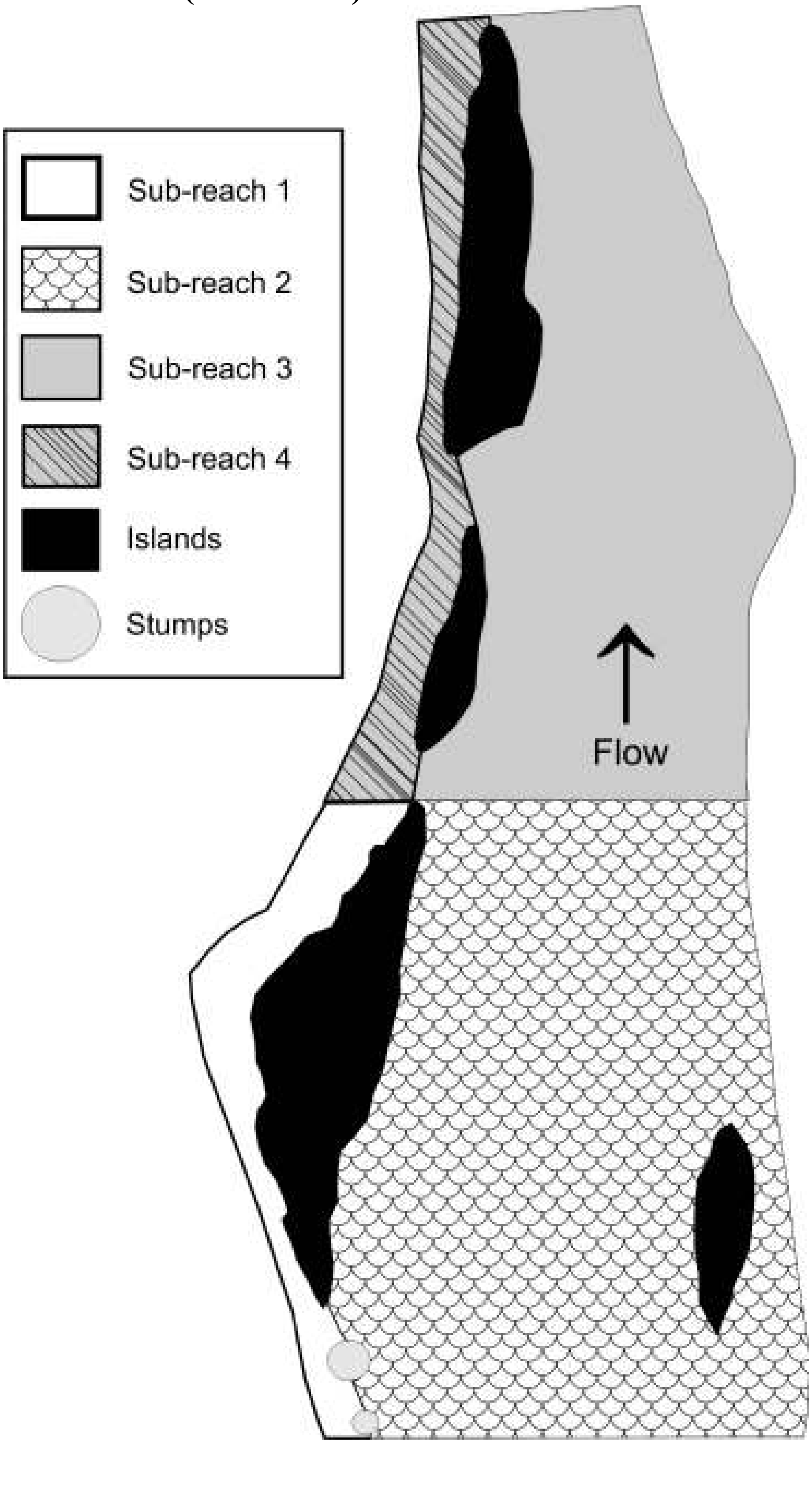
Reach/Sub	left bank	right bank
Beavertail 1	GGG	GGG
Beavertail 2	GGG	GGG
Beavertail 3	GGG	GGG
Beavertail 4	GGG	GTT
Beavertail 5	GGG	TTT

Appendix 3. Diagrams of sub-reaches.

Jackson reach (not to scale).



Smith reach (not to scale).



Beavertail reach (not to scale)

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