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ARTICLE

Spatial Consistency of Chinook Salmon Redd Distribution within and among Years in the Cowlitz River, Washington

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Abstract

We investigated the spawning patterns of Chinook Salmon *Oncorhynchus tshawytscha* on the lower Cowlitz River, Washington, using a unique set of fine- and coarse-scale temporal and spatial data collected during biweekly aerial surveys conducted in 1991–2009 (500 m to 28 km resolution) and 2008–2009 (100–500 m resolution). Redd locations were mapped from a helicopter during 2008 and 2009 with a hand-held GPS synchronized with in-flight audio recordings. We examined spatial patterns of Chinook Salmon redd reoccupation among and within years in relation to segment-scale geomorphic features. Chinook Salmon spawned in the same sections each year with little variation among years. On a coarse scale, 5 years (1993, 1998, 2000, 2002, and 2009) were compared for reoccupation. Redd locations were highly correlated among years. Comparisons on a fine scale (500 m) between 2008 and 2009 also revealed a high degree of consistency among redd locations. On a finer temporal scale, we observed that Chinook Salmon spawned in the same sections during the first and last week. Redds were clustered in both 2008 and 2009. Regression analysis with a generalized linear model at the 500-m scale indicated that river kilometer and channel bifurcation were positively associated with redd density, whereas sinuosity was negatively associated with redd density. Collecting data on specific redd locations with a GPS during aerial surveys was logistically feasible and cost effective and greatly enhanced the spatial precision of Chinook Salmon spawning surveys.

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Chinook Salmon *Oncorhynchus tshawytscha* are known to spawn consistently in the same areas year after year, and yet there have been few published papers that have statistically evaluated spatiotemporal consistency in spawning patterns of salmon (*Oncorhynchus* spp.) over decades. Furthermore, previous research on spawning distributions has been conducted at the reach scale (∼10^2 m; Geist et al. 2000) and at the basin scale (∼10^3 m or larger; Isaak and Thurow 2006; Isaak et al. 2007 [see a comprehensive review of previous research on salmonid spawning distribution at various spatial scales by Beechie et al. 2008]). To fully understand spawning patterns, it is important to examine patterns at multiple scales, both spatially and temporally (Geist and Dauble 1998; Fausch et al. 2002). On a reach scale, Geist et al. (2000) investigated the spatial and temporal patterns of fall Chinook Salmon spawning sites in a spatial grid with cells that were 20 × 20 m wide in 1994 and 1995 in the Hanford Reach, Columbia River (Washington). Isaak and Thurow (2006) examined basin-scale patterns over an entire watershed and among tributaries in central Idaho, using 28-km sections for analysis. In contrast to these previous studies, we evaluated spawning patterns of Chinook Salmon in the lower 80 km of the Cowlitz River at the segment scale (∼10^2 m), which is intermediate to the reach (∼10^3 m) and basin (>10^3 m) scales (Frissell et al. 1986).

Previous studies of redd distribution at a reach scale have emphasized patterns of sediment and water quality parameters in and adjacent to individual redds (Bjornn and Reiser 1991; Geist et al. 2000; Geist et al. 2002; Malcolm et al. 2003; Moir et al. 2004). To complement previous work at finer spatial scales, we investigated the effects of geomorphic features at a segment scale. Channel bifurcation (Dauble et al. 2003), sinuosity (Dauble and Geist 2000), tributaries (Martin et al. 2004; Rice et al. 2008), depth discontinuities (Brunke and Gonser 1997), and channel gradient (Dauble and Geist 2000) have been identified as potential segment-scale controls on redd distribution.

Fall and spring Chinook Salmon in the Cowlitz River are part of the Lower Columbia River Evolutionarily Significant Unit and are listed as threatened under the Endangered Species Act (Good et al. 2005). The number of wild adult fall Chinook Salmon spawning in the Cowlitz River was estimated at 100,000 adults historically but has dropped to less than 2,000 individuals recently (LCFRB 2004). There were 1,620 redds counted during aerial surveys in 2007, including both wild and hatchery spring and fall Chinook Salmon (Henning 2008). This decline in Chinook Salmon has been attributed to numerous causes but is most likely due to overfishing and habitat degradation. In the lower Cowlitz basin, there have been many human-caused changes such as dams, dredging, diking, and straightening of the main channel, which have had a negative effect on salmon habitat (LCFRB 2004). This habitat is crucial for juvenile salmon, but it also has a large impact on spawning adults and on the survival of their eggs (Sear and DeVries 2008).

Determining the patterns of Chinook Salmon spawning within the Cowlitz River is necessary for conservation and restoration. Additional information about where salmon are spawning and why they choose certain areas allows for more efficient management of the fishery. Fisheries managers can use this information to identify the locations and geomorphic characteristics of reaches that are occupied repeatedly by salmon and to more effectively protect these areas. The objectives of this study were to (1) examine temporal consistency (i.e., reoccupation) of spawning locations within a single year and among years, (2) determine if Chinook Salmon redds were distributed in distinct aggregations throughout the Cowlitz River, and (3) investigate the segment-scale habitat features that may be affecting redd distribution.

**METHODS**

**Study Area**

The Cowlitz River is located in southwestern Washington (Figure 1), and the lower Cowlitz basin encompasses approximately 1,140 km². The 82-km study section is located on the...
main-stem Cowlitz River between Kelso and the Barrier Dam, which is a diversion dam that allows fish to be captured and released in the upper river. Above the Barrier Dam, the Cowlitz River has three hydroelectric dams: Mayfield Dam, Mossyrock Dam, and Cowlitz Falls Dam. The Cowlitz River Salmon Hatchery is located at the Barrier Dam and has been operated by the Washington Department of Fish and Wildlife (WDFW) with support from Tacoma Power since 1968. Spring and fall Chinook Salmon and Coho Salmon _O. kisutch_ are produced in the hatchery but also spawn naturally in the Cowlitz River and upstream tributaries (Tipping and Busack 2004). There is no volitional fish passage through the Barrier Dam, and all fish that spawn in historic spawning areas above the Barrier Dam have been transported (Fulton 1968). The geologic setting of the lower Cowlitz valley consists of Eocene basalt flows and flow breccias and has a typical maritime climate with warm (16–24°C), dry (17–89 mm precipitation) summers and cool (8–17°C), wet (100–200 mm precipitation) winters. The majority of precipitation occurs as rain between October and March, resulting in peak flows occurring during these months; however, peak flows occasionally occur in the spring due to snowmelt. The flows below the Barrier Dam are regulated by hydroelectric dams, and any extremes in the hydrograph are moderated by flow regulation. Below Mayfield Dam, 80% of the land use within the basin is commercial timber harvest. Human population increases in Cowlitz and Lewis counties have also resulted in increased residential, industrial, and agricultural development along the river.

Forest climax species are western hemlock _Tsuga heterophylla_, Douglas fir _Psuedotsuga menziesii_, and western red cedar _Thuja plicata_, while red alder _Alnus rubra_, black cottonwood _Populus trichocarpa_, bigleaf maple _Acer macrophyllum_, and willow _Salix spp._ dominate the riparian areas (LCFRB 2004).

**Data Collection**

*Field surveys.*—Aerial surveys of redds on the lower Cowlitz River have been conducted by WDFW for Tacoma Power since the 1940s (Mark LaRiviere, Tacoma Power, personal communication) to evaluate population trends. We used data from 1991 to 2009 in this study because they were easily accessible and the methods from these years were most consistent. Four to six helicopter flights a year were conducted on a biweekly basis, depending on weather and river conditions, from mid-September through December. The accuracy and availability of redd data were dependent on weather and river conditions, which could cause very poor visibility due to high runoff during heavy rainfall. Chinook Salmon redds were easily observed from the air due to their large size and high visibility (Isaak and Thurow 2006). The river was divided into eight sections that ranged in length from 0.5 to 28.0 km and were demarcated by landmarks easily identified from the air, such as boat ramps and bridges (Figure 1). For each survey, Chinook Salmon redds were counted and recorded in each section. Each individual redd was counted whenever possible, but when densities were too high to count accurately, the number of redds was estimated.

Spring and fall Chinook Salmon both spawn in the main stem of the Cowlitz River, and we did not differentiate between the two runs when redds are counted during aerial surveys. There is evidence from carcass surveys that spring Chinook Salmon typically spawn in late September, during the time of the first aerial flight. For fish management purposes, WDFW uses a run timing date of September 30 to differentiate spring and fall adult salmon to the hatcheries. Carcass surveys show that the number of fall Chinook Salmon is consistently much higher than the number of spring Chinook Salmon, even during the time period when the two runs overlap. For example, in 2008 and 2009 the population estimates for spring Chinook Salmon were 425 and 763, respectively. Estimates for fall Chinook Salmon during these two years were 2,100 and 2,800, respectively (Q. Daugherty, Washington Department of Fish and Wildlife, unpublished data). Because the relative abundance of spring Chinook Salmon was so low in comparison to fall Chinook Salmon, we refer to Chinook Salmon redds in general for the purposes of this study. We do, however, refer to the two different runs in our analysis of the spatial distribution of the first and last redds.

In 2008 and 2009, a digital audio recorder (Olympus Digital Voice Recorder WS-2105) and a global positioning system (GPS; Garmin GPSmap 60CS) with a track log of geographic positions recorded at 1-s intervals were used to map the locations of each redd or cluster of redds. The recorded accuracy specified by the GPS at the time of measurement was approximately 15 m. All observations were made while the helicopter was in flight, but we were not able to hover over each individual redd. The entire flight was recorded in the GPS track log, and the times when redds were observed were noted on the audio recorder. When there were too many redds to identify individually, we attempted to count all of the redds in that area and then associated one GPS point with the aggregation of redds. This was often done in the section between Mill Creek Boat Launch and the Barrier Dam (Section 8) because there were high densities of redds and it was difficult to map each redd accurately with single GPS points. Visser et al. (2002) documented that redd counts are often underestimated due to high densities; therefore, these estimates may be slightly lower than the actual number. The length of Section 8 was approximately 500 m, and this distance was used as the minimum bin length (i.e., spatial resolution) for spatial analysis. Redd locations were georeferenced in the laboratory by synchronizing the GPS track log with the digital audio recordings from the flight. This information was then transferred into a geographic information system (GIS) database (ArcMap 9.3; Environmental Systems Research Institute, Redlands, California).

To characterize the depth patterns throughout the river, a Solinst LTC Levelogger Junior pressure transducer (vertical accuracy = 0.01 m; Model 3001; Solinst, Georgetown, Ontario) was towed behind a drift boat, near the river bottom, to record barometric pressure measurements every 2 s (Vaccaro and Maloy 2006). The drift boat floated with the current or was rowed at approximately 4 km/h in slow-moving sections
Spatial analysis and GIS.—Geomorphic variables at the 500-m segment scale that were evaluated in relation to redd distribution included distance upstream from the river mouth (river kilometer), channel bifurcation, tributary junctions, sinuosity, channel gradient, and depth discontinuities. To quantify these geomorphic variables, we used 1:24,000 U.S. Geological Survey (USGS) topographical maps, 2009 National Agriculture Imagery Program aerial photos (1 m resolution), and 10-m digital elevation models in ArcMap. A stream line was created using the National Agriculture Imagery Program photos. Linear referencing was used to assign route measures to the entire river, redds, and geomorphic features.

Segment-scale depth discontinuities are similar to transition areas between pools and riffles but on a larger scale (e.g., 500 m). The average relative depth over each segment was calculated from the barometric pressure measurements. We identified relative differences in the depth profile, where the river transitioned from a decreasing depth to an increasing depth. The absolute amount of change in depth was not calculated. Segments with depth discontinuities may have increased hyporheic–surface water interactions, which are known to affect redd site selection by spawning salmon (Brunke and Gonser 1997).

River characteristics that were evaluated included river kilometer, channel bifurcation, tributary junctions, sinuosity, and channel gradient. To examine channel morphology, we measured the length of multiple channels associated with islands in each section (Figure 2); the total length of channels by section provided a relative measure of the degree of channel bifurcation. Channel bifurcation was defined as the splitting of a channel into two or more active channels. To identify tributary junctions, we used a USGS topographical map and a 10-m digital elevation model to calculate flow accumulation (ArcMap Spatial Analyst toolbox). We included tributaries that appeared in both the flow accumulation analysis and were indicated on the USGS topographical maps. To calculate sinuosity, we divided the main-stem river route into 500-m segments and then used Hawth’s Tools (Beyer 2004) to measure sinuosity (Rayburn and Schulte 2009; Yan et al. 2010) for each segment. To calculate channel gradient, we used a method similar to Dauble and Geist (2000) based on USGS 1:24,000 topographical maps.

Statistical Analysis

Five different statistical analyses were conducted to examine the reoccupation, randomness, and habitat associations of the redds (Table 1). Fine-scale (500-m) spatial data were only available in 2008 and 2009. The coarse-scale spatial data were used only to investigate reoccupation historically. Reoccupation was examined at coarse and fine spatial and temporal scales. The fine-scale spatial data from 2008 and 2009 were used to determine whether redds were distributed randomly or in distinct aggregations. Regression analysis was performed to assess associations between habitat features and the number of redds; this analysis incorporated the fine-scale spatial data from 2009.

Reoccupation and spatial aggregation.—Reoccupation between the locations of historic redds (starting in 1991) and current redds in 2009 was examined by comparing redd counts in each section of the river over time (Figure 1). Due to availability of redd data, statistical analysis was performed for five nonconsecutive years: 1993, 1998, 2000, 2002, and 2009 (Table 1). We chose survey years that had at least five flights over the entire length of the river. There were five flights in 2004, but because spawning distributions in 2002 and 2004 were very similar, data from 2002 was used as that year had more redds. We
RESULTS

Reoccupation and Spatial Aggregation

Chinook Salmon consistently spawned in the same proportions in the same sections of the Cowlitz River during the years that were examined (Figure 3). The two sections closest to the Barrier Dam consistently had the highest density of redds. There were two reaches in which sections alternated in rank (i.e., sections 2 and 3 and sections 5 and 6). The lowest correlation coefficient between sections was 0.90, and the adjusted $P$-values were all less than 0.002. This indicated that (1) the ranks of sections by redd density for all of the years were highly correlated and (2) there was little variation in the ranks of the sections among years. The longitudinal trend in redd density with increasing density upstream was generally consistent among sections (Figure 3). The lowest correlation coefficient between section number and rank was 0.93, thus supporting the observation of the linear trend in Figure 3.

For the fine-scale reoccupation analysis of redd distributions in 2008 and 2009, the $G$-statistic was 17.14 ($P < 0.001$), indicating that redds occurred in the same locations in these 2 years (Figure 4). Spatial patterns of redd density were very similar in 2008 and 2009, even though the number of redds was 120% higher in 2009 ($n = 2,728$) than it was in 2008 ($n = 1,247$). Thus, we used data from 2009 for the habitat association study. The redds from the first and last weeks of the survey period occurred in the same sections in 2008 ($P < 0.02$) and 2009 ($P < 0.001$). Redds were clustered in 2008 and 2009 based on both the standard and median runs analyses ($P < 0.001$; Figure 4).

Segment-Scale Habitat Associations

Multicollinearity among explanatory variables in the 500-m model was not detected, and variance inflation factor values were slightly above 1 and none were larger than 2.0. Autocorrelation values were not larger than the 95% confidence interval lines, nor were there significant longitudinal trends; therefore, we assumed that there was no significant autocorrelation (Neumann...
et al. 2003). When using a Poisson distribution for the GLM, the data were overdispersed (Ver Hoef and Boveng 2007). The quasi-Poisson and negative binomial regressions both resulted in the same significant variables. The results from the negative binomial regression were used because (1) they included AIC values, which we used for model comparison purposes, and (2) quasi-Poisson regressions cannot calculate AIC values (Ver Hoef and Boveng 2007).

Stepwise model selection and AIC values and weights indicated that the best model for predicting redd distribution in 2009 included river kilometer, channel bifurcation, and sinuosity (Table 2; Figure 5). Redd density was positively associated with river kilometer and channel bifurcation and negatively associated with sinuosity (Table 3; Figure 5). River kilometer was the most significant variable but not the only important variable, as indicated by changes in AIC values. The 500-m model correctly
predicted the locations of 74% of the peaks in the observed data, but the model often underpredicted the total number of redds expected in those peaks (Figure 6).

DISCUSSION

Chinook Salmon in the Cowlitz River spawned in clusters and reoccupied the same areas at different spatial and temporal scales. To assess redd distribution at these different scales, we used data and analytical methods at scales that were different from previous studies. For example, our analyses were at the segment scale (80 km) and incorporated relatively high-resolution spatial data (500 m). Isaak and Thurow (2006) used cumulative curves and the Shannon–Wiener diversity index to demonstrate that redds were distributed nonrandomly in the Salmon River watershed in central Idaho, but these analyses were conducted at a basin scale. Neville et al. (2006) also examined randomness in the Salmon River redd data at a number of spatial scales (1, 2, 5, 10, and 20 km) and found that redds were distributed in clusters; however, they used autocorrelation function plots for
TABLE 2. Candidate GLMs and corresponding AIC values and weights. The top model was selected using backwards-elimination stepwise regression and AIC values and weights. The model with the lowest AIC was identified as the best model. Greater differences between respective models based on AIC weights indicate a better fit. Abbreviations are as follows: RKM = river kilometer, CB = channel bifurcation, SIN = sinuosity, TJP = tributary junction presence, DDP = depth discontinuity presence, and CG = channel gradient.

<table>
<thead>
<tr>
<th>Model</th>
<th>AIC value</th>
<th>AIC weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>RKM + CB + SIN</td>
<td>795.43</td>
<td>0.52</td>
</tr>
<tr>
<td>RKM + CB + SIN + TJP</td>
<td>796.45</td>
<td>0.31</td>
</tr>
<tr>
<td>RKM + CB + SIN + TJP + CG</td>
<td>798.26</td>
<td>0.13</td>
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<tr>
<td>RKM + CB + SIN + TJP + DDP + CG</td>
<td>800.24</td>
<td>0.05</td>
</tr>
</tbody>
</table>

FIGURE 5. Longitudinal profiles of bifurcated channel length, sinuosity, channel gradient (%), and redds (number/500 m) from 2009 in the lower Cowlitz River. Gray dashed vertical lines demarcate peaks in the 2009 Chinook Salmon redd distribution relative to spatial patterns of bifurcated channel length, sinuosity, and channel gradient.

generally understood that salmon spawn in clusters in the same areas each year; however, it is important to statistically examine these assumptions at different spatial and temporal scales to confirm that they are valid.

By comparing redd distribution between the first versus the last weeks of the spawning period, we were able to determine whether spring and fall Chinook Salmon were consistently spawning in the same areas in the Cowlitz River. The first redds of the year are built by spring Chinook Salmon, whereas the later redds are fall Chinook Salmon redds (Henning 2008). The redds from the first and last weeks of the survey period occurred in the same areas in both 2008 and 2009 (Figure 4). This is unexpected because typically in the Columbia River basin there is spatial separation between spring and fall Chinook Salmon spawning grounds, with spring Chinook Salmon spawning in smaller tributaries and upper reaches of principal tributaries and fall Chinook Salmon spawning in the lower river tributaries and main stem (Fulton 1968). For example, fall Chinook Salmon on the Yakima River only spawn in the lower river, typically below Granger, Washington, while spring Chinook Salmon spawn at least 100 km farther upstream, between the Easton Dam and Ellensburg, Washington, and in connecting tributaries (Major and Mighell 1969). On the Cowlitz River, spring Chinook Salmon spawn in the same areas as fall Chinook Salmon. Spring Chinook Salmon cannot migrate past the Barrier Dam and have to be transported in order to spawn in historic spawning areas (Fulton 1968). Therefore, some spring Chinook Salmon spawn in the lower portions of the Cowlitz River, which are preferred by fall Chinook Salmon. Our analysis used 500-m sections; therefore, we cannot conclude that redd superimposition is occurring in these highly used areas. However, the inability of spring Chinook Salmon to fully access their historic spawning areas suggests that migration barriers could cause competition between fall and spring Chinook Salmon for quality spawning habitat.

River kilometer was the most significant predictor of the spawning locations for the 500-m model predicting redd distribution in the Cowlitz River. The linear pattern of increasing spawning density up to the Barrier Dam is partially explained by the location of the Cowlitz River Salmon Hatchery adjacent to the Barrier Dam. This pattern also could be caused by the barrier
to the migration of salmon to their historic spawning grounds. Historically, all spring Chinook Salmon spawned above the Barrier Dam. There were also high-quality spawning grounds for fall Chinook Salmon directly above the Barrier Dam and farther upstream in a 13-km section that was inundated by Mayfield Reservoir (Fulton 1968). On the Yakima River, there is a similar linear trend in redd distribution up to the Easton Dam, which cuts off access to historic spring Chinook Salmon spawning areas (Dittman et al. 2010). There is fish passage at Easton Dam, but it is only operational during certain flows and most fish now do not pass the dam. Martin et al. (2004) also observed large numbers of Chinook Salmon returning to spawn directly below a fish barrier on the Green River that prevented migration to historical spawning areas.

Another factor that may contribute to the strong association of redd counts and river kilometer is that habitat quality increases on the Cowlitz River from rkm 30–82. In the first 30 km of the Cowlitz River, no redds were observed in 2008 and 2009; this area did not appear to have high-quality spawning areas, presumably due to high concentrations of silt and residential development in the lower Cowlitz River. Upstream of these highly developed residential areas, there is substantially less channel modification (e.g., levees and bank armoring), and the overall quality of spawning habitat is greater. Furthermore, sediment inputs in downstream reaches of the Cowlitz River have been high historically. For example, the Cowlitz River received large amounts of fine sediment from the Toutle River, which enters the Cowlitz River at rkm 25, due to the eruption of Mt. St. Helens in 1980. The volcanic eruption moved large amounts of sediment into both rivers, and recovery to preeruption sediment yields in the Cowlitz basin is not predicted for another 10 years (Major et al. 2000).

Channel bifurcation was positively associated with the occurrence of spawning in reaches in the Cowlitz River. Multiple channels are associated with intragravel flow on a large scale that is critical for incubating salmon (Brunke and Gonser 1997; Geist 2000). Increased intragravel flow often occurs at the upstream and downstream ends of channel bars and islands, where the river is slower and shallower (Brunke and Gonser 1997; Dauble and Geist 2000). Multiple channels also can be associated with an increased area of the riverbed available for spawning (Dauble and Geist 2000). High densities of salmon redds in the Cowlitz River were more likely related to islands and associated increased hyporheic flow as opposed to the increased area of the riverbed available for spawning. For example, a single split channel on the Cowlitz River was designated by fisheries managers in WDFW as an entire section for aerial surveys because of the high density of redds in the area. Dauble and Geist (2000) found that Chinook Salmon spawning in the Hanford Reach, Washington, were concentrated in braided river sections and areas that had complex channel formations. Coulombe-Pontbriand and Lapointe (2004) also found that large numbers of redds of Atlantic Salmon Salmo salar occurred near the upstream margins of channel islands in the Petite Cascapédia and Bonaventure rivers on the Gaspe Peninsula, Quebec.

Sinuosity was negatively associated with spawning locations in the Cowlitz River. The entire Cowlitz River had a very low sinuosity (1.6) and was often confined by levees and development, particularly on the lower river. Previous studies on the Columbia and Snake rivers have shown that areas with higher sinuosity have higher Chinook Salmon redd density at a 1.6-km scale (Dauble and Geist 2000). Additionally, Fukushima (2001) found that Sakhalin Taimen Hucho perryi preferred to spawn in sites located below highly sinuous reaches. However, sinuosity was only important as a predictor variable at a small scale (50 m). In higher-sinuosity streams that are not bounded by channel constraints, sinuosity has been associated with channel morphology and pool–riffle complexes that are associated with higher redd densities (McKean et al. 2008). However, on the Cowlitz River, sinuosity was not correlated with channel bifurcation or depth discontinuities from pool–riffle complexes. This is a potential explanation for the negative association between sinuosity and redd density in our study.

Tributary junctions, depth discontinuities, and channel gradient were not significant predictors of redd density on the Cowlitz River. These variables were positively associated with redd locations in previous studies at a reach and larger spatial scales. Tributaries can affect sediment inputs and create optimal locations for spawning (Rice et al. 2008). On the North Fork Stillaguamish River, Rice et al. (2008) found that patterns of Chinook Salmon redd distribution were not associated with tributaries at 1.1-km scale. However, tributaries were associated with spawning patterns at smaller spatial scales. Discontinuities in depth can also indicate areas of increased hyporheic–surface water exchange. Previous studies found redds in tailouts of pools and at the boundaries between pools and riffles (Bjornn and Reiser 1991), where a change in depth was associated with increased hyporheic–surface water exchange. These patterns have been described at multiple spatial scales (Baxter and Hauer 2000). We investigated these associations at a 500-m scale and found that depth discontinuities were not associated with redd locations in the Cowlitz River. Although we observed no association with channel gradient, lower-gradient areas typically have well-developed floodplains and gravel bars, and these areas have been
shown to have high densities of Chinook Salmon redd in the Columbia River basin (Fulton 1968; Dauble and Geist 2000; Dauble et al. 2003).

The GLM regression approach that we used effectively predicted areas of peak redd density (74% accuracy; Figure 6), but it underpredicted the number of redds at these peaks. The model also predicted that redds would be present in some locations where no redds were observed. The underprediction by the model of the number of redds at the peaks may be attributed to other factors and the scale(s) at which these factors were measured (Torgersen et al. 2012). For example, at the basin scale, the number of returning fish depends on ocean conditions, which were not incorporated into the model. Conversely, at small spatial scales, information such as sediment grain size, water chemistry, and velocity measurements, may be needed to obtain more accurate predictions. We found that segment-scale features accurately predicted where redds occurred in the Cowlitz River; however, to fully understand the observed patterns in redd distribution, a more detailed assessment at reach and basin scales is needed (Lapointe 2012). Further work on the Cowlitz River could involve spatially continuous surveys of sediment size and other reach-scale variables that could be included in predictive models (Brenkman et al. 2012).

Management Implications

Collecting location data with a GPS and digital audio recorder during aerial surveys of redd distribution is cost-effective and allows much greater flexibility for analysis of redd distribution across spatial scales. Many aerial redd surveys still rely on paper maps and require redd counts to be tallied in flight between landmarks over long sections (0.5–28.0 km) of river. With such low-precision techniques, important information about redd distribution patterns is lost, and analyses can only be conducted at coarse spatial scales. We found that relatively inexpensive GPS and digital audio technology can be used effectively in an aircraft and requires minimal postprocessing to analyze in a GIS. Furthermore, this approach can be used by fisheries managers who may have minimal training or experience with GPS or GIS.

Maps of salmon redd distribution and aquatic habitat are important tools in riverine fisheries management because salmon may spawn in the same sections of the river year after year, and this information can be used to prioritize habitat conservation and restoration efforts. In many rivers with anadromous salmonids in North America, river reaches with multiple channels provide more suitable areas for conservation and restoration. Knowledge of where salmon redds occur in relation to channel features that can be mapped using the publically available digital maps and data sources described in this study can help river managers plan reach- and segment-scale restoration efforts with greater confidence and potentially use engineered logjams to increase channel complexity (Roni et al. 2002). Segment-scale information of the type described by this study can be used in fisheries management to promote long-term population viability of Chinook Salmon in the Cowlitz River and in other similar rivers.

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