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DOES HYPORHEIC INTENSITY EXPLAIN SPAWNING SITE SELECTION?

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Pools and riffles are streambed geomorphic features that are important habitats for aquatic species. It is well-known that salmonid species utilize riffles or other transitional features between pools as spawning sites. Pools are characterized by deep water, low velocity and a gentle water surface slope, whereas the transitional riffles are characterized by shallow water depth, high velocity and a steep water surface slope. Here we hypothesize that hyporheic flow, which is an advective mechanism that brings oxygen-rich surface water into the sediment, may be an important cue for salmon spawning site selection. We analyzed the correlation between intensity of water surface curvature, used as a surrogate for hyporheic exchange and locations of Chinook salmon redds in Bear Valley Creek, central Idaho, USA. We used two-dimensional (2D) hydrodynamic model to simulate water surface elevations for low and bankfull discharges. Our results show that redd locations are highly correlated with areas of high potential hyporheic flow.

INTRODUCTION

Alluvial rivers are coupled with the subsurface groundwater system, abandoned side channels, oxbows and floodplain soils through hyporheic flows. The hyporheic flow can be defined as the exchange of surface and subsurface waters through the streambed sediment. It is a function of spatial and temporal variations in channel characteristics such as streambed pressure, alluvial volume and hydraulic conductivity [1-4] and it varies spatially and temporally [5-7]. The hyporheic zone can be divided into various biophysical zones based on magnitudes of physical, biological, and chemical processes in floodplain rivers [5]. The hyporheic zone is often defined hydraulically as the saturated streambed sediment enveloped by flow paths that enter the sediment in a high near-bed pressure zone and exit the streambed into the surface flow in a low near-bed pressure zone [4].

In downwelling flows, in-stream water enters the streambed sediment and transfers nutrients and dissolved oxygen to the pore waters, thereby regulating the type and quality of subsurface habitat available for different organisms[8].Upwelling flow transfers water including solutes from the subsurface to the stream [9]. Some studies have suggested that upwelling areas are more preferred by salmonids for spawning habitat than downwelling [e.g., 10]. However, Vronskiy and Leman [11] suggested that the amount of intragravel flow is more critical than flow directionality (upwelling or downwelling). Hyporheic flows have multiple important effects on riverine ecosystems by linking surface water fluvial processes, subsurface water, and riverine habitat for aquatic and terrestrial organisms. They also play a crucial role in the transport and retention of nutrients and organic matter in the subsurface zone. Thus, the hyporheic zone is an important element for the conservation, management, and restoration of the riverine ecosystems [2,12]. Furthermore, the hyporheic zone is crucial habitat for invertebrates and provides preferred spawning habitat for salmonid species [13,4].

Water surface elevation is representative of energy level in uniform flow and gradually varying streambed channels. Thus, water surface shape, i.e. convex or concave, can indicate upwelling or downwelling hyporheic flow areas [14]. However, uniform flow or gradually varying streambed channels are difficult to find in natural streams. Nonetheless, the water surface elevation may be used as a first-order approximation to estimate energy level, which is a driver of hyporheic flow [4].

Past studies have used hydrodynamic models to simulate hydraulic characteristics such as water depth, velocity and shear stress and to delineate spawning habitat. However, the magnitude of these hydraulic characteristics may vary significantly with the discharge and longitudinal slope of the stream. Additionally, these indices still do not entirely explain the selection of spawning sites. The curvature of the water surface has been suggested as a main driver for hyporheic exchange in gravel bed rivers with pool-riffle morphology.

We hypothesize that water surface curvature intensity, may be used as an indicator of hyporheic flow, and may help to predict the spawning site selection by salmonid: high curvature areas should be preferred over low curvature areas. We used a two-dimensional (2D) hydrodynamic model to simulate water surface elevations for low and bankfull discharges and computed water surface curvatures. Then we investigated the correlation between intensity of water surface curvatures and locations of observed salmon redds in Bear Valley Creek, central Idaho, USA.

METHODOLOGY

Study area

Bear Valley Creek is a tributary of the Middle Fork Salmon River (Figure 1) and has a watershed area of approximately 161 km^2. The hydrology is snowmelt dominated and the average annual precipitation is about 0.77 m. Base flows during the fall and winter vary between 0.8 and 1.3 m^3/s and bankfull discharge is approximately 7 m^3/s [7,15]. The stream is a pool-riffle reach type [16] with average channel width and slope of 15 m and 0.35%, respectively. The stream bed sediment is dominated by clean gravels (D_{50} = 54 mm). The channel flows through an extensive low-gradient meadow system and is highly sinuous (sinuosity index = 1.5) [15].

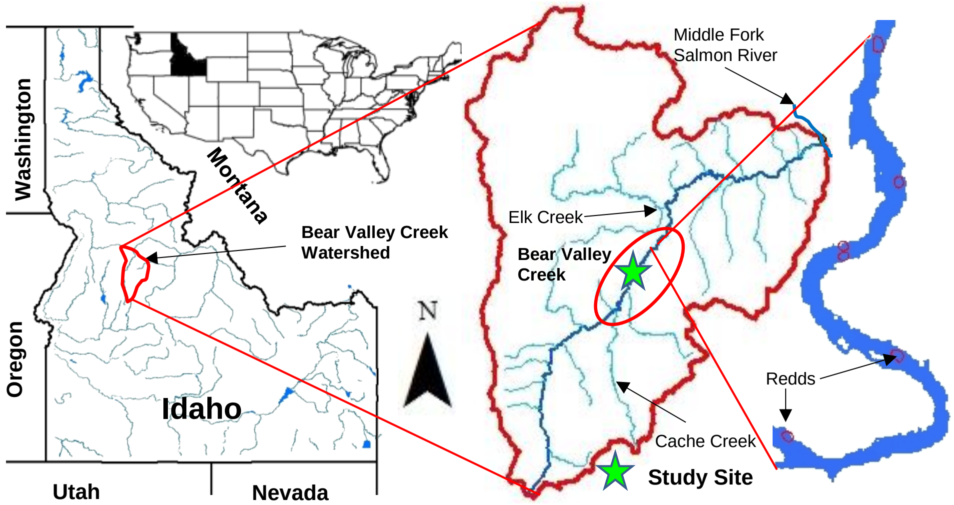

Figure 1. Beaver Valley Creek and redd locations

Redd survey

A salmon redd survey was conducted by the Rocky Mountain Research Station, USDA Forest Service, in 2012. Redds were located and the perimeters of disturbed sediment overturned by spawning fish were mapped in the field at each redd using global positioning system (GPS). These perimeter points around each redd were then used to create polygons of spawning activity.

Hydraulic model setup

We used the MIKE21 software as a 2D model for the study [DHI, 17]. The MIKE 21 flow model simulates unsteady two-dimensional hydraulic properties such as water surface elevations, depth-averaged flow velocities and bottom shear stresses based on channel bathymetry, bed resistance and eddy coefficients and employing a finite difference algorithm. The model solves the time-dependent, vertically-integrated Reynolds Averaged Navier-Stokes (RANS) equations of mass and momentum conservation in the two-horizontal directions [DHI, 17].

We set up the 2D model for a 13.5 km Bear Valley Creek between Cache and Elk Creeks utilizing a high-resolution (1 m grid cell) channel DEM, Manning's roughness and boundary conditions. Upstream and downstream boundary conditions were discharge and water surface elevations, respectively. We modeled two discharges: low (1.15 m^3/s) and bankfull (6.18 m^3/s) for the water surface simulation. The low flow coincides with the spawning period of Chinook salmon and the high flow corresponds with Steelhead trout spawning. Field observations have shown that Steelhead spawn in the same locations as the salmon. We assigned a uniform Manning's roughness for the entire study reach and optimized the roughness during model calibration.

Water surface elevations (WSE) are the typical benchmark for evaluating performance of hydrodynamic models of rivers. Thus, the model was iteratively calibrated to simulate a WSE comparable to the measured WSE for the low flow case. With the optimized Manning's roughness, the simulated low flow WSE matched the observed with a root mean square error of 0.11 m.

Water surface curvature

Two-dimensional (2D) water surface curvature in the direction of the maximum slope was computed from the input water surface on a cell-by-cell basis using a "Curvature" tool in a GIS program. Curvature was calculated as a second derivative value of water surface elevation. A positive second derivative corresponds to a locally convex water surface and thus upwelling flow, whereas a negative value corresponds to a concave surface and downwelling flow. Our hypothesis was that greater curvature caused greater hyporheic flow. We used absolute values of curvature because our study goal was to analyze the correlation between intensity, which can also defined as magnitude of curvature and salmonid redd locations. For each cell, a 9-term fourth-order polynomial equation was fitted to a surface composed of a 3x3 moving window [18,19]. The GIS program computes curvature of the surface on a cell-by-cell basis by fitting the surface through that cell and its eight surrounding neighbors. We computed curvature on a cell-by-cell (1 m grid cell) basis in the entire study area inundated by each specific discharge (i.e., 1.15 and 6.18 m^3/s).

Correlation between curvature intensity and redds

Curvature values were divided into classes based on the percentage of the curvature distribution using a quantile method for reclassification that assigns an equal number of values to each class (Table 1). We classified curvature distributions into 10 classes in order to calculate break values in the distribution. Thus, class 1 contains 10% of curvature values that had lowest intensity, whereas class 10 contains 10% of curvature values with highest intensity.

We extracted curvature values within the polygon around each observed redd location and averaged the values in the polygon to calculate the curvature intensity for each location. Later, this average curvature value was classified into the specific class using the class break values for curvature. Finally, we calculated the number of observed redds in each curvature intensity class for the two discharges in order to analyze correlations between curvature intensity and the incidence of observed redds.

RESULTS AND DISSCUSSION

A total of 73 redd locations were surveyed in the field. We defined low intensity curvature values for curvature class intensity 1 to 5, whereas high intensity curvature for classes 6 to 10. The areas with a curvature intensity of classes 1, 2, and 3 were the least used for redds with less than 5% of redds observed in these areas during both low and high discharges. Less than 23% (low flow) and 19% (bankfull) of redds were observed in low curvature intensity classes of 1 to 5 (Table 1). The greatest numbers of redds were constructed in areas with curvature intensity class 9 (Table 1).

Numbers of observed redds increased with higher curvature intensity for both discharges except for curvature intensity class 10 (Figure 2, left). The correlation coefficient (R^2) between numbers of redds and curvature intensity classes were 0.78 and 0.52, for low and bankfull discharges, respectively. Furthermore, correlation between frequencies of redds in each curvature intensity class for low and bankfull discharges was 0.79 (Figure 2, right). Thus, this analysis suggests that salmonids prefer areas with high curvature intensity for spawning.

Table 1: Break values for curvature intensity classes and redd frequencies in each intensity class for low and bankfull discharges.

CI class	CI Break value*		Frequency		Cumulative percentage	
	Q_l	Q_b	Q_l	Q_b	Q_l	Q_b
1	0.0061	0.0121	1	0	1	0
2	0.0133	0.0323	0	0	1	0
3	0.0269	0.0665	3	2	5	3
4	0.0482	0.1144	4	5	11	10
5	0.0801	0.1822	9	7	23	19
6	0.1343	0.2797	10	9	37	32
7	0.2301	0.4287	11	10	52	45
8	0.4197	0.6821	12	17	68	68
9	0.8919	1.2276	14	19	88	95
10	20.7939	37.3964	9	4	100	100

^{CI}Curvature intensity

*Curvature intensity break values based on whole study area

^{Ql}Low discharge ^{Qb}Bankful discharge

Previous studies [e.g., 14] have confirmed that water surface shape is an indicator of upwelling or downwelling hyporheic flow areas. Our results suggest that observed redds are predominately located within areas with high water surface curvature intensity and likely high hyporheic flows. These results are consistent with previous studies where salmonids preferred areas of greater hyporheic flow, even though other sites with otherwise similar physical habitat characteristics, such as substrate size, were available [20,13].

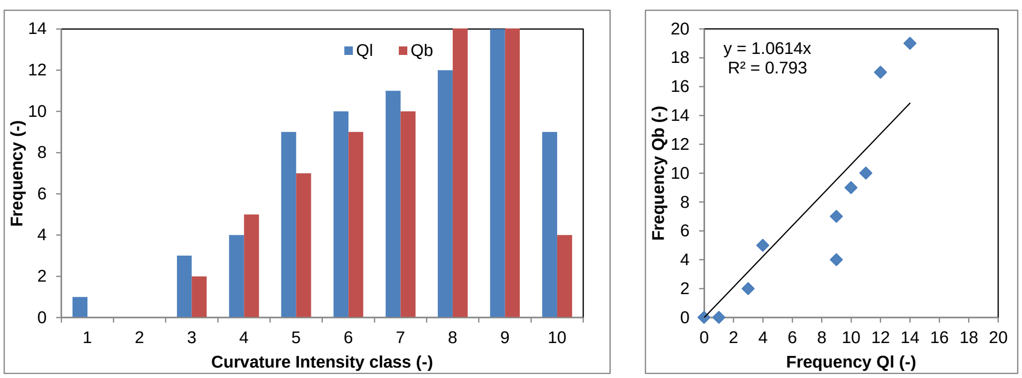

Figure 2. Numbers of redds observed in different curvature intensity classes (left) and correlation between frequency of redds in each curvature intensity classes for low and bankfull discharges.

In this stream, curvature intensity class does not change with magnitude of discharge, although the absolute magnitude of curvature does change. Thus, our approach to divide curvature intensity into 10 classes is justified and the approach is robust with different discharges. Hence, this approach can be used to analyze the correlation between redd locations and curvature intensities. We propose that water surface curvature is a key indicator of salmonid spawning habitat and thus should be included in spawning habitat analyses along with channel substrate particle size distributions, flow velocity and water depth.

CONCLUSIONS

Previous studies have used multiple parameters such as water depth, velocity and substrate to predict spawning habitat for salmonid species. The prediction can be improved by introducing other geomorphic and hydraulic parameter such as hyporheic flow. We hypothesized that hyporheic flow intensity approximated by a strong water surface curvature can explain site selection for spawning habitat by salmonid species. Our result showed that there is a strong correlation between site selection and water surface curvature intensity. Furthermore, the classified intensity of curvature is insensitive to discharge and the approach developed in this study can likely be used in other areas to analyze salmonid habitat.

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