New Tools for Aquatic Habitat Modeling

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Abstract: *Modeling of aquatic microhabitat in streams has been typically done over short channel reaches using one-dimensional simulations, partly because of a lack of high resolution subaqueous topographic data to better define model boundary conditions. The Experimental Advanced Airborne Research Lidar (EAARL) is an airborne aquatic-terrestrial sensor that allows simultaneous high resolution surveying in both environments over spatial domains of up to several hundred kilometers of stream length. Here we use the USGS two-dimensional finite difference fluid dynamics model, FaSTMECH, run under the graphical user interface MD-SWMS and supported by EAARL bathymetric data, to investigate spawning habitat of threatened fish species in central Idaho, USA. We run the model at several discharges to quantify the effects of flow regime on habitat quality of salmonid spawning and rearing sites under present and future climate scenarios which generated two distinct mean water year hydrographs. Results indicate that predicted climate-change induced variations in the annual hydrograph will lead to overall improved steelhead trout habitat relative to that of chinook salmon.*

Keywords: *Lidar, aquatic habitat, two dimensional numerical modeling*

1. INTRODUCTION

Riverine systems represent some of the most critical landscapes on earth due to their social, economic and ecological importance. However, the demand of human societies to harvest fresh waters has been decreasing their ecosystems quality (Johnson *et al.*, 2001). Large dams (41,000 globally), diversions, flood control projects, land use, and dewatering because of the needs of a growing human population contribute to the decline of aquatic habitat and species (Johnson *et al.*, 2001; Nilsson *et al.*, 2003; Nilsson *et al.*, 2005; Ward, 1998). In addition to the variety of anthropogenic factors that have influenced declines of aquatic habitats over many decades, the effects of temperature and precipitation variability due to climate change also need to be included as influencing species persistence. For instance, observational studies have shown increasing trends in both temperature and precipitation over the western United States over the past century (Hamlet *et al.*, 2005), a decrease in the April 1 peak snow water equivalent levels, and a trend toward earlier spring snowmelt.

Beginning in the late 1970s aquatic habitat modeling employed the in-stream flow incremental methodologies (IFIM), a 1 dimensional hydraulic model inside a physical habitat simulation model such as PHABSIM (Bovee, 1982) to determine minimum recommended flows based upon weighted usable area (WUA) (Leclerc *et al.*, 1995; Mouton *et al.*, 2007). These 1D hydraulic models rely upon cross-section measurements to derive reach average depth and velocity at the hydromorphological unit ("homogenous" area between cross sections) (Tickner *et al.*, 2000) or cross-sectional velocity and depth profiles based on cross-section topography (Beven & Kirkby, 1978). This habitat modeling has several limitations: 1. low spatial and temporal resolutions; 2. mean depth and velocity values that are only reliable as long as the calibration of the roughness coefficient is applicable; 3. predictions outside of the measured discharge interval or for an area of less than 10 m^2 are not reliable; 4. areas subject to wetting and drying due to discharge variations are not easily calibrated; 5. field campaigns are time and cost intensive (Leclerc et al., 1995).

Recently two-dimensional hydraulic models have been developed to overcome these deficiencies especially the prediction of aquatic habitat at a scale relevant to fish (Crowder & Diplas, 2002; Ghanem *et al.*, 1996; Hardy, 1998). Two-dimensional models are advantageous over their 1D counterparts in that spatial resolution can accurately describe spatial gradients of hydraulic parameters within cross sections, wetting and drying at different discharges, and flow resistance variables (Leclerc *et al.*, 1995). The high resolution of hydraulic conditions made available by two-dimensional models allows for flow field parameters that are difficult to measure, such as the total hydraulic strain describing turbulence (Nestler *et al.*, 2008), to be incorporated into the calculation of WUA. However, a limitation of two-dimensional models is the need of accurate and detailed topography of streams and surrounding floodplains. The advent of robotic total stations, differential global position systems (DGPS) and remote sensing, such as the Experimental Advanced Airborne Research LIDAR (EAARL), is ameliorating this problem (McKean *et al.*, 2009a, 2009b; McKean *et al.*, 2009c). EAARL uses a low-power, narrow-beam green laser with short pulse length to gather and record reflected energy from terrestrial and submerged morphological features (McKean *et al.*, 2009c). Pulse data are geo-located using GPS and inertial navigation trajectories. Data processing is done with the Airborne Laser Processing Software (ALPS) developed by the US Geological Survey (USGS) and the National Aeronautics and Space Administration (Bonisteel *et al.*, 2009; Nayegandhi *et al.*, 2006). The results include measurements of basic channel bathymetry with errors often in the range of ±8-13 cm, and support one and two-dimensional fluid dynamic models. The resulting topographical errors have negligible effects on hydraulic model predictions (McKean *et al.*, in review).

Here, we used the Multi-Dimensional Surface Water Modeling System (MD-SWMS)(McDonald *et al.*, 2005), a two-dimensional computational fluid dynamic model to evaluate the effect of climate change on salmonid habitat through hydrograph simulations of an important salmonid stream. We focused on two life stages (spawning and rearing) of threatened species of steelhead trout (*Oncorhynchus mykiss*) and Pacific Chinook Salmon (*Oncorhynchus tshawytshca*).

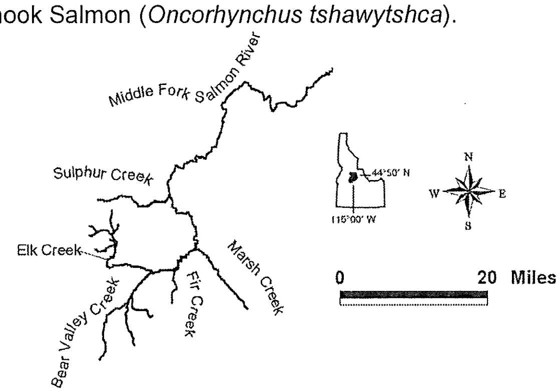

Figure 1 Bear Valley Creek located in the Middle Fork of the Salmon River headwaters, Idaho, USA.

2. STUDY AREA

The study concentrates on a 1.6-kilometer meandering reach of Bear Valley Creek, a headwater tributary of the Middle Fork of the Salmon River located within the Boise National Forest (Figure 1). The mean watershed elevation is 2152 m a.s.l. with 70% forest cover largely composed of lodgepole pine and subalpine fir forest with extensive meadow systems (USFS, 1990). The study site has a mean bankfull width of 15 m, mean streambed slope of about 0.003 $m \cdot m^{-1}$ and median bed surface diameter (d_{50}) of 0.052 m. Wet winters and dry summers characterize the local climate. As with most of the western United States, annual precipitation for the drainage falls as snow from November through March (Thurow, 2000). Precipitation stored in the snow pack and groundwater is the primary source of base flows during the dry summer months. Depending on elevation and topography average annual precipitation in the area ranges from 370 to 820 mm and average annual temperatures range from 1.4 to 6.8°C. Stream hydrographs are characteristic of a snowmelt-driven system, in which peak stream flows correspond with spring and early summer snowmelt, which begins around April and can extend into early June. The remainder of the year is dominated by low flows (Figure 2a). Global climate change predictions for the Pacific Northwest indicate negligible change in the total amount of precipitation but considerable variation in timing and type of precipitation. They predict higher amounts of early spring rains, reduced snowpack and more summertime precipitation. These alterations in precipitation pattern will force an earlier lower hydrograph peak with possible rain-on-snow winter floods (Figure 2b).

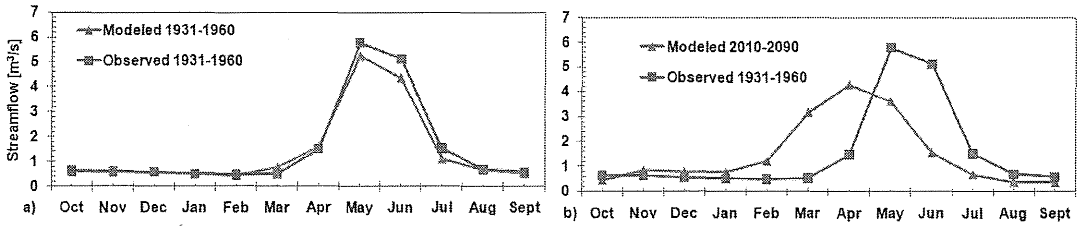

Figure 2 a) Comparison between modeled and observed 1931-1960 averaged water year and b) present (1931-1960) and predicted (2010-2050) averaged water year for Bear Valley Creek.

3. METHOD

3.1. Hydrologic model

The averaged water year for Bear Valley Creek was estimated from the USGS gauge Station Bear Valley Creek NR Cape Horn, ID (Nr. 13309000). The averaged water year measured at the USGS gauging station was scaled to the expected low discharges in Bear Valley (Figure 2). The Variable Infiltration Capacity (VIC) land surface hydrology model (Liang *et al.*, 1994) was utilized to simulate streamflows in a 1/16° spatial resolution for the future period of 2011 to 2090. The VIC model is a macro-scale grid-based water and energy balance model, which has been successfully applied over many large river basins with reasonable results (Abdulla *et al.*, 1996; Maurer *et al.*, 2002; Tang & Piechota, 2009). The future meteorological forcing (precipitation and temperature) data for the VIC model was statistically downscaled from the IPCC the Fourth Assessment Report AR4 (Intergovernmental Panel on Climate Change (IPCC), 2007) (Figure 2).

Table 1 Grain size distribution

Diameter [m]	Percent of Finer	Shear Stress [Pa]	Erosion [m]	SI
0.003	0.01	2.1	0.001	1
0.005	0.03	3.4	0.002	1
0.006	0.07	4.2	0.003	1
0.008	0.11	5.9	0.005	1
0.011	0.13	8.3	0.008	1
0.016	0.16	11.7	0.012	1
0.023	0.21	16.7	0.020	1
0.032	0.31	23.6	0.036	0.9
0.045	0.42	33.3	0.069	0.5
0.064	0.61	47.1	0.180	0.1
0.091	0.80	66.6	0.562	0
0.128	0.91	94.3	1.878	0
0.181	0.96	133.3	No armor layer	0
0.256	0.99	188.5	No armor layer	0
0.362	1.00	266.6	No armor layer	0

3.2. Hydraulic modeling

The EAARL sensor provided the channel and terrestrial topographic information used as input to MD-SWMS. The model solves the vertically averaged shallow water equations on a curvilinear coordinate system grid with isotropic turbulence (D. J. Smith & McLean, 1986). We developed a 1m-by-1m numerical grid for the 1.6 km long reach. Tonina & McKean (2010) calibrated the model at low flows (1 $m^3 \cdot s^{-1}$) for the same stream reach and provided the calibration values of z_0 (depth at which velocity is equal to zero in the law-of-the-wall model (McDonald *et al.*, 2005)) equal to 0.006 m and of the lateral eddy viscosity to 0.05 $m^2 \cdot s^{-1}$, which we kept both constant at all flows. A quasi-three dimensional flow model associated with MD-SWMS was used to predict water depth, flow velocity and bottom shear stress based on hydraulics over a range of discharges from 1 (base flow) to 6 (bankfull) $m^3 \cdot s^{-1}$. Convergence of the numerical simulations was reached when mass balance was between ±3% at each cross section.

Table 2 Suitability Index

Chinook Spawning						Chinook Rearing					
Depth [m]	SI	Velocity [m/s]	SI	Sediment [m]	SI	Depth [m]	SI	Velocity [m/s]	SI	Sediment [m]	SI
0	0	0	0	0	0	0	0	0	0.25	0	0
0.1	0	0.15	0	0.002	0	0.15	0.5	0.008	0.5	0.002	0.2
0.15	0.3	0.2	0.2	0.011	0.6	0.3	1	0.05	1	0.011	0.4
0.26	0.6	0.3	0.3	0.013	1	0.8	1	0.2	1	0.013	1
0.3	1	0.45	0.5	0.025	1	0.9	0.4	0.35	0.9	0.052	1
0.9	1	0.5	1	0.13	1	1.2	0.1	0.38	0.75	0.11	0.5
1.5	0	0.9	1	0.2	0.5	1.5	0	0.7	0.1	0.13	0.3
		1	0.8	0.3	0					0.15	0.2
		1.5	0							0.17	0.1
										0.2	0.1
Steelhead Spawning						**Steelhead Rearing**					
Depth [m]	SI	Velocity [m/s]	SI	Sediment [m]	SI	Depth [m]	SI	Velocity [m/s]	SI	Sediment [m]	SI
0	0	0	0	0	0	0	0	0	0.2	0	0
0.2	0	0.2	0	0.002	0	0.05	1	0.02	0.5	0.002	0.6
0.25	1	0.3	0.5	0.013	0.3	0.25	1	0.04	0.75	0.013	1
0.6	1	0.4	0.8	0.025	1	0.4	0.6	0.1	1	0.025	1
0.73	0.5	0.5	1	0.052	1	0.5	0.3	0.25	1	0.052	1
2	0.5	0.75	1	0.13	0.5	0.6	0.1	0.3	0.75	0.13	1
		1.05	0.5	0.2	0	3	0.1	0.35	0.5	0.2	1
		1.4	0					0.4	0.25	0.31	1
								0.5	0.15		
								0.75	0		

3.3. Habitat modeling

The habitat model is based on literature-derived univariate habitat suitability curves of water depth, flow velocity and streambed material for each species and life stage (Bjornn & Reiser, 1991; Groves & Chandler, 1999; Hampton, 1988; Hardy & Addley, 2001; Raleigh *et al.*, 1984; A. K. Smith, 1973). Near-bottom shear stresses were analyzed to test whether they were large enough to mobilize sediment and scour salmonid eggs. Scour depth was estimated with the Borah model (Borah, 1989), which is based on applied shear stress and streambed material. The method estimates the scour depth E subtracting the size of the smallest grain D_a composing the armor layer from the size of the active-layer thickness T:

$$T = \frac{D_a}{(1-e)P_a} \tag{1}$$

where e is the porosity of the bed material and P_a the fraction of the armor sizes present in the bed material. Table 1 reports for each particle size the critical shear stress, which mobilizes the particles and the corresponding erosion depth.

Suitability of a physical characteristic is expressed as an index ranging from 0 to 1. The product of the suitability indexes for each physical parameter (SI_v, SI_d, SI_s, SI_τ, the suitability index for velocity, depth, substratum and shear stress, respectively) determines the overall suitability for the cell (CSI). This method for defining habitat quality assumes independent physical parameters, i.e. no correlation among velocity, depth, substratum, and shear stress in characterizing a habitat, neglects behavioral choices or biotic factors such as food availability, predator presence, and considers one species at a time without relation with other organisms. The habitat quality at the reach scale is then estimated using two parameters the weighted useable area (WUA) and the hydraulic habitat suitability (HHS) (Bovee, 1978).

$$WUA = \sum_{i=1}^{n} CSI_i\, A_i \quad and \quad HHS = \frac{WAU}{A_W} \tag{2}$$

where n is the number of cells within the wetted area A_w of the stream and A_i is the area of the i-th cell. Both parameters, which are functions of discharge, provide information about the proportion of area and suitability of habitat in the stream.

Fall Chinook salmon typically spawn in Bear Valley Creek between late July and early September and Steelhead salmon between middle of March and middle of July. After hatching, both species will rear in the reach for 1 to 2 years before migrating downstream.

4. RESULTS AND DISCUSSION

4.1. Climate change

Comparison between the measured and predicted hydrographs for Bear Valley shows a good match with a 9% error on the peak discharge (Figure 2a). This result provides support for the application of the VIC model in predicted the future averaged flow regime in Bear Valley Creek (Figure 2b). The 2010-2090 predicted hydrograph shows a lower (26%) and earlier (approximately 30 days) peak than the historic hydrograph with longer and smoother tails and higher winter flows (Figure 2b). This pattern is probably due to a warmer spring period, which may trigger earlier snowmelts.

4.2. Aquatic habitat

Figure 3 reports the current WUA and HHS for Chinook and steelhead spawning and rearing. Both species rear for 1 - 2 full years with WUA ranging from 18000 to 11000 m^2 and from 9500 to 18000 m^2 for Chinook and steelhead, respectively. Chinook and steelhead spawning WUA is important only during spawning season, which is shown in Figure 3, and it varies from 8500 to 15000 and from 4000 to 16000 for Chinook and steelhead. WUA may vary due to changes in wetted area as well as fluctuations in habitat quality. To account for the changes in area we also plotted the HHS, which shows a wider range of variability of habitat quality for both species and life stages. Spawning WUA increases with discharge up to 5 $m^3 \cdot s^{-1}$ and then decreases, whereas rearing habitat quality decreases with increasing discharge reaching the lowest value at the highest flow.

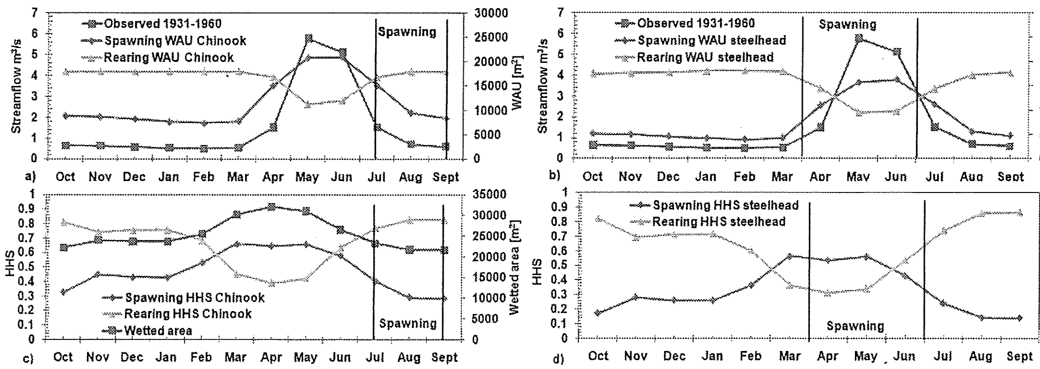

Figure 3 Current weighted useable area (WUA) (a. and b.) and hydraulic habitat suitability (HHS) (c. and d.) for spawning and rearing along the study site in Bear Valley Creek for Chinook and steelhead salmonids.

Table 3 Percent change in weighted usable area (WUA) and wetted area due to predicted climate change

Month	Hydrograph	Chinook Spawn		Chinook Rearing		Steelhead Spawn		Steelhead Rearing		Wetted area
		WUA	HHS	WUA	HHS	WUA	HHS	WUA	HHS	
	[m³·s⁻¹]	[m²]		[m²]		[m²]		[m²]		[m²]
Oct	-27			0	4			4	9	-4
Nov	37			-1	-5			-5	-10	5
Dec	37			0	-5			-5	-9	4
Jan	50			0	-6			-6	-11	6
Feb	151			-3	-15			-16	-26	14
Mar	503			-24	-44	301	198	-39	-54	34
Apr	185			-26	-39	56	28	-30	-43	22
May	-37			17	30	11	23	11	23	-10
Jun	-70			39	76	-30	-12	47	85	-21
Jul	-54	-38	-30	7	21			20	37	-12
Aug	-46	-34	-29	0	7			8	16	-7
Sept	-38	-27	-23	0	5			6	11	-5

The predicted 2010-2090 hydrograph has reduced late spring and summer flows and higher winter and early spring flows, which provide almost unchanged Chinook rearing fall and winter conditions and improved summer conditions (Table 3). In contrast, the forecast larger spring flows cause a decrease in Chinook rearing habitat WUA and HHS. However, these values are still larger than in the current WUA or HHS because of the predicted lower peak flows (Figure 2b). Steelhead rearing habitat deteriorates in the future climate between November and April, but it increases the remaining part of the year. The WUA and HHS decrease is within the yearly variability noticed in the current conditions. Chinook spawning habitat suffers a considerable reduction of 27% to 38%. Conversely, steelhead have a substantial improvement as we simulated almost a 200% increase in HHS in March from the present situation. The future climate seems to provide better aquatic habitat conditions for steelhead than Chinook. Although rearing conditions improve for Chinook salmon, spawning conditions deteriorate due to low flows. However our analysis does not account for temperature variations, which may cause additional stress on Chinook populations.

New emerging techniques such as the EAARL system, which allows mapping large river networks, powerful and low-cost computers and faster numerical flow models coupled with biological models are allowing us to analyze the impact of anthropogenic activity or climate change at unprecedented spatial scales approaching whole rivers.

5. CONCLUSION

Here we showed that new remote sensing techniques coupled with physical and biological numerical models may be used to analyze complex processes such as aquatic habitat at a meaningful biological scale. Our results suggest that aquatic effects of climate change can be complex and must be locally analyzed. Our preliminary predicted changes in flow regime in Bear Valley Creek are expected to improve steelhead spawning and rearing habitat, but may reduce the spawning habitat for Chinook salmon.

6. ACKNOWLEDGMENTS

Funding for this research was provided by the U.S. Forest Service through the National Fire Plan program and the Rocky Mountain Research Station, Boise, Idaho.

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