

CLIMATE CHANGE IMPACT ON SALMONID SPAWNING IN LOW-GRADIENT STREAMS IN CENTRAL IDAHO, USA

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Climate change is often predicted to cause a significant perturbation to watershed hydrology. It has been generally associated with negative impacts on natural systems, especially in conjunction with conservation and protection of sensitive ecosystems. In the U.S., spawning habitats of threatened and endangered salmonid species are important areas that are potentially vulnerable to climate change through variations in flood timing and magnitude, water temperature, and sediment input. In this work, we used a numerical model to investigate whether changes in flow regime, of the type predicted by some climate change scenarios for mountain streams in the western U.S.A., would affect spawning site stability. We ran a two dimensional hydraulic model that simulated several flow regimes from low to bankfull stage and mapped grain mobility. We defined the model boundary conditions with high-resolution airborne bathymetric lidar surveys of an important spawning stream in central Idaho, USA. Our analyses showed that such unconfined low-gradient streams have not a great danger of extensive bed mobility, even at high flows. Consequently, in this landscape, alterations in flood timing due to climate change are unlikely to decrease the success rate of salmonid egg incubation by the mechanism of increased channel bed scour.

INTRODUCTION

Climate and geology have a profound impact on watershed hydrology, morphology, land use and land cover [1, 2]. These ecosystem attributes influence river networks and aquatic habitat as they affect magnitude, frequency, duration, and rate of change of flood events [3, 4]. In turn, changes in flood timing and magnitude affect water temperature, erosion and deposition patterns, wood recruitment and riparian vegetation density and type [5, 6]. Many mountainous watersheds in the western United States have a typical snowmelt-dominated annual hydrograph with peak flows during the spring and early summer and very low flows in autumn and winter. Stream fishes in these areas have evolved life stages and behaviors that are adapted to this hydrologic regime. For example, successful fish populations have spawning strategies that include avoiding times of high flow and bed mobility, avoiding sites of excessive mobility or burying their eggs beneath the typical depth of bed mobility [7-10]. Thus, spawning Chinook salmon (*Oncorhynchus tshawytscha*), deposit their eggs in the gravel beds of mountain streams in late summer and their embryos and alevins develop in the gravel interstices during the winter low flows. Fry emerge from the streambed into the water column in spring before peak high flows [7]. In contrast, summer steelhead (*Oncorhynchus mykiss*) spawn primarily in spring (late March-mid June), typically just prior to the peak snowmelt, with fry emergence in June-July, after peak flows.

Recent studies in the western United States suggest an emerging shift from the normal snowmelt-dominated hydrologic regime toward a more rainfall-dominated system, with abnormally high flows caused by large winter rainfall or rain-on-snow events as well as earlier seasonal snowmelt [11]. Potentially these mid-winter high flows could be large enough to scour the egg nests (redds) constructed in the streambed during the previous autumn by Chinook salmon, and an earlier snowmelt could be detrimental to steelhead spawning.

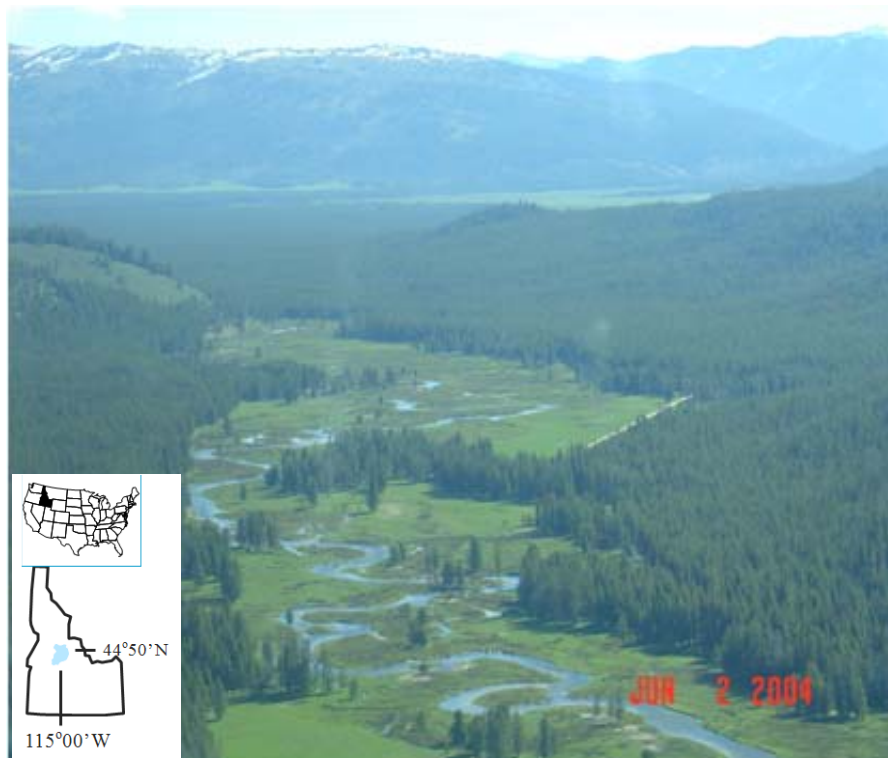


Figure 1. Study site of the Bear Valley Creek (central Idaho, USA) near bankfull stage.

Here, we investigate whether climate change-induced winter floods may trigger extensive streambed sediment mobility, scour incubating eggs and hence threaten salmonid populations. Our study area is a segment of a salmonid spawning stream that we mapped with the bathymetric Experimental Airborne Advanced Research Lidar (EAARL) [12, 13]. We used a two-dimensional hydrodynamic model to predict near-bed shear stresses at discharges ranging from low to high flows. We then predicted the streambed sediment mobility and investigated the effect of seasonal flow regime changes on embryo survival.

METHODS

Study site and field surveys

Bear Valley Creek is an important salmon-spawning tributary of the Middle Fork Salmon River in central Idaho, USA (Figure 1). Wide alluvial valleys and narrow confined canyons characterize its course with the former sites hosting the natal beds for autumn-spawning Chinook salmon and spring-spawning steelhead. We chose this stream because of its ecological importance and concerns of the consequences that climate change may

have on these species. We selected a 1.6-kilometer meandering reach with mean bankfull width of 15 m and streambed slope of about $0.003 \text{ m}\cdot\text{m}^{-1}$ in a wide alluvial valley section of the stream (Figure 1). This section contains important spawning sites, which are located on convexities between pools in the streambed. The substrate material is primarily gravel with median surface diameters (d_{50}) equal 0.052 m and 0.035 m for the overall reach and for the spawning sites, respectively. Figure 2 shows the grading curves, which were estimated with a surface pebble-count technique for spawning sites and for the entire study reach [14]. The entire reach is coarser than the spawning sites because it encompasses also plane bed reaches with large cobbles. We also measured surface water elevations in a 200-meter long sub-reach and the mean vertical velocity along one cross-section at a discharge of $0.93 \text{ m}^3\cdot\text{s}^{-1}$. This information was used to calibrate the two-dimensional hydraulic numerical model. In October 2007, we conducted a detailed survey of the aquatic topography with the EAARL. This is a narrow beam laser able to collect both submerged bathymetry and terrestrial topography simultaneously. The EAARL system has a vertical root-mean-square-error of approximately 0.1 m in point elevation measurements, but tests show this uncertainty has limited impact on the near-bed shear stress distributions predicted with a two-dimensional model in this stream [13]. We generated a 3m-by-3m raster for the stream and surrounding floodplain from the lidar point cloud, which has an approximately 0.3 point per meter density.

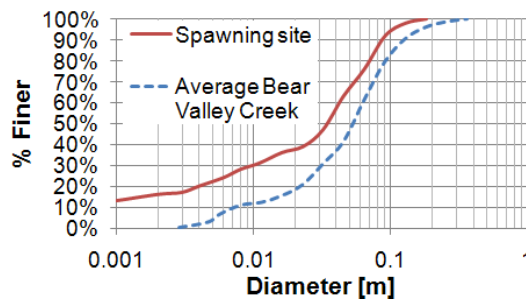


Figure 2. Grain size distribution for the entire reach and for the spawning sites within the reach.

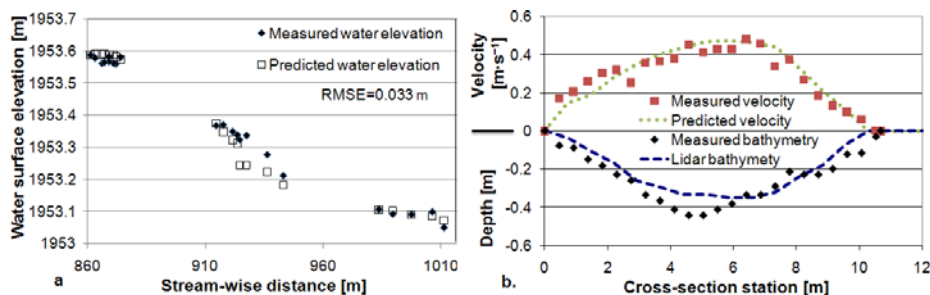


Figure 3. Comparison between a. measured and predicted water elevation, b. between measured and predicted cross-sectional velocity distribution and between ground and EAARL measured bathymetry.

Numerical model

We used the Multidimensional Surface Water Model System (MD-SWMS) developed by the US Geological Survey [15] to predict surface water, flow velocity, and shear stress at the stream bed. The model solves the vertically averaged shallow water equations on a curvilinear coordinate system grid [16]. It predicts shear stresses based on a drag coefficient, whose value may be constant or spatially variable. The resistance varies spatially in either method, because it depends on water depths [16]. We defined the drag

coefficient based on the z_0 parameter, which indicates the depth at which velocity is equal to zero (no-slip condition) in the logarithmic distribution of the vertical velocity [15]. We used a numerical grid space of 1m-by-1m and we calibrated the roughness with the available water surface elevation measured at a low discharge $0.93 \text{ m}^3\cdot\text{s}^{-1}$. We defined the z_0 equal to 0.006 m, which corresponds to 15% of the d_{50} of the entire reach, and the lateral eddy viscosity to $0.05 \text{ m}^2\cdot\text{s}^{-1}$. This calibration provides a good match between measured and predicted water elevation (Figure 3a) and flow velocity (Figure 3b).

After calibration, we kept z_0 and the lateral eddy viscosity constant and ran the model at different discharges between 1 and $6 \text{ m}^3\cdot\text{s}^{-1}$ (bankfull discharge) with increments of $1 \text{ m}^3\cdot\text{s}^{-1}$. Note that while z_0 is constant, the drag coefficient correctly decreases with discharge and water depth.

Table 1. Grain class diameters and their critical shear stresses evaluated with equations (1) and (2)

Class Diameter [m]	Critical Shear Stress [Pa]
0.001	18.5
0.002	19.7
0.003	20.5
0.004	21.1
0.006	21.9
0.008	22.5
0.011	23.1
0.016*	24
0.023*	24.8
0.032*	25.6
0.045*	26.4
0.064*	27.3
0.091*	28.2
0.128*	29.1
0.181	30.1

*preferred substratum size for Chinook salmon spawning areas

Sediment mobility

We estimated grain size mobility by comparing the applied shear stress predicted by the numerical model at each node with the critical shear stress of each grain size (Table 1). Grain size heterogeneity causes a hiding effect that reduces the mobility of fine particles that are sheltered by coarse sediment, and increases the mobility of large grains as they are more exposed to the flow than in a streambed with uniform material. The work of Andrews and Parker [17] provides a relationship for estimating the dimensionless critical shear stress $\theta_{c,i}$ (Shields number) for any grain of diameter d_i in a heterogeneous stream bed based on the surface material distribution:

$$\theta_{c,i} = \theta_c \left(\frac{d_i}{d_{50}} \right)^m \quad (1)$$

where d_{50} is the median diameter of the surface material and the parameters θ_c and m are equal to 0.0455 and -0.9067, respectively. The critical shear stress for each grain size is

$$\tau_{c,i} = \theta_{c,i} g (\rho_s - \rho_w) d_i \quad (2)$$

where g is the acceleration of gravity, and ρ_s and ρ_w are the density of the sediment and water, respectively. Thus, particles will be mobile when the applied shear stress is larger than the critical value.

RESULTS AND DISCUSSION

Figure 4 shows the near-bed shear stress distribution in the study reach at low discharge, which is representative of the present winter flow regime, and at bankfull, which represents the discharge causing the maximum bottom shear stress. In this unconfined stream, discharges larger than bankfull flow inundate the floodplain, which prevents the stress from increasing further. Shear stresses are low in most of the channel at both discharges and only increase in transitional areas where the surface water shallows, e.g. some of the downstream tails of pools, riffle crests and the upstream pool heads. Only at a few of these sites are the stresses large enough to mobilize spawning gravels with a diameter greater than about 20 mm (critical shear stress ≥ 24 Pa).

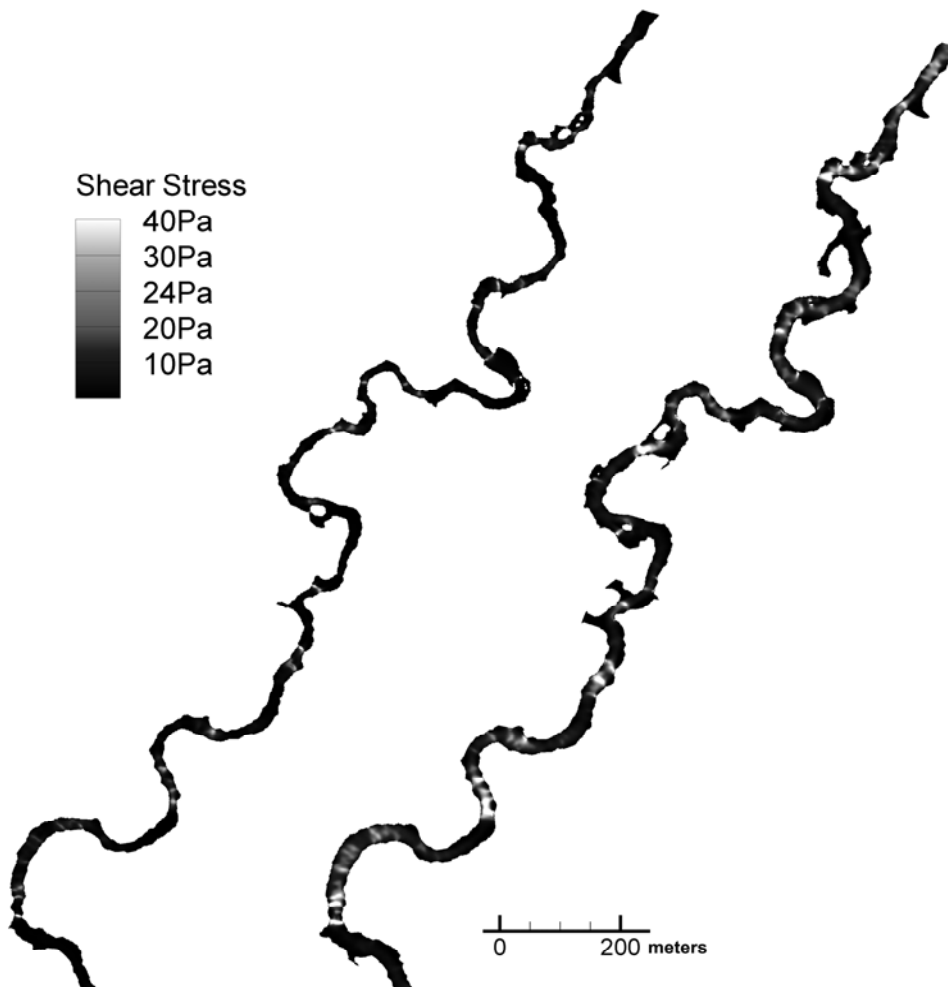


Figure 4. Shear stress distribution on the streambed. Left) base flow ($1 \text{ m}^3 \cdot \text{s}^{-1}$) and Right) bankfull flow ($6 \text{ m}^3 \cdot \text{s}^{-1}$).

In Figure 5, we plot, just for the spawning sites, the percent of area with an applied shear stress equal to or higher than the critical shear stress for each grain size. Figure 5 shows that at base flows medium-sized gravel (triangle-up symbol, 0.016m) would be mobile in only 5% of the surface area of the streambed at spawning sites, and the largest particles (cross symbol, 0.181m) would be mobile in only 2% of the area. At bankfull flows, the medium gravel and the largest particles are mobile in 22% and 10%, respectively, of the spawning sites. We can conservatively assume that particles of the size of the d_{50} (0.035m) need to be mobile for the flow to scour the streambed appreciably because 50% of the particles are mobile and armoring would not prevent excessive scouring. Using this assumption, only about 15% of the spawning area is prone to scour at bankfull flows.

However, the results of Figure 5 should be modified to account for the amount of particular grain sizes that are actually available at the streambed as well as the critical shear stress for each of those grain sizes. We accounted for the amount available of each size fraction using the grain size distributions shown in Figure 2 with the result shown in Figure 6.

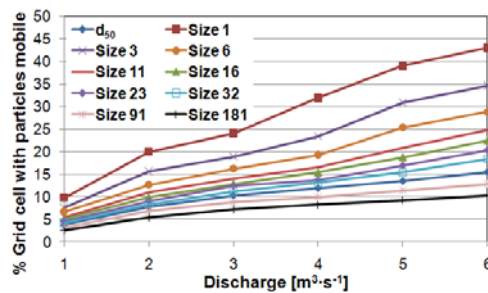


Figure 5: Percentage of grid nodes with particles mobile at each discharge. Bankfull flow is at $6 \text{ m}^3 \cdot \text{s}^{-1}$ and particle size in mm.

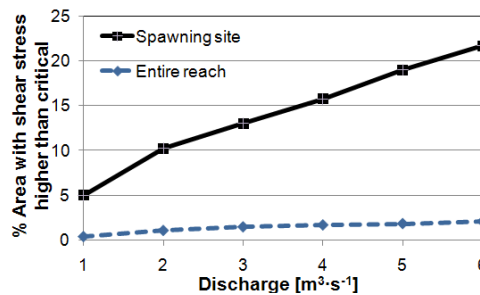


Figure 6: Percent of streambed area mobile as a function of discharge.

Usually, most of the streambed of a gravel bed river would be mobile at bankfull flows [18]. However, here very little of the overall streambed is mobile even at the bankfull maximum discharge. This behavior is probably due to the low streambed gradient that prevents the development of large shear stresses. Nevertheless, the channel is still somewhat dynamic and migrates laterally through bank materials that are typically smaller than the gravels on the streambed. Relict channels in the floodplain document this activity (Figure 1). Again, the spawning areas in Figure 6 are more mobile because they are typically located in flow transitions around riffle crests where higher shear stresses develop. However, less than 25% of the surface area of spawning sites is mobile even at bankfull flows. These results suggest limited mobility and scour of the channel

bed occur at any discharge in unconfined low-gradient streams in this landscape. Direct field observations of almost no gravel transport during near-bankfull conditions support this numerical model result. Therefore, regardless of the changes in mid-winter flows caused by climate change, the channel bed should only be locally mobile and extensive scour does not appear to be a large threat to embryo and alevin survival. We are extending this research to other streams to define the geomorphic domain of channel slope and confinement, substrate size and discharge within which this conclusion is consistent.

CONCLUSION

Results from our process-based numerical model show little danger of extensive bed mobility, even at high flows, in these unconfined low-gradient streams. Consequently, changes in flood timing and magnitude due to climate change are unlikely to decrease salmonid egg incubation success because of increased channel bed scour in similar streams.

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