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RIOC
REVISTA INGENIERÍA DE OBRAS CIVILES

Efectos de la canalización y rectificación de cauces en la calidad del hábitat del salmón Chinook durante las etapas de desove y juvenil

Effects of reach channelization and straightening on the habitat quality for Chinook salmon at spawning and juvenile stages

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Resumen

La calidad del hábitat de ciertas especies en tramos específicos de ríos puede ser alterada por cualquier cambio a la morfología, condiciones hidráulicas o hidrológicas y calidad o usos del agua. Estos cambios pueden mejorar, empeorar o no tener ningún efecto en la idoneidad del hábitat de esta especie en cierto momento de su vida. Una evaluación adecuada de los posibles efectos que diferentes escenarios, en un proyecto que considera modificaciones en algún tramo de río, pueden generar es necesaria para minimizar cualquier consecuencia negativa y al mismo tiempo maximizar los beneficios. En este estudio el efecto de la canalización y rectificación de un tramo del río Lehmi, ubicado en el estado de Idaho, Estados Unidos, sobre la calidad del hábitat del salmón Chinook durante dos etapas de su ciclo de vida, desove y juvenil, son analizados por medio del uso de índices de idoneidad y comparación de la calidad de hábitat. La distribución espacial del flujo es obtenida usando un modelo numérico cuasi tridimensional. Nuestros resultados muestran que la idoneidad del hábitat durante la etapa de desove se reduce significativamente cuando el tramo ha sido canalizado y rectificado. Durante la etapa juvenil los tramos natural y modificado no presentan diferencias significativas. Si se considera un año completo el periodo de excedencia de la superficie ponderada útil en el tramo rectificado es prácticamente constante tanto para las etapas de desove y juvenil, sin embargo el tramo natural muestra mayor dependencia al caudal que fluye en determinado momento.

Abstract

For certain species the habitat quality in a specific reach may be modified by any change to the morphology, hydraulic and hydrological conditions, water quality and water use. These changes can improve, reduce or have little to no effect on the habitat suitability of that specie at a certain life stage. An adequate evaluation of the possible effects that different scenarios aid to minimize the negative consequences and maximize the benefits of the required or designed modification. The effect of channelization and straightening of a reach in the Lehmi River, ID, USA, on the Chinook salmon habitat quality at spawning and juvenile life stages is here studied. To evaluate the suitability indexes at these two stages and quantify the differences in habitat quality between a natural and a modified reach the flow field was obtained using a quasi three dimensional numerical model. Our results show that the suitability for spawning is significantly reduced when the reach has been channelized and straightened. At juvenile stage the natural and modified reaches do not display significant differences. During a year-round period the exceedance time of the weighted usable area at the straightened reach is almost constant for both spawning and juvenile stages, however the natural reach seems to be more dependent on the discharge.

1. Introduction

To sustain a viable long-term population suitable environmental conditions and resources must be available in form of quantity, quality and timing (Statzner et al. 1988 [1]). These conditions are dependent of multiple variables such as river hydrological properties, hydraulics (e.g. water depth, velocity, and shear stress), water quality (e.g. pH, temperature, and salinity), topography, morphology, bed texture and the presence of roughness element (e.g. large woody debris and large boulders). All of them interact in different ways creating a temporally and spatially variable template that defines the suitability and environmental conditions necessary for species survival at different life stages. A quantitative description of the linkage between physical attributes and their fitness for a certain species is commonly done by means of the habitat suitability criteria or habitat requirements. Any change to the current reach conditions can result in an improvement, deterioration, or have little to no effect in the habitat suitability. For instance construction of hydraulic structures such as bridges and dams can interrupt migration routes, change water depth and velocity, enhance or reduce sediment transport fluxes and alter the bed substrate which changes the natural habitat of different species. Another common river engineering project that alters significantly river properties is the channelization and straightening of a certain reach for flood control, recreation or urbanization. It is difficult to know a priori the effect of any modification and how this will affect a certain species, or even more, habitat requirements changes at different life stages so the definition of the species of interest and the required habitat must be well defined and also must be considered during early stages of any project. To assess the potential effects on any modification project numerical simulations and habitat suitability studies are used (see for example: Shirvell, 1989 [2]; Ghanem et al, 1996; Bradford and Higgins, 2001) because they offer the possibility to simulate several different scenarios including diverse geometries and boundary conditions and also because they are relatively more economical and fast than laboratory experiments. A spatial description of the flow field can be obtained using these techniques and several different scenarios can be analyzed to achieve the desired goal.

Here the effect of the channelization and straightening of a reach on the habitat quality at spawning and juvenile stages for the Chinnok salmon is studied using habitat suitability criteria and a quasi 3D hydrodynamic model (FaSTMECH, Nelson et al, 2003). Comparisons of the weighted usable area () and hydraulic habitat suitability () of a natural reach with the modified one are presented and differences in habitat quality are described when these morphological changes are implemented.

2. Study Site

In this study we compare the changes in habitat quality for the Chinook salmon (Oncorhynchus tshawytscha) at two reaches at the Lemhi River, Idaho, USA. The Lemhi River is 90.3 km long and 0.00067 slope. It flows through a mountain valley into the Salmon River (Figure 1). Site 3 is an 87.5 m long, 16 m width channelized and straightened reach located at UTM 12 T 292683.7 m E, 4971250.2 m N. Site 4 is a 225.5m long, 11 m width natural reach located at UTM 12 T 303715.4 m E, 4958449.3 m N.

Figure 1: Location of the study reaches

Detailed topographic measurements at a density of about 1 point/0.25 m2 (Figure 2), median bed grain size spatial distribution, water surface elevation and the corresponding discharge () were collected and are available for both sites. This information is later used to calibrate a quasi 3D flow numerical model.

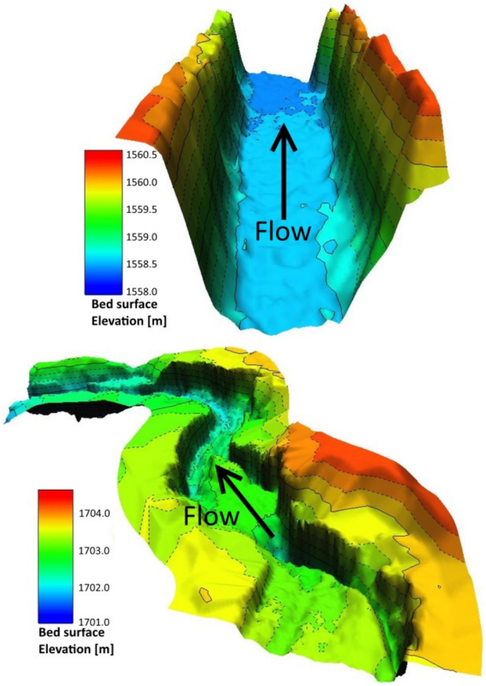


Figure 2: Bed Surface elevation at both sites. Vertical scale was amplified 10 times to have a better perspective

3. Methods

The habitat quality for the Chinook salmon is compared at these two reaches at two different life stages: Spawning and juvenile. For this purpose, the weighted usable area () and the hydraulic habitat suitability () are used as reference. To obtain the and two complementary techniques are used here. The hydraulic properties, water depth and velocity, of both reaches, are calculated using the quasi 3D numerical model FaSTMECH (Flow and Sediment Transport and Morphological Evolution of Channels) which was developed by the U.S. Geological Survey (Nelson and McDonald, 1995). The model solves the full vertically averaged and Reynolds-averaged momentum. The vertically averaged equations are cast in a channel-fitted coordinate system. To calculate the depth-averaged solution the model assumes steady, hydrostatic flow and models turbulence with an isotropic eddy viscosity. The momentum equations are solved over a curvilinear orthogonal finite difference grid, which in this case is 0.5 m in both x and y direction at both reaches. Once the spatial distributions of velocity and water depth are obtained a spatial distribution of habitat suitability is calculated using suitability curves based on the bed median grain size () and these two variables (water depth and velocity). Suitability curves were obtained from literature reports (Figure 3). Combined preferences are obtained using the geometric mean methods as are further described later.

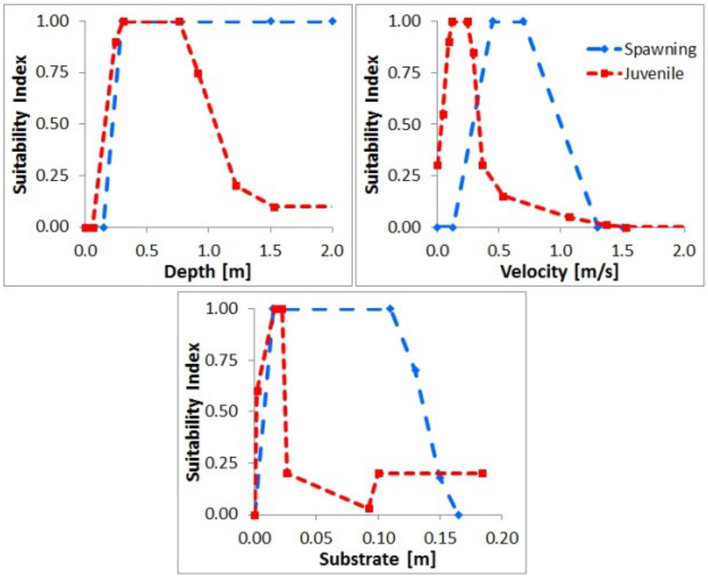


Figure 3: Suitability index for spawning (From Shirvell, 1989 [2]; USFWS curve) and juvenile (From Raleigh et al, 1986) life stages.

The process to obtain the and curves can be summarized in the following steps: a) Calibration of bed roughness as function of the roughness height (), b) Calibration of the lateral eddy viscosity coefficient (), c) Using the calibrated roughness height re-calibration of for the different discharges, d) Calculation of the spatial distribution of the suitability indexes for water depth, velocity and substrate and e) Calculation of the and curves. These steps are performed for both sites and are explained in detail below.

Z_0 was calibrated by matching the model predicted water surface elevation to the measured water surface profile. First, at Site 3, we provided the model a constant discharge upstream boundary condition of 3.3 m3/, a constant downstream water surface elevation of 1558.56 m and, at Site 4, a constant discharge upstream boundary condition of 1.77 m3/ and a constant downstream water surface elevation of 1702.11. These values correspond to measured values at the time when the topography of both places was obtainen. At both sites the lateral eddy viscosity, for the first simulation, was constant and equal to 0.005 m2/s. A Constant drag coefficient was first used. The coefficient was selected to minimize the root mean square error (RMSE) of the predicted vs measured water surface elevation and manually changed until the RMSE was within 3 cm. Once this was achieved a spatially variable roughness, function of the computed flow depth from constant roughness conditions and the local (4), was used.

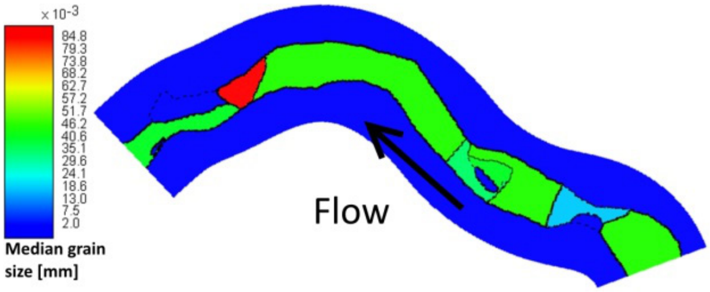


Figure 4: Median grain size spatial distribution at Site 4

The roughness height was adjusted by changing the coefficient at 1 until the predicted vs measured water surface elevation RMSE was again lower than 3 cm.

$$Z_0 = C \cdot D_{50} \qquad \text{Eq. 1}$$

Once was calibrated the was checked for consistency using 2

$$n = 0.011 \cdot U \cdot H \qquad \text{Eq. 2}$$

where is the reach averaged velocity and is the reach averaged water depth. was found to be correct if the difference between its value between subsequent simulations was lower than 3%. The RMSE change cross-sectional mass conservation was checked to ensure that it reached a stable value for more than 500 iterations and also the percent deviation from normalized discharge is lower than 3% in every cross section.

Once the model was calibrated four discharges at each site were simulated. These discharges represent a simplified version of the period Jul/2011 – Jun/2012 hydrograph and correspond to 100, 200, 300 and 400 cfs measured at the USGS gage 13305000 Lemhi River Nr Lemhi ID (5). At Site 4, which is upstream Site 3, the discharges were corrected to account for the existent sources between both sites.

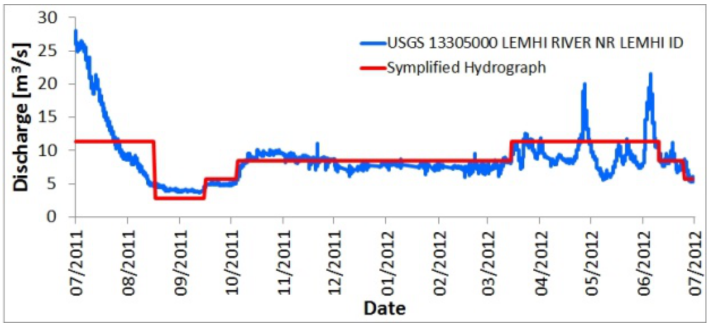


Figure 5: Measured and simulated hydrograph

For each site and discharge the spatial distributions of water depth, velocity and substrate were used to calculate, in each cell, the Suitability Index of the numerical domain. The suitability index can be understood as a quantification of the likelihood of a specie to use a certain spot or if a certain place meets the habitat requirement at certain life stage. To account for these three physical variables simultaneously (water depth, velocity and substrate) a combined preference was used. Using a weighted product the combined preference is (3):

$$SI_i = \sqrt[3]{SI_{H_i} \cdot SI_{U_i} \cdot SI_{D50_i}} \qquad \text{Eq. 3}$$

where is the suitability index for water depth at the cell "", the suitability index for velocity and the suitability index for the median grain size or substrate. The weighted usable () is calculated with:

$$WUA = \sum_{i=1}^{m} A_i \cdot SI_i \qquad \text{Eq. 4}$$

where is the area of the cell and the number of cell of the numerical domain. The Hydraulic habitat suitability () is the ratio of the to the wetted area. By normalizing by the wetter area the gives a better index for habitat quality comparisons between sites because is no longer function of the extent of the considered reach.

4. Results

At Site 3 the calibrated simulation has a RMSE for predicted vs measured water surface of 2.5 cm (Figure 6), the average drag coefficient is about 0.019 ranging from 0.02 to 0.120, coefficient is 0.1 and 0.0021 m2/s. At Site 4 the RMSE for predicted vs measured water surface is 2.2 cm, the average drag coefficient is about 0.043 ranging from 0.008 to 0.20, coefficient is 0.08 and 0.0015 m2/s.

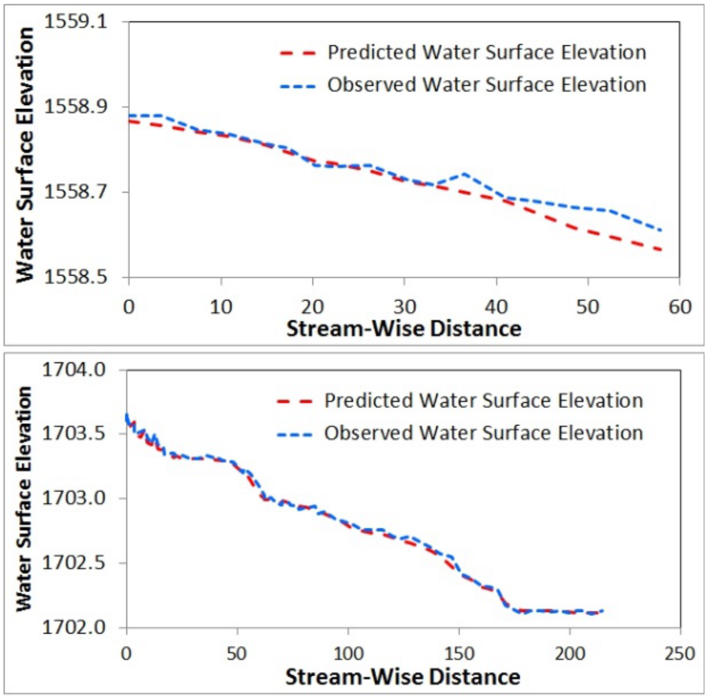
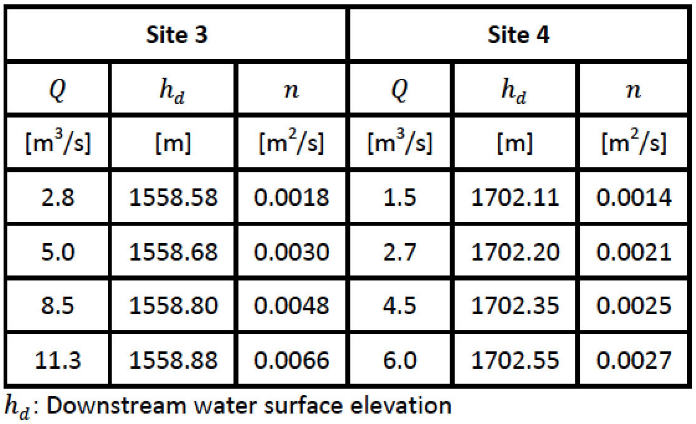


Figure 6: Calibrated result for observed vs predicted water. Vertical and horizontal scales are in [m]

Using the calibrated results the four simulated scenarios at each site are summarized at Table 1



Site 3			Site 4		
Q	h_d	n	Q	h_d	n
[m^3/s]	[m]	[m^2/s]	[m^3/s]	[m]	[m^2/s]
2.8	1558.58	0.0018	1.5	1702.11	0.0014
5.0	1558.68	0.0030	2.7	1702.20	0.0021
8.5	1558.80	0.0048	4.5	1702.35	0.0025
11.3	1558.88	0.0066	6.0	1702.55	0.0027

h_d: Downstream water surface elevation

Table 1: Lateral eddy viscosity coefficient for the simulated scenarios at both sites

The quasi 3D numerical model, FaSTMECH, used to calculate the spatial distribution of the physical variables, water depth and velocity gives the result of these variables in each node of the numerical domain. The calculations of and are based on grid areas, so one problem arises when one or more nodes are dry. If at least one node is dry, over that area the depth or velocity cannot be defined as the average of these 4 nodes values, but it can be considered as the average of those values that are wet. To account for the fact that only wet nodes are being considered in calculations of the wetted area, the area of each cell (which originally was defined by four nodes) is reduced in a percentage equivalent to the number of dry nodes, so if two nodes are dry the wetted area will be 0.5 times the area defined by the 4 original vertexes (7)

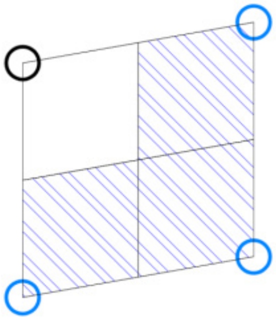


Figure 7: Wetted area calculation for cells that have one or more dry cells. Blue circles represent wetted nodes, black circles are dry nodes. The wetted area is reduced to ¾ times the original area as shown in blue lines.

Results for spawning stage at both sites are shown at 8

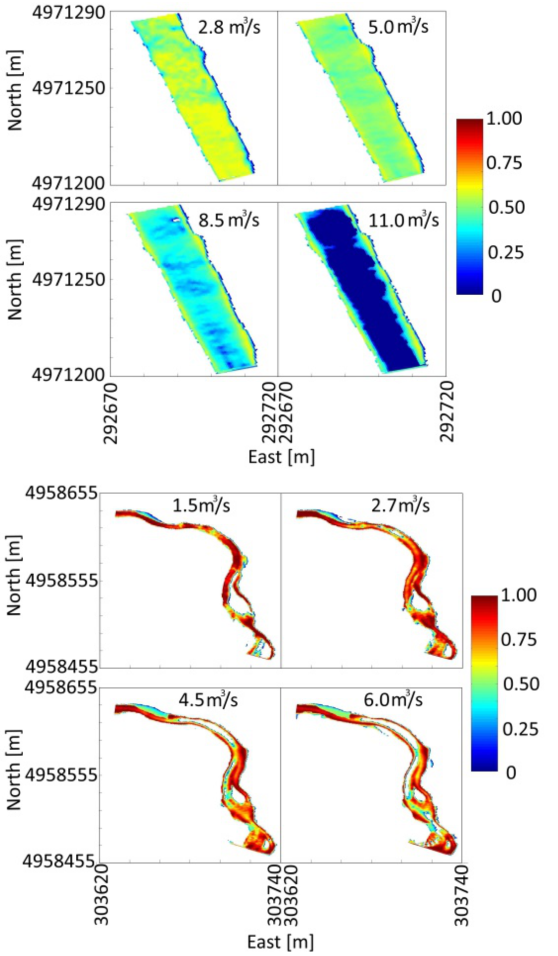


Figure 8: Suitability index for spawning stage at Site 3 (upper) and Site 4 (lower)

For these two site the and are summarized at 9

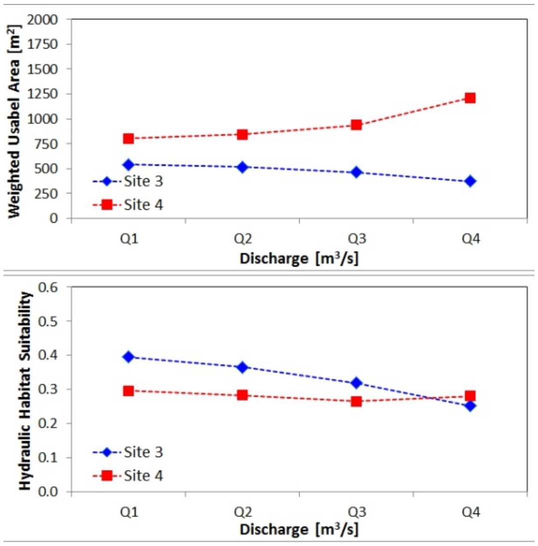


Figure 9: Weighted usable area and hydraulic habitat suitability for both sites during spawning stage. The discharge shown at the horizontal axes corresponds to 100, 200, 300 and 400 cfs at each site.

The is significantly larger at site 4 mainly because the area covered by this site is also larger. In this case the is more suitable to compare different the different reaches. As the discharge increases the at Site 4 also increases, the opposite trend is found at Site 3. The is always higher at Site 4, the maximum is about 0.57 and after this value it starts to decrease as the discharge increases. At Site 3 an increase in the discharge always makes the to decrease.

Results for spawning stage at both sites are shown at Figure 10

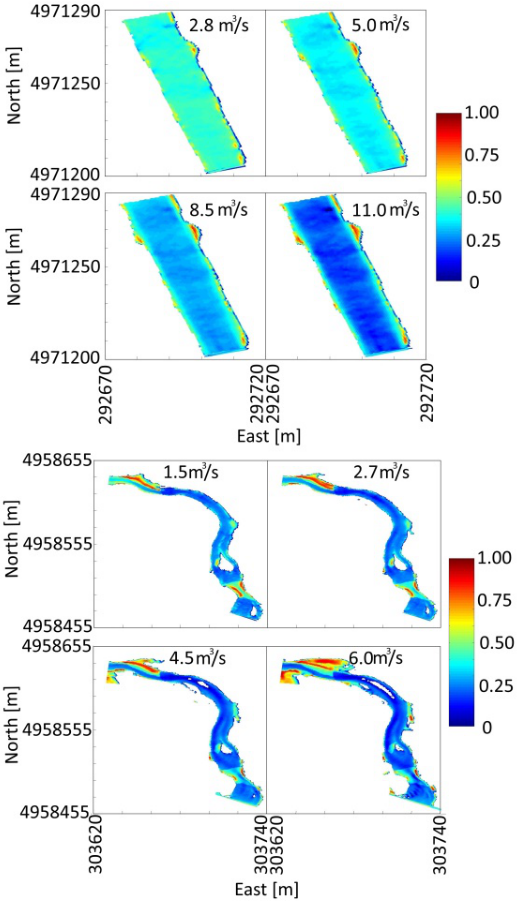
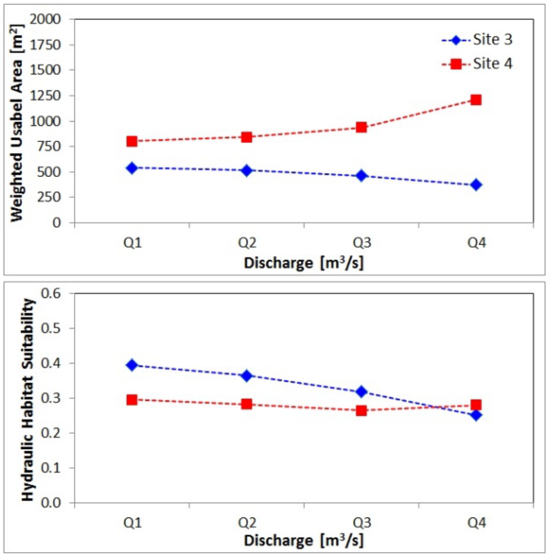


Figure 10: Suitability index for juvenile stage at Site 3 (upper) and Site 4 (lower)

For these two site the and are summarized at



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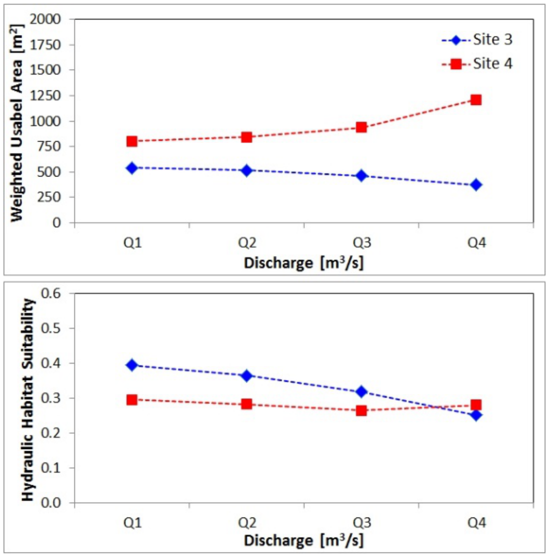

Figure 11: Weighted usable area and hydraulic habitat suitability for both sites during juvenile stage.

The weighted usable area is again larger at Site 4, however compared to spawning stage now it has been reduced. At Site 3 the is almost constant, with a minor decreasing, and the is slightly deteriorated as the discharge increases (Figures 11 and 12). Both sites show a very similar but noticeable lower compared to the spawning stage for the three first discharges.

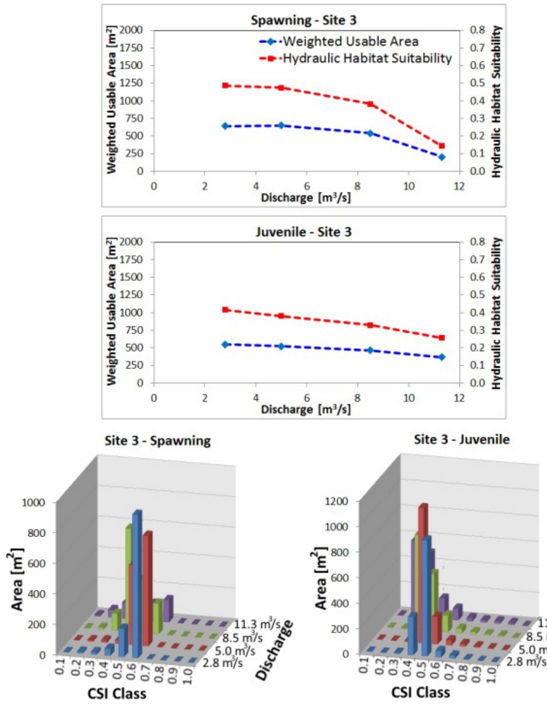

Figure 12: From the top to the bottom: and for both stages and area occupied by each CSI class for each simulated discharge at Site 3

At Site 3 most of the area is clustered around 0.3-0.5 for both stages. Almost no area has a suitability index higher than 0.7. Differences of for Site 4 are shown at

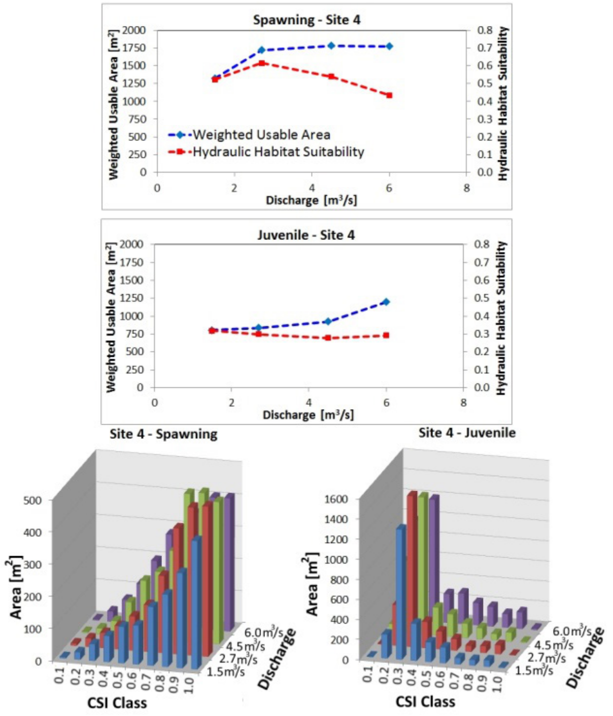

Figure 13: (Above) and for both stages at Site 4, (below) area occupied by each CSI class for each simulated discharge

It can be observed that for spawning stage the CSI class is skewed toward the higher values and in a consistent trend though all the different discharges, however the shows that the habitat quality gets worse as the discharge increases. At the Juvenile stages they are clustered on the lower values, with single peak values of area around the 0.3 for all discharges. The remains almost constant for this stage.

If the habitat quality, in terms of the , is analyzed at both sites (14), it is possible to see that, for both stages, at Site 3 it remains almost constant for almost the whole the year. During more than the 60% of the year it is possible to found more than 500 m2 of good quality habitat. At Site 4, for spawning purposes, almost 95% of a year (more than 11 months) there is close to 1750 m2 of god quality habitat. Caution must be taken when this data is analyzed, because even when the appropriate conditions or a high weighted usable area can be found, fishes may not be present at that moment.

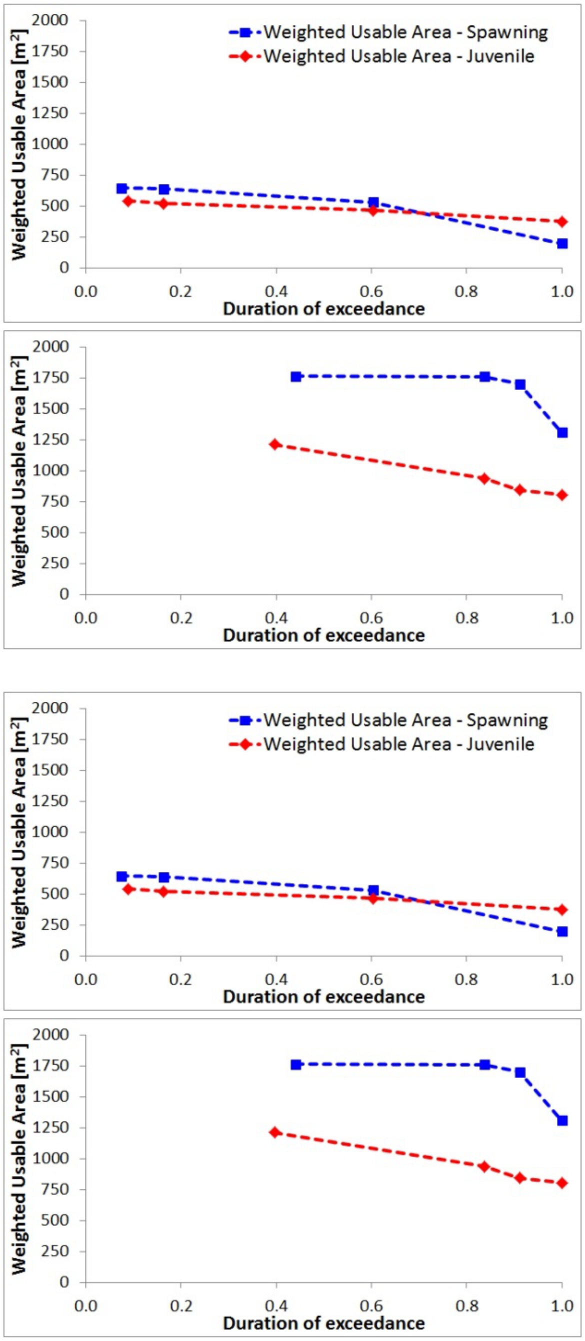

Figure 14: Percentage of exceedance of a certain area during a complete year for Site 3 (upper) and Site 4 (lower)

5. Discussion

The results shown here suggests that based on the for the spawning stage Site 4 has a better habitat quality while for juvenile stage the difference is reduced significantly. For this reason the channelization and straightening of a certain reach, under the conditions available at the Lemhi River, reduced the likelihood to meet the habitat requirements for Chinook salmon while they are spawning. This doesn't mean that they will not spawn there, but in a natural reach is likely easier to find a place to do it. A quasi 3D numerical model was used to estimate the spatial distribution of velocity and water depth, which are the predictor variables for calculations of the and curves. The calibration performed based on RMSE of measured vs predicted water surface elevation ensures that the model is adequately capturing the hydraulics of the river at these reaches.

A sensitive analysis on the mesh and grid size would be beneficial to understand the dependence of the solution on these conditions, however, the strict criterion used to simulate each discharge (at least 500 iterations on a stable value of RMSE change cross-sectional mass conservation, less than 3% deviation from normalized discharge and less than 3% in change on the lateral eddy viscosity in subsequent simulations) ensures with a high degree of certainty that the solutions are correct.

One vital element for this study is an adequate selection of the SI curves (Figure 3). The curves used here correspond to Category 1, which are curves obtained from literature. Selection of different SI curves may affect the final result or individual and HHU curves. For instance just by changing the given SI curve for velocity for spawning stage by the one suggested by Nechako (Shirvell, 1989 [2]) the estimated habitat quality changes significantly as shown at Figure 15. The trends remains pretty similar, but the values are consistently lower for all discharges.

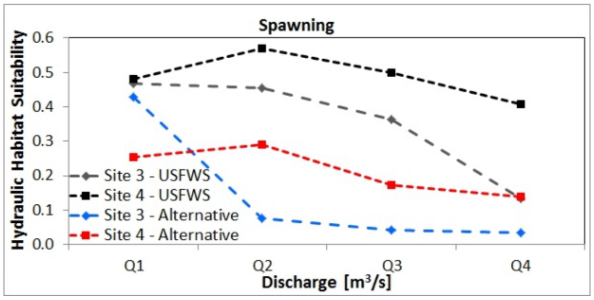

Figure 15: Changes in curves due to the use of a different SI curve for velocity. Grey and black lines correspond to those value reported at Figure 12 and Figure 13

The present study uses three variables to define the habitat quality, expressed here as the . In addition to them other variables, such as water temperature or level of late summer nitrate-nitrogen, could be also considered as predictors. Another assumption used here is the use of a weighted product, which means that identical weights are assigned to each variable. This assumption could generate different values of if another method were used to obtain the combined preference. To be consistent in the present study, all the calculations were performed using the same methods (only weighted product). By doing so, comparisons between the reaches are more reliable.

6. Conclusion

A comparison of the habitat quality, expressed here as the hydraulic habitat suitability, for the Chinook salmon between a natural and a channelized and straightened reach was presented in this study. In the analysis two different stages were considered: Spawning and juvenile. Spatial distributions of water depth and velocity were obtained using a quasi 3D numerical model and a simplified hydrograph of the discharge at the Lemhi River, ID, was used to account for the changes during a complete year. The results show that the natural reach presents better habitat quality than the straightened one for the spawning stage. was significantly larger at site 4, the natural reach, mainly because the area covered by this site is also larger. The use of the is, in this case, more suitable for comparison purposes. At spawning stage, as the discharge increases the at Site 4 also increases, the opposite trend is found at Site 3, the channelized reach, were also 3 the always decreases as discharge gets higher. The at Site 4 is lower than at Site 3 for the juvenile stage. At Site 3, for juvenile stage, both the and remains almost constant for the whole discharges range. Both sites show a very similar for all discharges but noticeable lower compared to the spawning stage for the three first discharges. As the discharge increases decreases for Site 3. The results are sensitive to the suitability indexes curves chosen for the calculation. The selection of the curves must be carefully done and must be consistent through all the study. Slight changes in the curves produce significant changes in the results of.

7. References

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