Predicting Riparian Habitat Quantity and Diversity Using 2D Landscape Evolution Modeling

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Abstract

Alteration of river systems has resulted in morphologically simple rivers, and poor-quality riparian habitat. As the relationship between habitat diversity and ecosystem function becomes more apparent, management has begun to focus on restoring natural habitat-creating geomorphic processes. Widening the erodible river corridor is one restoration strategy, but determining the corridor width needed to facilitate an increase in habitat can be challenging. This study explores the use of CAESAR-Lisflood, a 2D cellular hydraulic model, as a tool for quantifying site-specific differences resulting from different erodible corridor widths. The North Fork of the Snoqualmie River near North Bend, Washington was used for modeling. Non-erodible rock revetments were modeled on the banks of the main channel and set back one river width. After 100 years of simulated flow, the resulting morphology was compared to an unconstrained condition. The unconstrained condition had more active side channels at the end of 100 years than the constrained conditions, and more side channel activation throughout the duration of modeling. These results suggest that a wider erodible corridor does facilitate habitat formation. Additionally, the successful translation of model output to habitat quality provides a starting point the use of 2D modeling as a tool for restoration. Further studies should focus on developing appropriate habitat assessment indices to make this an accessible tool for managers.

Introduction

Habitat heterogeneity, defined as a spatially diverse distribution of physical and biological habitat components in an environment, has been shown to influence the level of biodiversity that can be supported by a river ecosystem (Ward and Tockner 2001). The relationship between habitat heterogeneity and biological diversity is particularly evident in riparian systems, as the interface between aquatic and terrestrial ecosystems is associated with a variety of microhabitats that support more biological niches, and therefore more species (Ward, Tockner, and Schiemer 1999, Malmqvist 2002). Studies have expressed the importance of biodiversity as a facilitator of ecosystem productivity and resilience (Isbell, Polley, and Wilsey 2009, Mace, Norris, and Fitter 2012), and for this reason, many restoration efforts aim to increase local biodiversity.

Human modifications to river systems, including alteration of flow regimes, canalization, and bank stabilization, have eliminated much of the spatial and temporal diversity associated with riparian habitat (Bunn and Arthington 2002, Ward, Tockner, and Schiemer 1999). Many of these modifications, particularly river channelization through use of bank stabilization structures, destroy both small-scale habitat features and the geomorphic processes that promote habitat heterogeneity at a larger scale (Abbe and Montgomery 1996; Segura and Booth 2010). Because erosion and flooding can damage property and other public and private assets, management tends to focus heavily on bank stabilization. Whether accomplished using traditional rock riprap, or using softer approaches, like engineered wood or bank planting, bank stabilization can eventually narrow the river corridor, diminishing the potential for natural habitat creating processes and ecological succession (Piégay et al. 2005). Finding the right balance between stability and the ecological benefits associated with instability is a challenge faced in management.

Managers may consider the removal of bank stabilization structures and widening of the erodible corridor as means to reactivate geomorphic processes and enhance biodiversity, but assessing the potential outcomes of different plans is difficult. Studies suggest that widening the erodible corridor, the management-defined area that a river can erode, is beneficial in terms of habitat formation. It is, however, unclear how wide the corridor must be to allow for measurable habitat improvement (Buijse et al. 2002; Palmer et al. 2007). Additionally, variation between sites makes it difficult to apply a “one size fits all” management strategy (Piégay 2005).

Hydraulic modeling has been proposed as a way to evaluate potential morphologic forms resulting from different management strategies at a particular site (Richards, Brasington, and Hughes 2002). However, being predictive is difficult, and modeling is computationally demanding; therefore, hydraulic modeling has not yet been used for this purpose. Recent changes to 2D cellular hydraulic models, a class of grid-based models, have made them more efficient and better able to represent instream hydraulic conditions (Coulthard, Hicks, and Van De Wiel 2007). Because of the efficiency of these models, they provide a feasible option for exploring predictive modeling.

CAESAR-Lisflood, a numeric 2D cellular model, was chosen for use in this study. This project seeks to utilize the CAESAR-Lisflood model to:

1. Determine whether CAESAR-Lisflood can reasonably model changes in morphology over 100 simulated years, and whether the program can model the area of a typical restoration site quickly enough to be a practical tool for management.
2. Evaluate potential habitat differences resulting from the placement of modeled buried rock revetments (a commonly used bank stabilization structure) at varying levels of setback from the main river channel.

A low-cost, predictive tool that can operate quickly, and quantify differences in potential outcomes, would give restoration project managers, engineers, and those involved in conservation management a better framework for making decisions about project implementation.

Literature Review

Determining a method for improving ecological integrity is a critical challenge faced by restoration managers. This review will explore the body of literature surrounding restoration planning, and possibilities for informing the decision-making process. First, I will summarize the literature pertaining to river restoration strategies, focusing on the benefits associated with the restoration geomorphic processes. Then, I will discuss the potential use of modeling as a tool for restoration. Finally, I will evaluate several metrics for habitat assessment, and suggest how they could be incorporated with a model to provide an effective tool for enhancing diversity.

River restoration goals and methods

River and stream restoration has become an increasingly critical undertaking as people begin to understand river system services (Palmer et al. 2005). Rivers provide a variety of ecosystem services, including water filtration, nutrient cycling, and climate regulation, and more biodiverse systems are better able to provide these functions (Isbell, Polley, and Wilsey 2009; Mace, Norris, and Fitter 2012). As this relationship becomes clearer, restoration projects have emphasized the improvement of ecological integrity as a principle focus.

Restorative efforts are moving from a "state-based" approach that focuses on achieving a particular set of characteristics to a "process-based" approach that emphasizes the importance of large-scale drivers of riparian function (Beechie et al. 2010). Rather than installing instream habitat features, like spawning gravel or logjams, contemporary projects seek to be self-sustaining by removing "barriers" (both literal and figurative) to natural river evolution. Beechie et al. (2010) argue that riparian dynamics are influenced by "hierarchically nested" physical, chemical and biological processes acting at broad spatial and temporal scales. They describe the importance of designing restoration efforts to address large-scale processes, like sediment transport and seasonal flow regimes, rather than the individual symptoms of larger issues. Restoration at an ecosystem scale may not be possible at all sites due to economic constraints, but efforts based on these principles can lead to success even at a smaller scale (Beechie et al. 2010).

One of the main issues with “state-based” strategies is the difficulty of defining a reference state (Dufour and Piégay 2009). In the past, most restoration efforts focused on restoring a river to a historical state, but identifying the desired state proved difficult. Dufour and Piégay (2009) argue for an approach similar to that of Beechie et al. (2010) that focuses on function over state. However, Dufour and Piégay do not believe that a process-based approach will always lead to desired outcomes, and suggest integrating human and societal needs into design to ensure success.

Restoration of geomorphic processes is complicated by societal desires for a stable river channel. While beneficial for property and other societal assets, river regulation and bank stabilization can eliminate processes that create morphologic diversity (Segura and Booth 2010; Collins, Montgomery, and Haas 2002). Processes like erosion have been shown to increase morphological diversity, and by doing so, provide habitat benefits to riparian species. For example, side channels have been shown to provide valuable habitat for living and breeding for many species (Stella et al. 2011). Rivers with braided flow patterns, or various channels of active flow weaving around islands, are associated with greater populations of fish species (Montgomery et al. 1999). In gravel-bedded streams, the pool-riffle sequence with areas of low velocities and high depths alternating with high velocities and low depths have been shown to be especially important for fish, both for breeding spawning (Beechie et al. 2005). Other physical elements play seasonal roles. For instance, overhanging banks provide shade and cooler water for fish, and oxbow lakes provide slow-water refuge in high-flow events (Beechie et al. 2005, Ishida et al. 2010). These benefits must be weighted against the costs associated with an active erodible corridor, particularly the threat of property damage, and projects must be responsive to societal needs to ensure success.

Modeling as a tool for restoration

Currently, most decisions regarding river restoration strategies are based on information gained from other restoration projects, and research about restorative tools (Buijse et al. 2002). This information is valuable in guiding decisions, but it is not site-specific, and tends to be “fragmented,” only evaluating the effects of a strategy on one particular component of the riparian zone (Buijse et al. 2002, 889). It can be challenging to compare proposed designs, particularly when the approaches utilize a variety of tools and are intended to affect multiple components of the riparian zone. This becomes even more challenging when evaluating similar designs. A team may be deciding between implementation of buried revetments set back one or two channel widths from the main channel. A way to compare the habitat quality and quantity that would result from these different restoration strategies would be useful for helping distinguish between two approaches.

There are many strategies for evaluating existing habitat diversity and complexity, including stream categorization, hydraulic modeling, and spatial variability indicies (Yarnell, Mount, and Larsen 2006; Benjanker, Koenig, and Tonina 2013), but evaluating future outcomes of specific management plans is limited to evidence based on the successes and failures of other restoration projects (Buijse et al. 2002). There is need for a site-specific assessment strategy, particularly one that can quantify the differences in habitat resulting from different strategies.

Richards, Brasington, and Hughes (2002) propose that it could be possible to use hydraulic models to evaluate future situations, not just categorize current conditions. No substantial work has been done on the topic since, as modeling is computationally demanding, and challenging to validate (Van de Wiel et al. 2011). However, recent updates to cellular hydraulic models have improved their computational efficiency, and as the body of knowledge about model calibration expands, they have become an increasingly viable option for use in predicting habitat (Coulthard, Hicks, and Van de Wiel 2007).

2D cellular hydraulic models use a grid-based map of elevation and sediment sizes accompanied with water and sediment transport equations to simulate river flow and erosion processes (Coulthard, Hicks, and Van de Wiel 2007). Coulthard, Hicks, and Van de Wiel (2007) identify two major categories of cellular models: Landscape Evolution Models (LEMs), which use steady flow equations, and non-steady flow hydraulic models. LEMs are useful over long spatial and temporal scales, but neglect important hydraulic information. Non-steady flow models are much more computationally demanding, but are closer to reality in their representation of in-channel flow.

Coulthard et al. (2013) combined both types of models into a new model called CAESAR-Lisflood. This model in particular is a good option for predicting future habitat conditions, as managers must evaluate both long-term changes that result from a management choice, as well as the immediate hydraulic conditions, as they are relevant to habitat. Additionally, because it is more computationally efficient than other 2D cellular models, it is possible to simulate 50-100 years of flow (an important time-scale for managers) in a short enough time period to be useful for managers.

The model is run using an elevation map for the area to be modeled, daily flow volumes and velocities, and a sediment size distribution from the site. For each cell in the model, sediment and water are added from upstream. If the capacity for sediment transport (which is calculated based on flow velocity) exceeds the supply, sediment is taken from the bed, and the bed is lowered. If the sediment supply is greater than the transport capacity, the bed raises. The model also allows specification of cells as bedrock that cannot be eroded. This function provides an easy way to model bank stabilization structures. The source code for the model is also freely available, which allows users to integrate modifications, and presents no financial burden to managers seeking to use the model.

In their review of 2D hydraulic models, Coulthard, Hicks, and Van de Wiel (2007) noted that while cellular models are a useful type of model, they do have certain technical problems that mean they should not be used for exact prediction, but instead to predict sets of possible futures, or morphological forms. One of the main issues they identify is the difficulty associated with modeling lateral erosion. However, the equations used in these models makes them more effective at representing braided river systems than other morphological patterns (Coulthard, Hicks, and Van de Wiel 2007). Ziliani et al. (2013) supplemented these findings by comparing the CAESAR model to a real system, and found that the model effectively simulated general morphologic changes and sediment output, but was less effective at representing finer scale features, like braiding intensity. These studies collectively indicate CAESAR-Lisflood is appropriate option for modeling future habiat conditions.

From model output to habitat comparison

While methodologies exist for evaluating spatial variation and habitat heterogeneity in river morphology (Yarnell, Mount, and Larsen 2006), there is currently no metric incorporating both biotic preferences and spatial variation. Creating an index for assessment based on species preferences would allow managers to better evaluate how a management plan affects important focal species in an area.

In the Pacific Northwest, salmonids can be a useful indicator of biological integrity. Because of the direct use and cultural values attached to salmonids, they are often the driving force behind restoration efforts. These species have complex life history strategies that require a variety of microhabitats (Beechie et al. 2014; Saraeva and Hardy 2009), making them a good indicator of habitat diversity. They are also an important group of species economically. Salmonids sit at the intersection between ecological and social restoration goals, making them a particularly useful focal species for this project.

Conclusions

Habitat modeling could provide extremely useful information to managers, and is now possible with updated models. These models should not, however, be used to predict exact futures due to the stochastic nature of river systems. A good habitat index to assess model output will take into account many of the diverse features of the riparian landscape, including off channel habitat, geomorphological features, like off-channel pools and gravel bars, as well as hydraulic information, including water depth and velocity. The importance of these features has been evaluated individually, but combining them provides a new way of assessing habitat quality. The predictions based on model assessment could better allow managers to work toward restoring natural processes that could enhance habitat in the long run, rather than artificially creating habitat features.

Methodology

Study Site

I performed modeling on a 2.5 km stretch of the North Fork of the Snoqualmie River near North Bend, Washington. This is a gravel-bedded, braided river system. The site contains a bridge that may be at risk of failure if erosion on the south bank continues (Ruebel, personal communication). King County is developing a plan to protect the bridge, but intends to use softer engineering approaches in order to activate geomorphic change at the project site (Ruebel, personal communication). While modeling cannot be used to predict exactly what the river will look like in the future, the exploration of different morphologic forms and the resulting habitat conditions from different management design strategies may be of use as the county deliberates between plans. Because 2D models are most accurate when representing braided river systems (Coulthard, Hicks, and Van De Wiel 2007), this is an appropriate choice for a project site.

Experimental Design

I simulated three different conditions representing increasing erodible corridor width using the bedrock function in the CAESAR model: buried revetments along the banks of the main channel, buried revetments set back one river width from the main channel, and an unconstrained condition (Figure 1). A Digital Elevation Map (DEM) obtained from 2009 King County LIDAR was used as the initial condition for modeling. I obtained average daily flow values for the past 50 years from USGS stream gauge 12142000, a gauge located upstream from the project site, and duplicated the data to represent 100 years of flow. To minimize run time, only the top 2% of flow volumes were used, as calculations using the Bedload Assessment in Gravel-bedded Streams (BAGS) calculator indicated that 98% of sediment transport occurred with the top 2% of flows (Wilcock and Crowe 2003). A sediment distribution for the site including 9 sediment sizes was inputted to the model, and sediment was recirculated through the model. Two additional test runs including the low flows were performed to evaluate the difference between the narrow revetments and the unconstrained condition. These runs used inputted sediment calculated based on flow velocities using BAGS. 4 sediment sizes were used in these simulations. These runs incorporated use of the vegetation and sediment deposition parameters. All other model parameters are described in appendix 1.

After simulating 100 years of flow, the resulting DEMs were modeled for two days with an average summer low flow (see appendix 1) to determine which channels were active during non-flood conditions. Model output was analyzed in ArcGIS.

At every moment of simulated time, the model records a value for each cell for water depth, velocity, and average sediment size. After simulating 100 years of flow and running a summer low flow through the resulting DEM, I used ArcGIS to find cells that met depth and velocity conditions corresponding with habitat preferences for Coho and Chinook presmolt as described by Goodman et al. (2014). While Snoqualmie Falls blocks the passage of anadromous fish, defined as those fish that migrate from the ocean to freshwater to spawn, studies indicate rainbow trout, a species that is present at the site, have the same habitat requirements as Coho and Chinook salmon (Quinn 2005, 202-203). This age group tends to be limited by habitat availability, making it an appropriate, albeit not entirely inclusive, indicator of habitat quality (Goodman et al. 2014).

Results

The simulation of 100 years of high flows took approximately 11 hours (see appendix 1 for computer specifics). After 100 simulated years, the unconstrained condition showed small side channels activated even during a summer low flow (Figure 2). Comparison with the original DEM suggests that the river is reoccupying abandoned channels. The constrained conditions did not have any active side channels summer flow, with the exception of one channel split present in the narrow condition that was present in the initial condition (Figures 3 and 4).

A cross-sectional analysis of the unconstrained condition showed a relatively wide channel with gently sloped banks. D50, the average sediment diameter, was lower on the floodplain and higher in the middle of the channel (Figure 5). This is consistent with normal river conditions. The narrow condition had a sharper channel slope and an irregular sediment size pattern through the cross-section that was coarser than seen in the unconstrained position (Figure 6). The set back condition resulted in a wider channel than both the unconstrained and narrow conditions, but the sediment size profile was similar to that of the unconstrained run (Figure 7).

The cumulative time inundated for each cell over the period of 100 years can be seen in Figures 8, 9, and 10. These figures show that the side channel activation in the unconstrained run was more consistent over the duration of the simulation than the constrained runs. On the right ride of the map of the unconstrained condition (Figure 8), there are several red to orange colored channels braided in a way that is typical for a braided river system. There is also one red to orange colored channel near the top of the map. This was a historic channel, and it appears as though the river has reoccupied this channel many times during the simulation. In figures 9 and 10, the side channels visible on the bottom of the maps, closer to the left side, are located closer together, and would not be consistent with a pattern of multiple channels activated simultaneously.

Figure 11 shows the river profile through the center of the main channel of the unconstrained run during the low flow simulation. The pattern of high velocities associated with low depths and larger average sediment size (D50) is consistent with what would be expected for a pool-riffle gravel-bedded river. Sediment sizes for each of these locations are appropriate, given the sediment size inputs.

The cumulative amount of sediment flux was plotted over time for all three scenarios (Figure 12). All three conditions produced fairly linear outputs, but the most sediment flux occurred in the setback condition and the least in the narrow condition. Comparison to USGS historical records stating historical sediment flux reveals the values for the unconstrained and set back conditions are within an appropriate sediment flux range, but the value for the narrow condition is too small.

For the trial runs including the low flows, model time was approximately 15 hours. Cross-channel elevation and sediment profiles were consistent with expected results. The narrow condition had a sharp incline and coarse sediment in the middle of the channel. The unconstrained condition had a wider channel, slightly wider than the initial channel, and sediment size in the middle of the channel was larger than on the floodplain, but still smaller than in the constrained run.

The velocity output of the low flow trial runs was mapped, and velocities were characterized based on typical transitions between morphologic units as identified by Pasternak and Senter (2011). Plane bed is defined as a velocity less than 0.3 m/s, inset channels as between 0.3 and 0.6 m/s, steep inset channels as greater than 0.6 m/s. The final category, the areas with velocities more than 0.9 m/s, are defined as the run morphologic unit. In the narrow run (Figure 13), the channel is very narrow and there range of morphologic units is difficult to distinguish. In the unconstrained run (Figure 14), the channel is wider, and the spatial pattern is recognizable, and consistent with what would be expected for a gravel-bedded river. The fast areas (blue) are on the inside of bends, and the slower parts (green and yellow) are in the side channel areas.

Salmonid habitat area (defined by Goodman et al. 2014) was mapped for the high flow runs (Figures 15 and 16). The habitat areas (Table 1) for each run were fairly consistent. There was less area in the unconstrained run than in the narrow run. The most habitat area was in the setback run. However, much of the habitat area in the unconstrained run was in the side channels.

In summary, physical diversity was more in the unconstrained runs than in the constrained runs. While habitat measurements suggest more habitat in the constrained run, much of the habitat in the unconstrained run was in the side channels.

Discussion

The unconstrained condition had the most side channel activity out of the three trials, both at the end of the trial and cumulatively during simulation. This is consistent with the literature suggesting a wider erodible corridor can enhance morphologic diversity. As expected, in the narrow corridor, the main channel was stationary throughout the duration of the run. The cross-channel profile of the narrow corridor conditions revealed that the channel became narrower and deeper, which is consistent with observations in real systems (Beagle et al. 2015). However, the sediment profile suggests that too much fine sediment may be eroding from the system. Adding an appropriate amount of sediment to the system, rather than recirculating sediment, may result in a more realistic sediment profile.

In the set back condition, the channel widened, and cumulative sediment flux was higher than in the unconstrained condition. Judging by the cross-sectional profile and comparison of the final elevation map to the initial condition, it appears that the channel eroded until it came to the revetments, and "bounced off," running into the revetments on the other side. Because the erodible corridor was relatively narrow, this process continued, resulting in a wider active channel and more sediment flux than for the unconstrained condition (Figure 12). Time constraints prevented modeling of the set back condition with all flows, but this result would likely be improved by supplying sediment.

The habitat area in the unconstrained run was less than the set back run, and all three runs were fairly similar in calculated habitat area. However, the side channel area did appear to be an important contributor to habitat area (Figure 14). The model outputs velocity and depth at each time step, meaning that this is simply a snapshot of what habitat exists at a single point in time. A modification to the model allowing the tracking of cumulative time a cell meets the specified habitat condition would likely be more representative of the long-term habitat changes associated with different management strategies.

The all flow model results suggest that this strategy may be a better indicator of future habitat conditions than the solely high flow condition. Originally, I tried a few trials with all flows, but because I was using 9 grain sizes, it was extraordinarily slow. However, reducing the number of grainsizes decreased run time significantly. While it is possible to run the model with all the flows and grainsizes, it would take a very long time, and may not be suitable for management. However, this would be a necessary test for the theoretical experiments about the importance of river corridor width.

The habitat parameters used in this study were very limited. Developing an index for assessing the physical output of the model spatially, similar to the use of Shannon's diversity index performed by Yarnell et al. in 2006 would be the first step in turning the output of the model into a useful tool for restoration. This could be applied to the maps for all flows classifying certain habitat units. The use of an index like Shannon's diversity index would be another useful tool for exploring habitat quantity. Incorporating other available parameters, like sediment size, would also increase its utility. Connecting currently existing river morphologies to local biological integrity estimates would be an important way of field validating the results.

These preliminary tests indicate that the CAESAR-Lisflood model has the potential to quantify differences between possible restoration strategies, and in a reasonable amount of time. The channel profile for depth, average sediment size, and velocity indicated that the model is capable of representing the pool-riffle sequence expected in a gravel-bedded river system. While the validity of the constrained conditions would be improved by adding sediment to the system, the model is capable of producing reasonable river morphology and appropriately distributing sediment.

Future studies should explore other model parameters, and incorporate more sediment sizes, and use of a common biological index. Further exploration of the model's operation could result in a useful and approachable tool for restoration.

Tables and Figures

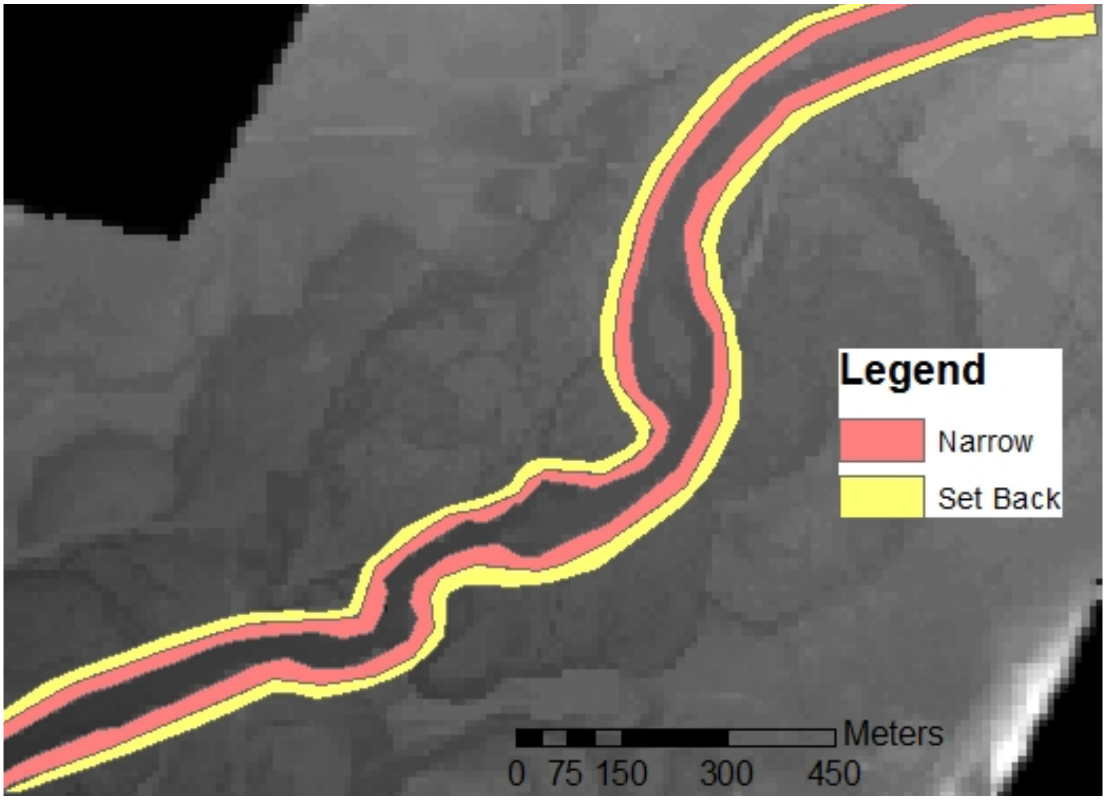

Figure 1. Positions of non-erodible rock revetments used for CAESAR model runs. Revetments are placed along the banks of the existing channel.

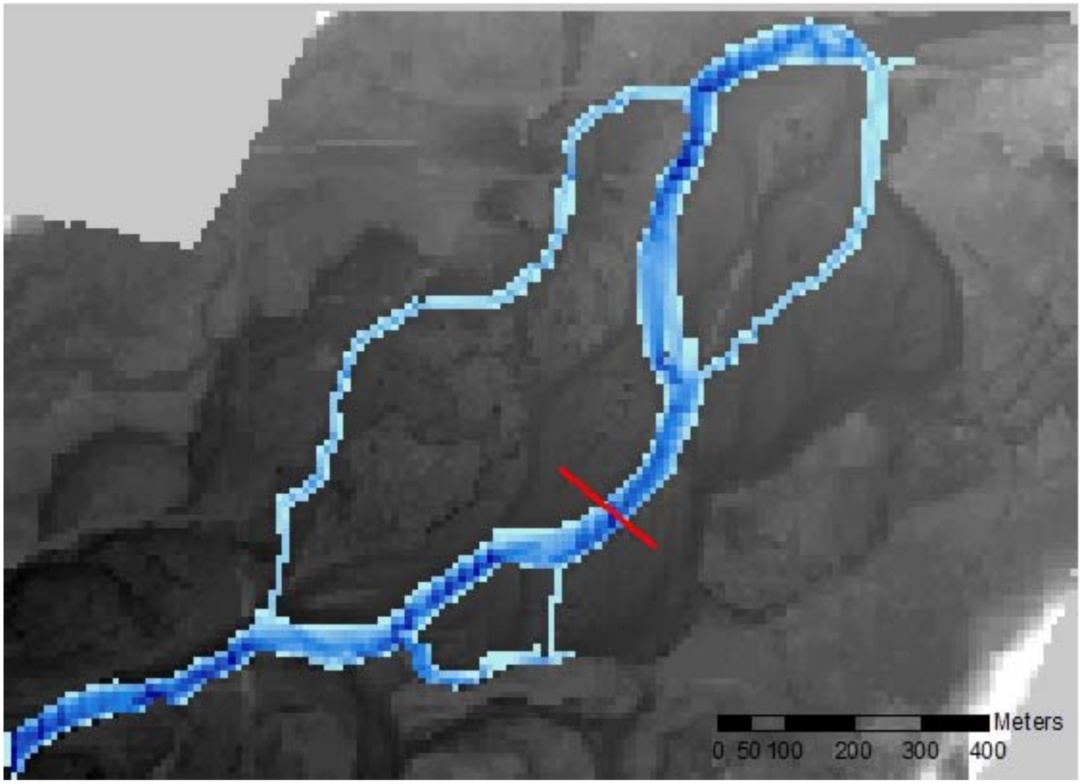

Figure 2. Unconstrained condition after 100 years of simulated flow. Resulting DEM is modeled with a summer low flow (4 cms). Colors represent velocity with darker blue indicating greater velocity. Red line indicates position of cross-section (Figure 5).

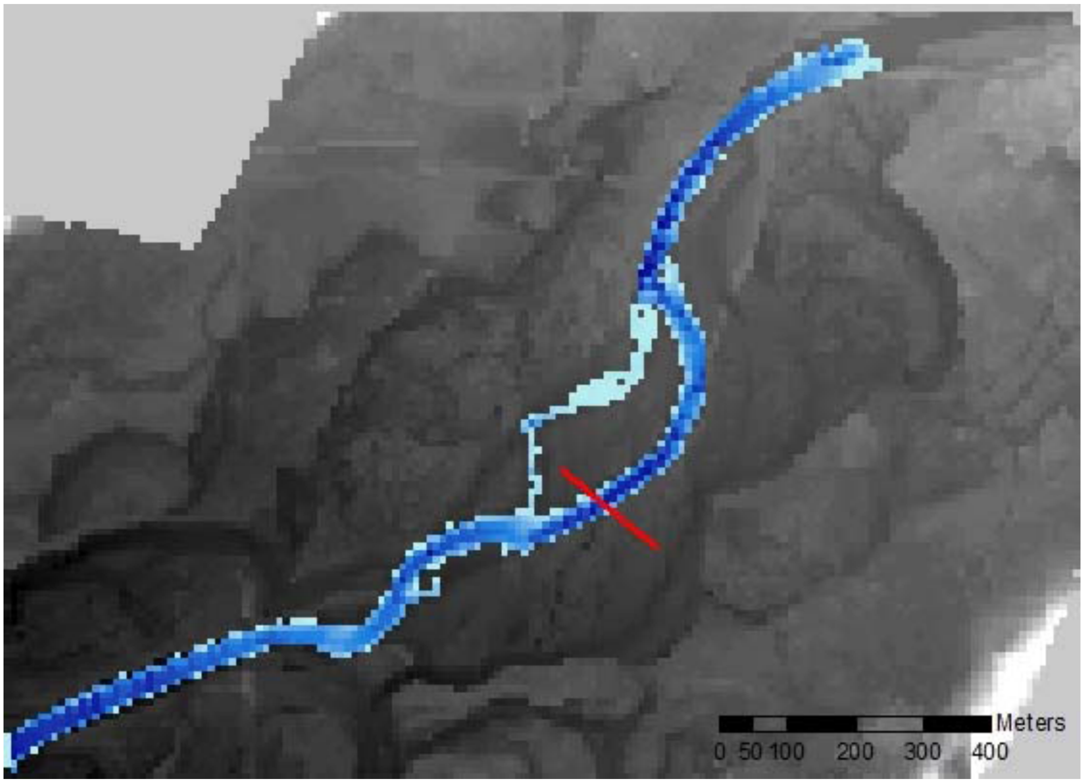

Figure 3. Narrow condition after 100 years of simulated flow. Resulting DEM is modeled with a summer low flow (4 cms). Colors represent velocity with darker blue indicating greater velocity. Red line indicates position of cross-section (Figure 6).

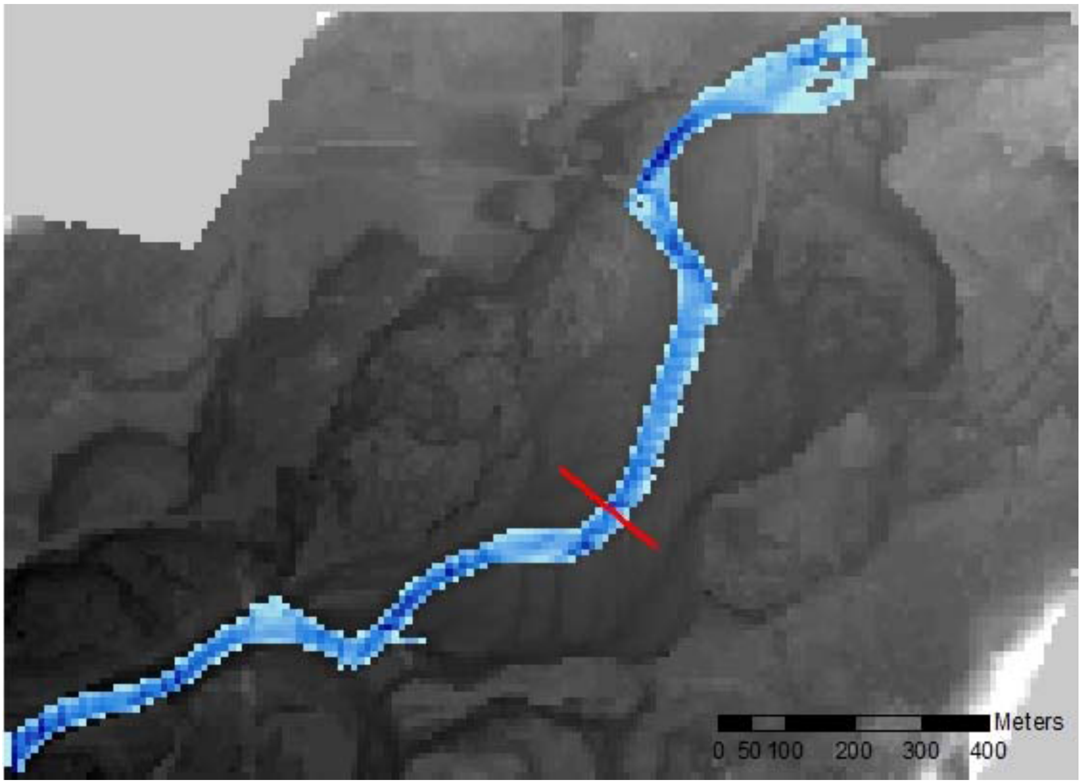

Figure 4. Set back condition after 100 years of simulated flow. Resulting DEM is modeled with a summer low flow (4 cms). Colors represent velocity with darker blue

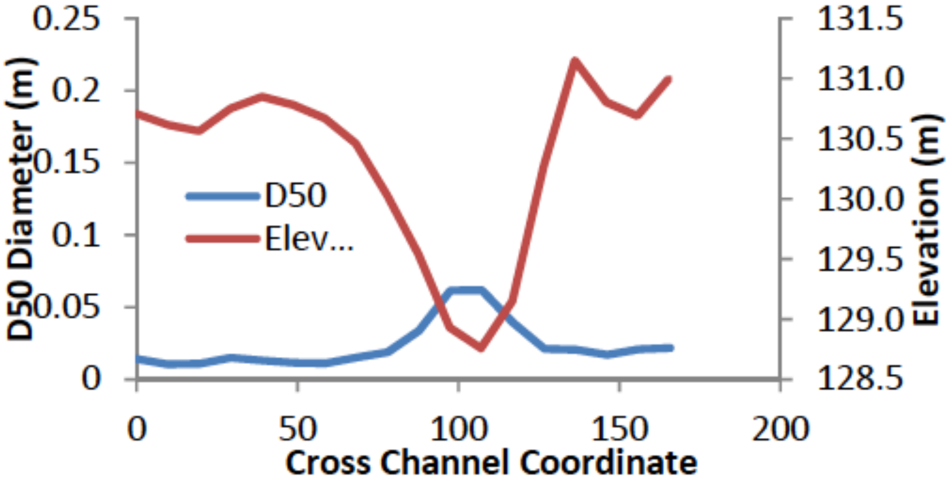

Figure 5. Cross-section of unconstrained condition after 100 years. Average sediment diameter is larger in the middle of the channel than the floodplain.

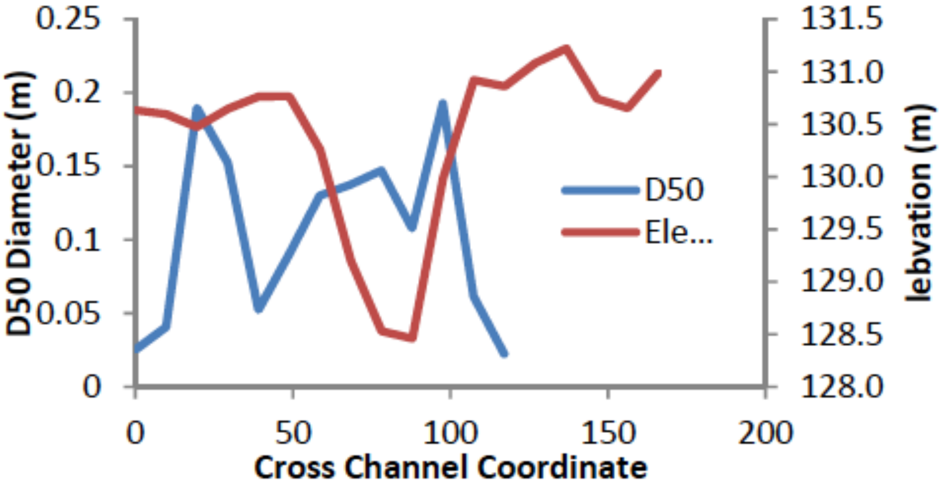

Figure 6. Cross-section of narrow condition after 100 years. Average sediment diameter shows no pattern across the channel profile.

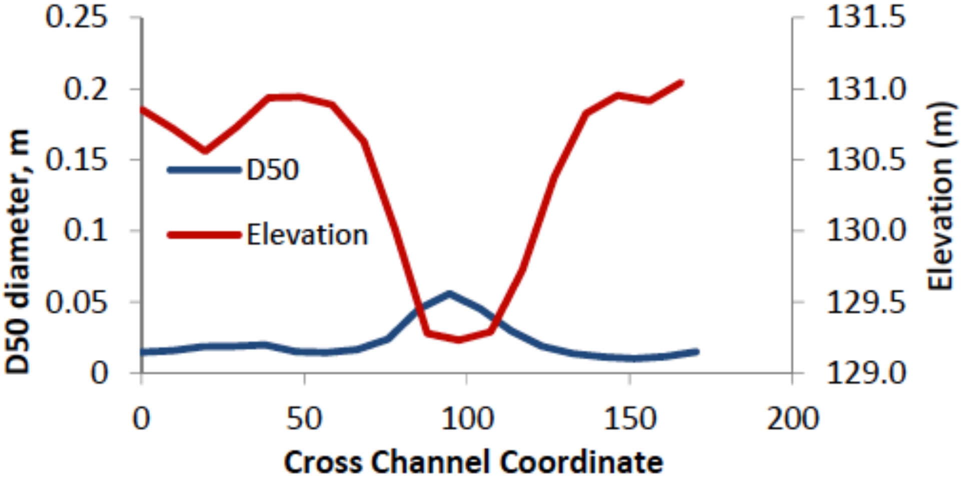

Figure 7. Cross-section of set back condition after 100 years. Average sediment diameter is larger in the middle of the channel than the floodplain, and channel is wider than in the unconstrained condition (Figure 5).

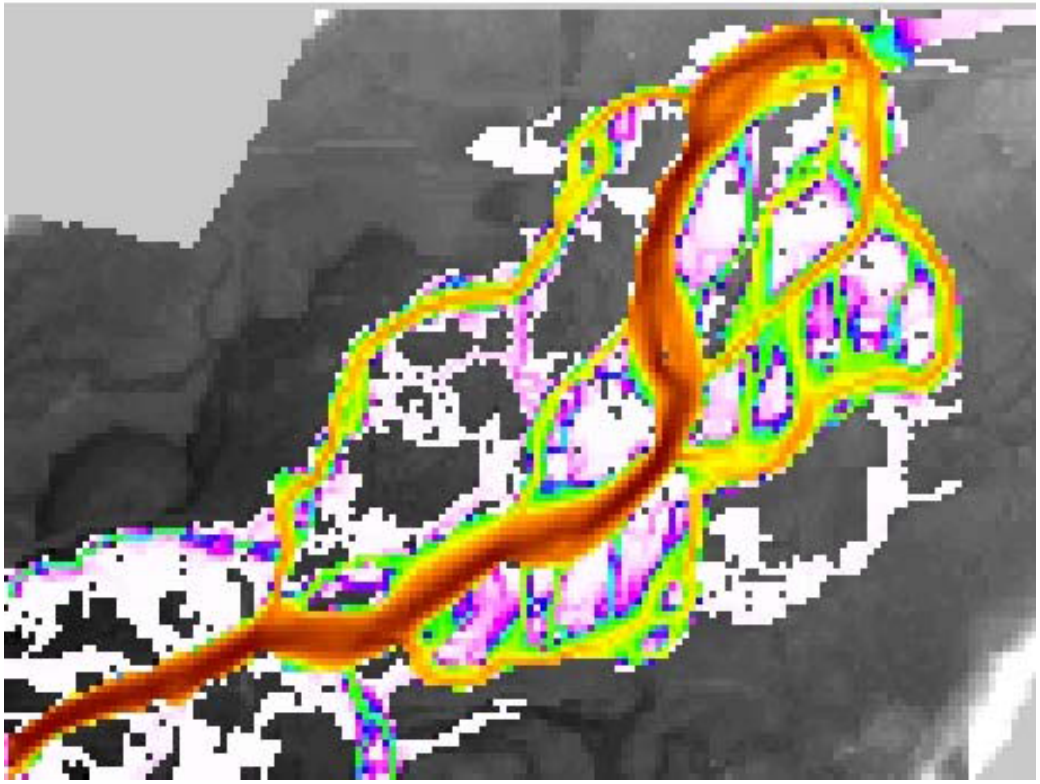

Figure 8. Cumulative time inundated during 100-year simulation for unconstrained condition. Colors range from purple to red for increasing time inundated. Side channels (orange) visible on the both sides of the main channel (red) were inundated for longer than the surrounding floodplain.

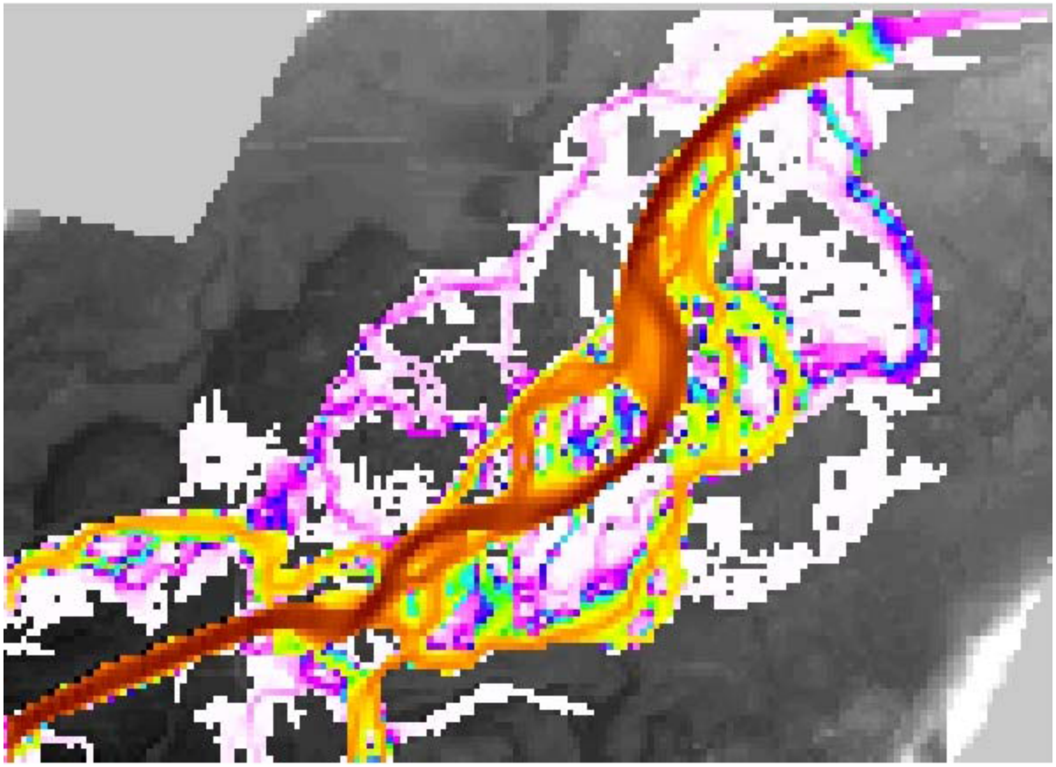

Figure 9. Cumulative time inundated during 100-year simulation for narrow condition. Colors range from purple to red for increasing time inundated. Side channels (orange) can be seen primarily on the south side of the main channel (red).

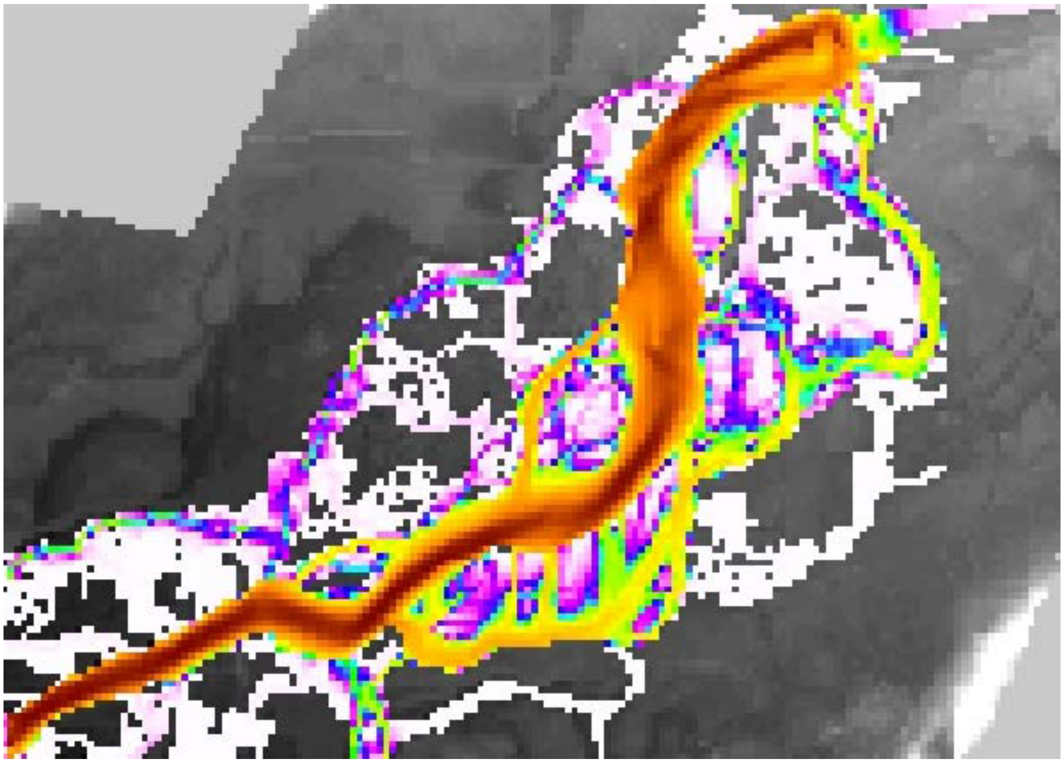

Figure 10. Cumulative time inundated during 100-year simulation for set back condition. Colors range from purple to red for increasing time inundated. Very few areas outside the main channel (red) were inundated for a significant portion of the simulation.

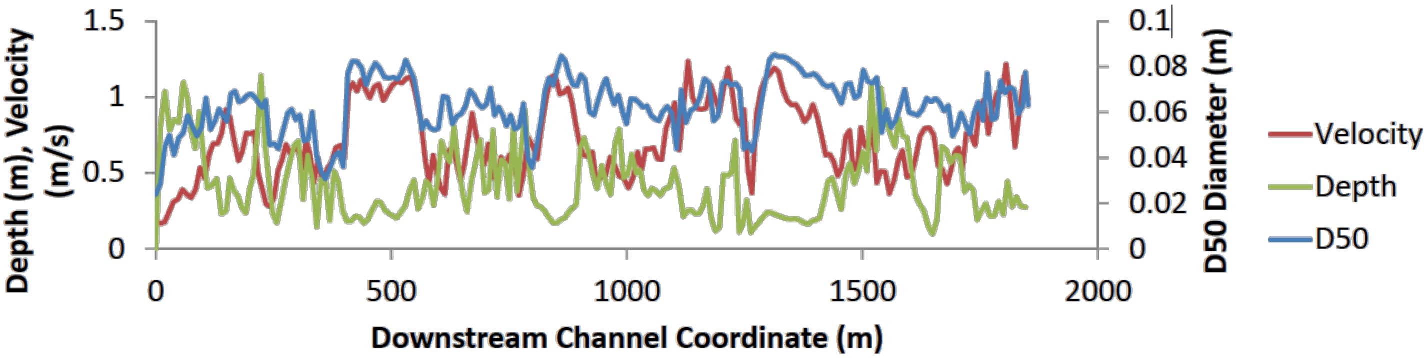

Figure 11. Depth, velocity, and average sediment diameter (D50) profile for the length of the main channel of the unconstrained condition after 100 years simulation. Sediment size and velocity are inversely correlated with depth, as expected for a pool-riffle sequence.

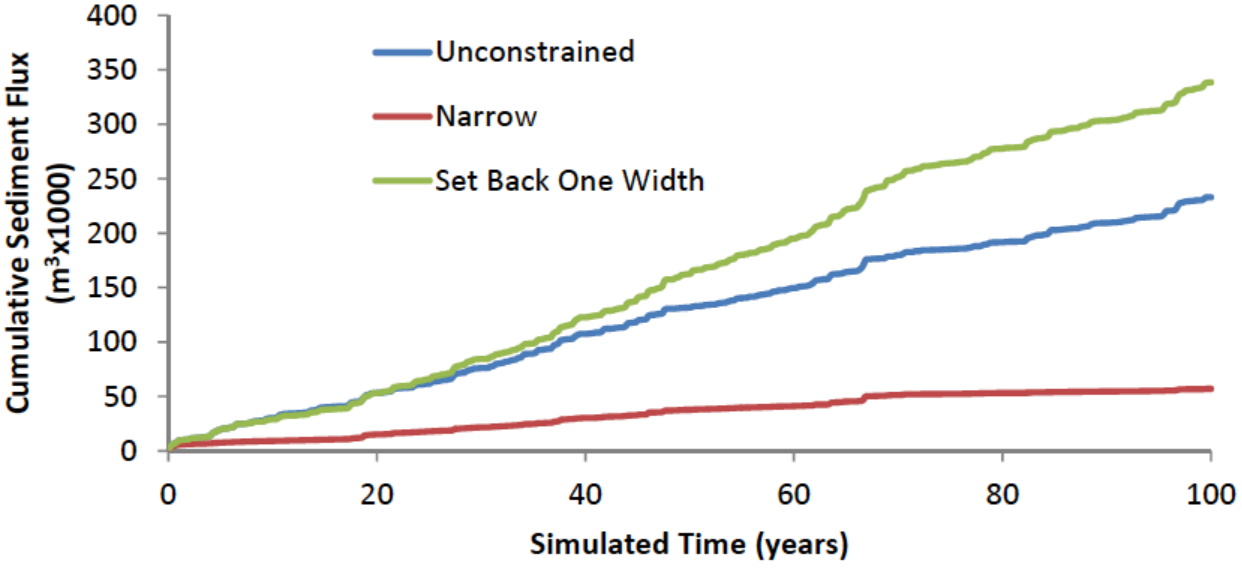

Figure 12. Cumulative sediment flux over time for the unconstrained, narrow, and set back conditions.

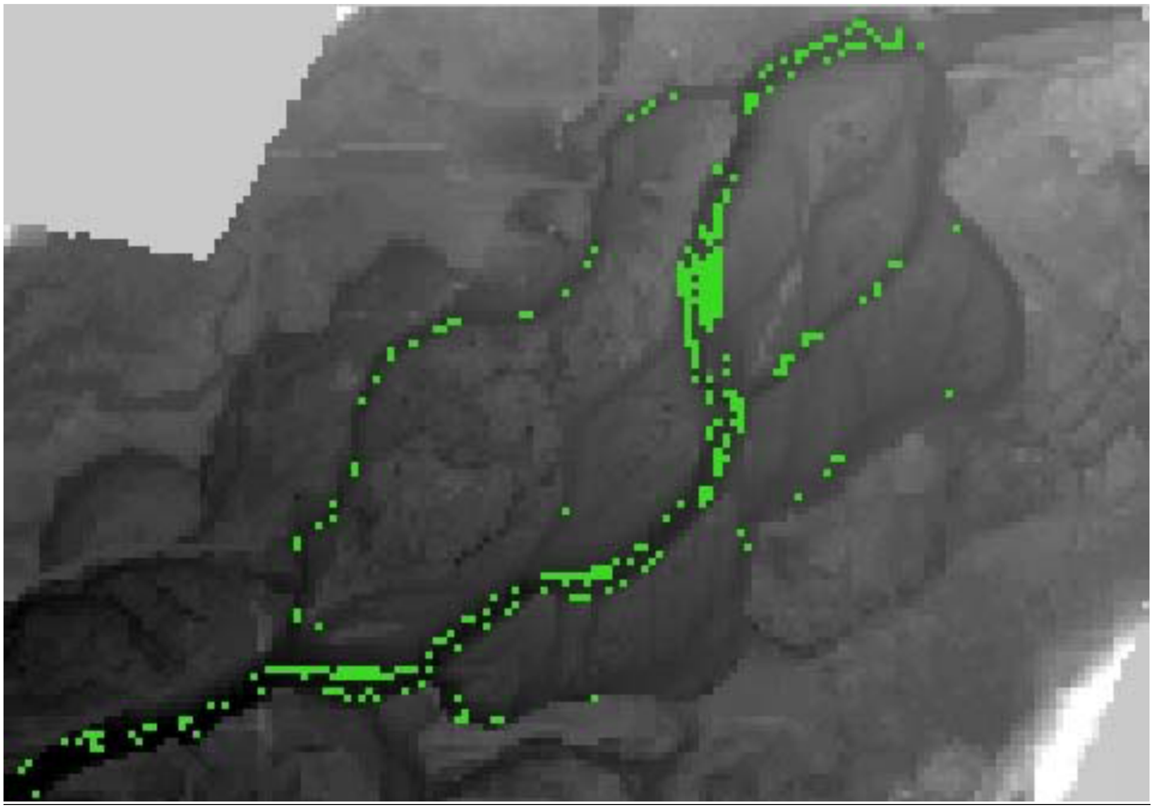

Figure 15. Habitat area in unconstrained condition for Coho/Chinook presmolt after 100 years of flow (Depth <1 m, velocity <1m/s).

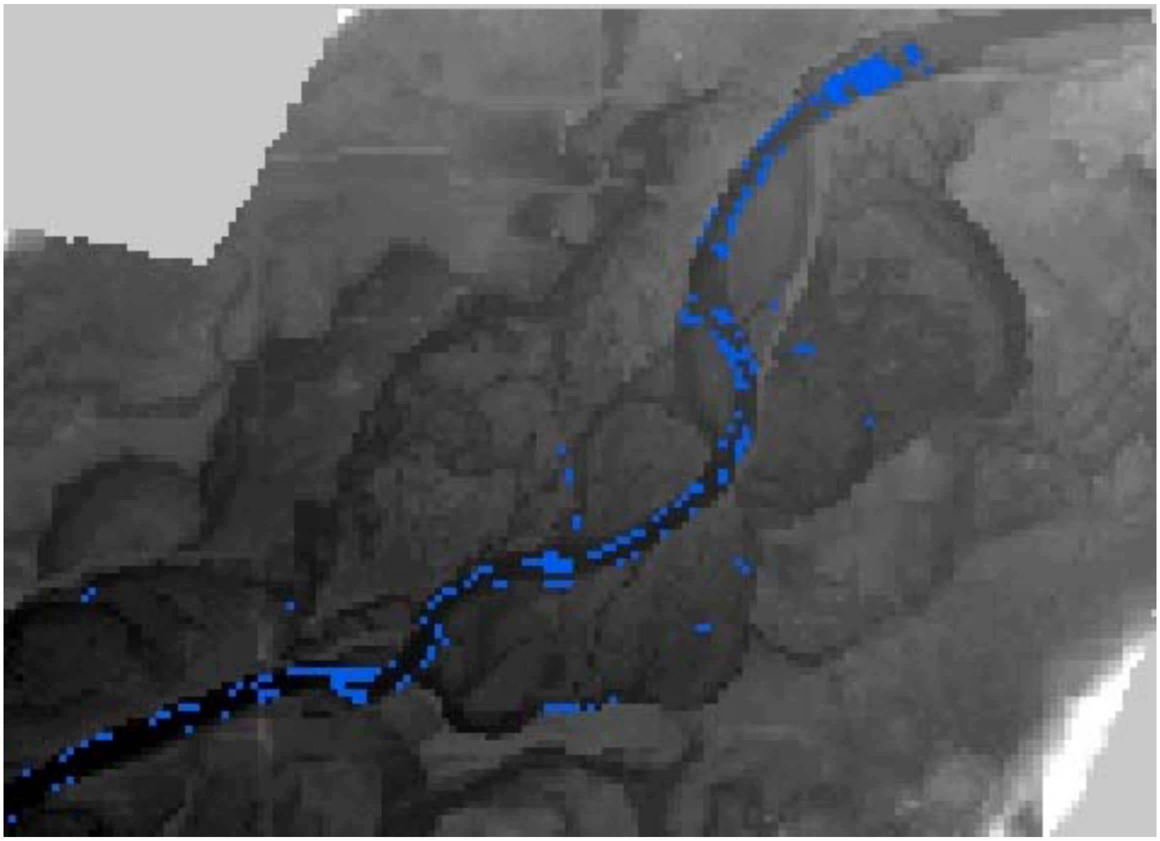

Figure 16. Habitat area in constrained condition for Coho/Chinook presmolt after 100 years of flow (Depth <1 m, velocity <1m/s).

Table 1. Habitat area calculated during summer low flow after 100 simulated years.

Test Conditions	Habitat Area
Unconstrained	2970 m^2
Narrow	2410 m^2
Set Back	3140 m^2

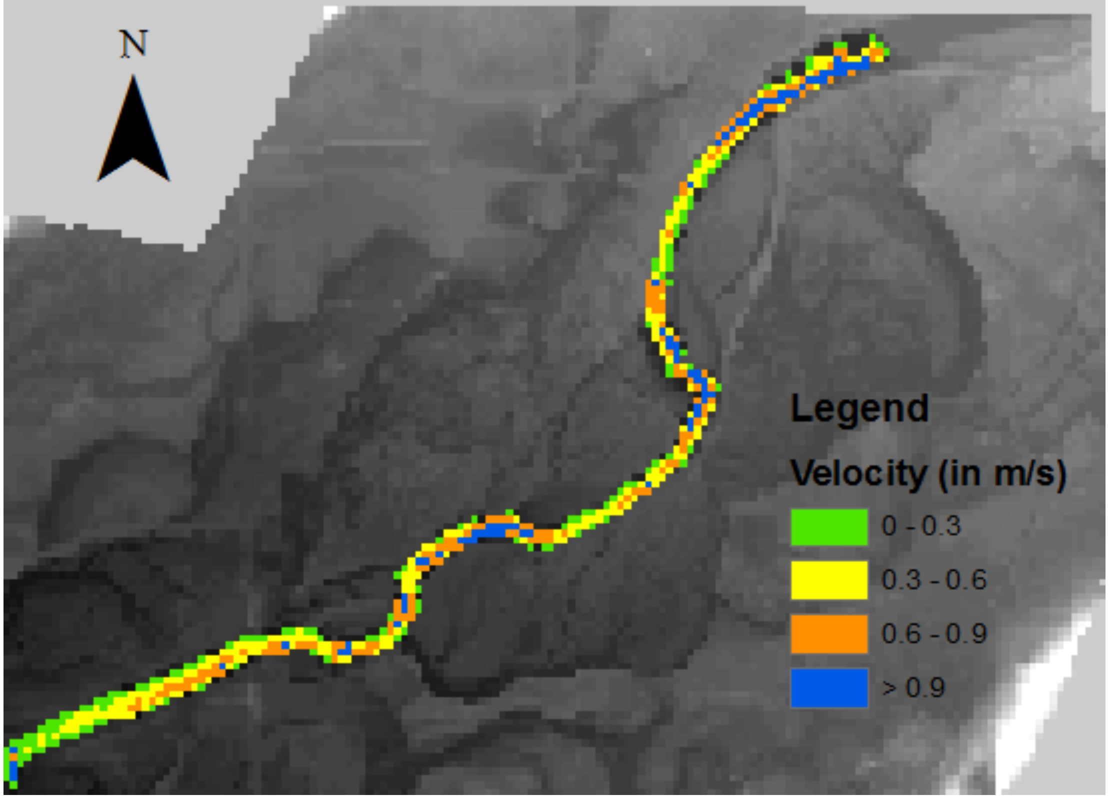

Figure 13. Velocity during low flow in constrained run after 100 simulated years with all flows. Low velocities can be seen along the edges of the channel, and there is little area of high velocities (blue).

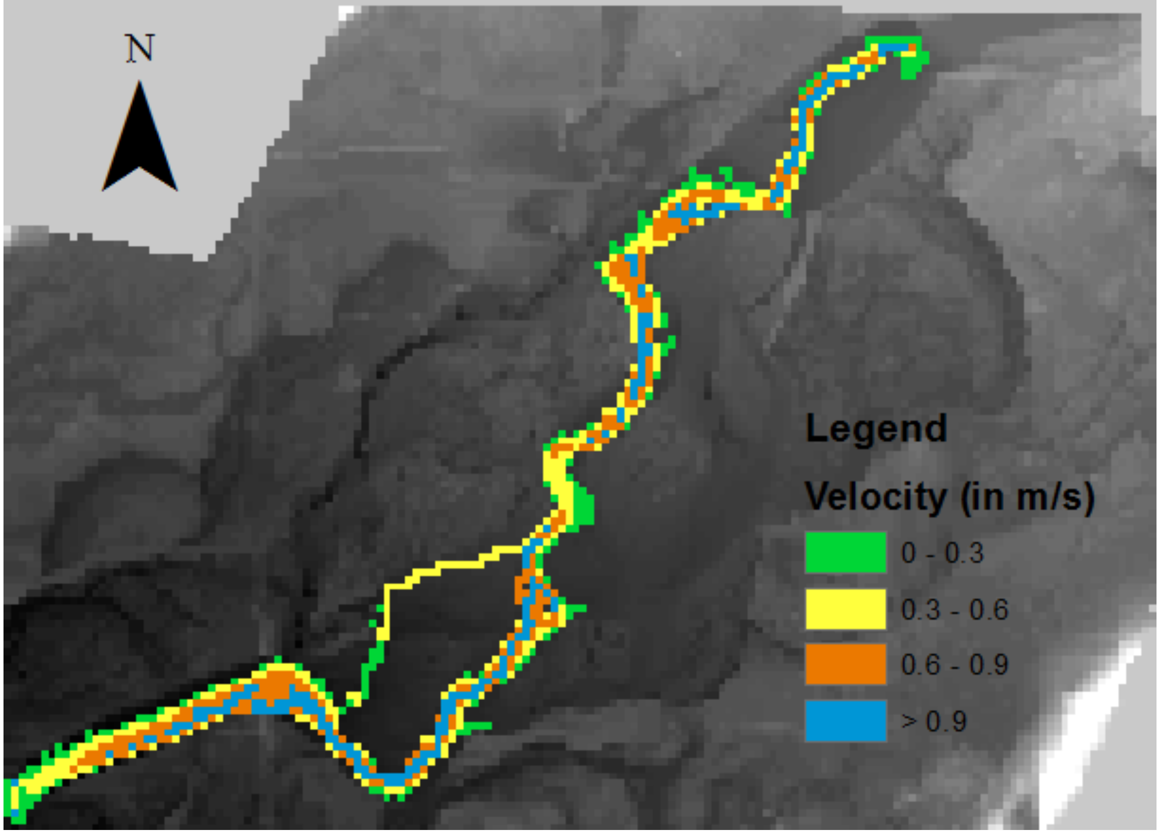

Figure 14. Velocity during low flow in unconstrained run after 100 simulated years with all flows. Velocity is properly sorted along edges, and there is a consistent distribution of morphologic units.

Appendix 1

Model Information

CAESAR-Lisflood is a 2D cellular model that integrates the CAESAR landscape evolution model (LEM) with the LISFLOOD-FP hydraulic model (Coulthard et al. 2013). Combining the models provides greater efficiency for larger spatial and temporal scales without the loss of precision provided by non-steady flow hydraulic equations, making this model an appropriate choice for this study.

In addition to the model efficiency, the model was selected because:

- It uses size-specific sediment transport equations (Wilcock and Crowe, 2003) to represent fluvial erosion and deposition, thereby allowing simulation of changes in bed texture
- Output provides water depth, velocity, and average sediment particle size values for every cell on the grid, which can be used to calculate habitat area at any point in the simulation
- Source code is available for customization, allowing us to track cells meeting conditions for habitat ranges

Computer

Used 4 core 3.5 ghz Xeon PC

DEM: 18,012 cell grid (114 x 158), 10m cells

Model Input

Hydrology	Average daily flow values were obtained from USGS stream gage 12142000. Flow enters the model at three arbitrarily chosen points close to the north edge of the map. Low flows used a flow of 9 cms.
Digital Elevation Map (DEM)	The map used was obtained from 2009 King County LIDAR. It was corrected for water depth based on color in an aerial image, resampled at 10 m resolution, and modified in ArcGIS to prevent flow from leaving the northern boundary.
Sediment	Distribution was calculated from a bar-top pebble count. The supply is specified by recirculating sediment leaving the lower boundary of the map.
Revetments	These are represented by a bedrock file created by modifying the original DEM
Lateral erosion	This is a parameter that must be calibrated for a particular study site by experimentation. I tested a range of values from 0.01 to 0.00001, and found that for this site, a value of 0.0002 resulted in an appropriate morphology with curvature expected given the current and historical conditions of the site.
Hydraulic Roughness	This parameter affects the velocity of the in-channel flow. Manning's n was found by calibration to high water marks.

All other model parameters were left unaltered.