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REACH-SCALE MORPHOLOGIC AND ECOLOGIC RESPONSES TO RESTORATION IN A SIMPLIFIED CHANNEL-FLOODPLAIN SYSTEM

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An emergent paradigm within restoration science is that restoration of natural physical processes is the best way to restore habitat for native organisms. This concept, which underpins many restoration projects, is based on the notion that the establishment of an actively migrating, alluvial river channel-floodplain system will provide a number of desired ecological functions, each related to specific physical processes that occur at the habitat-scale. Here we quantify the rates of morphologic change, channel migration and the development of high-quality habitat, using a recently restored gravel-bed reach of the Merced River, California, USA. DEM-derived differences in bed elevation indicate that sediment storage accelerated processes of bar-building, pool scour, and bank erosion, leading to more asymmetric cross-sectional geometry. The volume of sediment stored on developing point bars was correlated with the migration distance of the outer bank, suggesting that channel migration was influenced by sediment supply as well as by channel curvature. The documented channel changes have had marked results on flow hydraulics, leading to decreased velocities over riffles and increased velocities in pools during low flow spawning conditions. Habitat modeling indicates that the quality of Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat has increased, primarily due to deposition on riffles. These changes in morphology, hydraulics and habitat availability occurred largely during two sustained periods of overbank flow. Collectively, these results highlight the importance of overbank flows and a sediment supply sufficient for bar growth in meander migration and creating channel complexity and high-quality habitat.

1.0 INTRODUCTION

1.1 River restoration

The alteration of river systems and loss of aquatic ecosystems has lead to worldwide efforts to rehabilitate freshwater habitats [1; 2], and within the United States an average of $1 billion is spent per year on restoration projects [3]. Stream and river restoration is often motivated by the goal of recovering populations of endangered species, but much work remains to establish a scientific basis to guide these projects [4]. An important step in establishing scientifically sound restoration practice is the quantification of the geomorphic processes commonly assumed to promote the creation and maintenance of high-quality habitat.

An emergent paradigm within restoration science is that restoration of physical processes is the best way to restore habitat for desirable populations of organisms [5]. This concept, which underpins many restoration projects, is based on the idea that the establishment of a self-regulating, alluvial river channel-floodplain system will provide a number of desired ecological functions, each related to specific physical processes that occur at the habitat-scale [6; 7]. Trush *et al*., [6] proposed that the physical processes required to maintain ecological functions in gravel-bed rivers include: 1) lateral migration via bank erosion and point bar growth to provide spawning and shallow water rearing habitat; 2) pool scour to promote rearing habitat; 3) erosion and deposition on riffles for spawning habitat; 4) deposition of fine-grained sediment on channel floodplains to promote terrestrial and riparian habitat. Each of these physical processes are in turn linked to specific flow magnitudes and frequencies, such that the bed is mobilized every 1-2 years by bankfull flows while sediment is delivered to channel floodplains by infrequent, large overbank flows. In this conception, river restoration involves manipulation of channel form, bed grain-size and flow magnitude.

While this model offers perhaps the richest conceptual view of the linkages between geomorphic processes and ecological functions, we are unaware of any field studies that quantify the physical and biological processes that are expected to result from the manipulations or the rate of channel evolution from its design state. Thus it is difficult to predict how the availability and quality of habitat will change over time as the channel evolves under a stochastic regime of flow and sediment supply. This is particularly important because rivers are dynamic systems that adjust their morphology in response to the imposed flow and sediment supply conditions over time. Thus habitat availability is likely to vary over time, a point which is often overlooked in restoration projects. Here we explore the extent to which a recently restored river-channel floodplain system develops physical and ecological complexity, by quantifying rates of channel change, hydraulic adjustments and the development of high-quality habitat. We focus specifically on the development of spawning habitat for the fall-run Chinook salmon (*Oncorhynchus tshawytscha*) but our intention is to illustrate a more general pattern of the evolution of physical and ecological complexity related to changes in channel morphology.

1.2 Field Setting

The Merced River is a tributary to the San Joaquin River in the Central Valley of California, and drains a watershed area of approximately 3,305 km^2. This study focuses on the Robinson reach, part of a larger effort to restore salmon habitat and channel-floodplain functionality following 150 years of gravel pit mining. The Robinson reach was constructed in February, 2002 following extensive flooding and a channel avulsion that occurred in 1997. The re-engineered 2.25 km long channel has a single-thread, meandering planform, with a bed slope of 0.0025, average bankfull width of 30 m and bankfull discharge of 48 m^3/s. The median grain-size of 0.055 m was scaled to the post-dam hydrology, with the expectation that it would be mobilized by the bankfull discharge. The channel was initially designed with alternating wide, deep pools and shallow riffles, and lacked point bars on the inside of meander bends. Given the initial simplicity of the channel, this field-scale laboratory site offers an unparalleled opportunity to investigate the evolution of physical processes, morphologic change and the development ecological habitat.

1.3 Field Data

1.3.1 Topographic and grain-size surveys

Following construction, a total of 25 cross-sections were surveyed along the 2.25 km reach [8]. Monitoring cross-sections were located in the center of pools and riffles along 12 meander bends. Higher-resolution topographic surveys were completed with a total station over 800 m of the reach in March 2005, October, 2005, November, 2006 and September 2007. The surveys included the active channel and roughly 10 m of floodplain on either bank, with a mean cross-section spacing of 20% of the channel width. Each dataset was interpolated to form continuous topographic surfaces using kriging methods developed by Legleiter and Kyriakidis [9]. Grain-size data was collected using traditional pebble counts along bar surfaces, riffles and in pools.

1.3.2 Hydrologic and Hydraulic Data

Reservoirs upstream of the project reach, primarily the New Exchequer Dam, dominate the flow hydrograph. There is typically a fall and spring flow release of between 31 and 42 m^3/s (~65-90% of the bankfull discharge). Following construction of the channel there have been two periods of sustained overbank flows, the first during the spring of 2005 and the second occurring in spring 2006 during which the discharge reached 2.9 times bankfull. The topographic surveys bracket these floods in order to capture the channel change. Water surface and velocity data were collected for calibration and validation of a hydraulic model (see section 2.2). The water surface elevation was surveyed at the wet-dry boundary roughly every 10 m for discharges ranging from 4.25 – 42.5 m^3/s. Vertically-averaged velocity (0.6 depth) was measured over 90 s periods at eight cross-sections during a flow of 6.3 m^3/s on March 15, 2007 using a Sontek ADV Flow Tracker. The cross-sections were located in four pools and four riffles and consisted of a total of 159 velocity readings (~ 20 verticals per transect).

1.3.3 Biological Data

The location of salmon redds in the project reach was recorded in the fall of 2002 through the fall of 2006 [10; 11]. Depth, velocity and particle diameter were measured at each observed redd location and used to construct local spawning habitat suitability indices (HSI) for the project reach [10].

2.0 METHODS

2.1 Morphologic Change

Digital elevation models with a 1 m^2 grid size were developed from the channel surveys for February 2002 (as-built), March 2005, October 2005, November 2006 and September 2007. The channel change between successive surveys was calculated simply as the difference between bed surfaces at each point in the grid. These maps were used to assess patterns of sediment storage, bar growth, pool scour and riffle erosion and deposition. Rates of bank migration were calculated by digitizing the left and right bank position and then interpolating a centerline for each topographic survey. Bank migration distance was calculated as the distance between the older and newer centerlines following the methods of Lauer and Parker [12].

2.2 Hydraulic Model

To assess how the habitat quality evolved over time, flows were modeled using the USGS Multi-Dimensional Surface Water Modeling System (MD-SWMS) [13; 14]. The computational grid used in this study was approximately 780 m in length, and 51 m in width. This formed a grid that covered the entire channel width and roughly 10 m on each bank, comprised of 39729 nodes and a grid spacing of 1.0 m in the downstream and cross-stream directions. Model calibration using measured water surface elevation profiles resulted in a drag coefficient of 0.015 for a spawning flow of 6.4 m^3/s. The root mean square (RMS) error between the observed and predicted WSE was 0.05 m over the reach. Velocity validation performed for a discharge of 6.3 m^3/s resulted in an RMS error of 0.13 m/s or approximately 20% of the measured mean velocity.

2.3 Habitat Suitability Criteria and Biological Validation

The HSI curves developed by Gard [10] were used to quantify the availability of spawning habitat over time. Model simulations were performed at a design flow of 6.4

m^3/s for the time periods represented by each topographic survey. To assess the predictive capability of the habitat model, the available habitat was simulated and compared to observed redds from the fall 2004 [11]. Similar analyses are underway for the 2005 and 2006 redd data. This approach offers a degree of biological validation for the habitat modeling and has been used successfully by previous authors [15; 16; 10].

3.0 RESULTS AND DISCUSSION

3.1 Morphologic Evolution

Maps of the channel change between the first four surveys (e.g. 2002 – 2006) are shown in Figure 1. The bed elevation change between November 2006 and September 2007 was too small to detect consistent patterns and the remainder of the analysis will focus on the time period from 2002 – 2006. The pattern of morphologic response related to the three brief near-bankfull and bankfull flows between 2002 and March 2005 show deposition of up to 1 m on the three point bars accompanied by sub-meter pool scour (Figure 1a). Erosion at the head of the riffles and paired deposition downstream on riffle centers and tails were also observed, resulting in a decreased riffle slope. Rates of bank erosion during this period were highest at the uppermost bend at 1.4 m, compared to 1.0 and 0.7 m at the next downstream bends.

A) Feb 2002 – Mar 2005 **B**) Mar 2005 – Oct 2005 **C**) Oct 2005 – Nov 2006

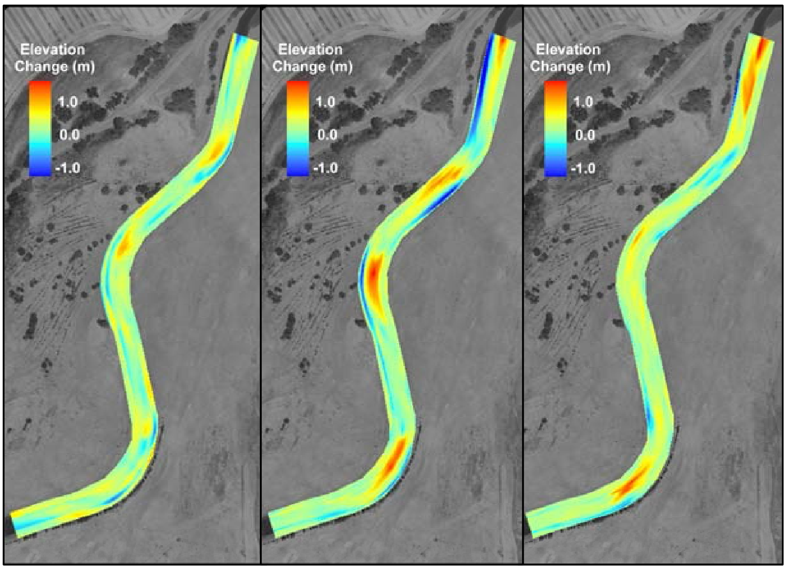

Figure 1. Bed elevation differences between successive surveys of the Robinson Reach of the Merced River, CA between: **A**) February 2002 (as-built) – March 2005; **B**) March 2005 – October 2005 and **C**) October 2005 – November 2006.

Substantial channel change also followed the high flow period between March 2005 and October 2005 (Figure 1b). The most prominent morphologic change was point bar growth of up to 1.2 m of aggradation (Figure 2). Bar growth was accompanied by pool scour in excess of 1 m, and bank erosion rates of 1.8, 2.6 and 2.0 m. The patterns of morphologic response between October 2005 and November 2006, show continued patterns of bar growth. Despite the greater magnitude and extensive duration of flooding, pool scour and bank erosion rates were more similar to the February 2002 – March 2005 period. These differences in bank retreat may be explained by the reduced sediment storage following the spring 2006 flood event. Bed material storage on point bars has been shown to influence bank retreat in other gravel-bed rivers [17; 18; 19] and is correlated here as well, suggesting that channel migration was influenced by sediment supply as well as by channel curvature.

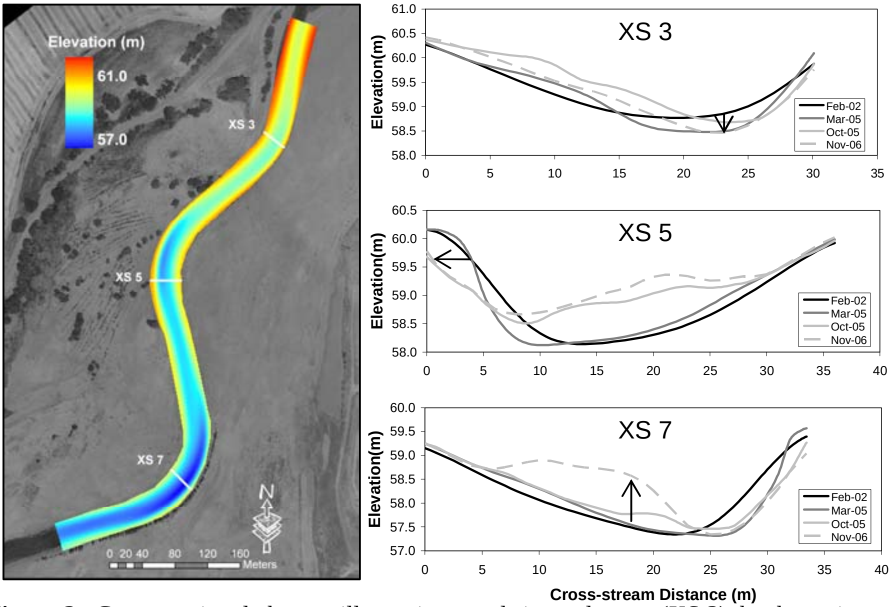

Figure 2. Cross-sectional change, illustrating trends in pool scour (XS 3), bank erosion (XS 5) and bar growth (XS 7).

3.2 Hydraulic and Habitat Simulations

Clear changes in channel hydraulics can be seen as the bed and physical processes evolve. Initially, velocities are highest over the riffles while pool velocities are slow and uniform across the channel (Figure 3a). As seen in figures 3b - 3d, deposition on the riffle gradually reduces the velocity from a maximum of 1.2 m/s to roughly 0.9 m/s. Point bar growth leads to greater velocities in the pools due to enhanced topographic steering [20; 21] (Figures 3b – 3d).

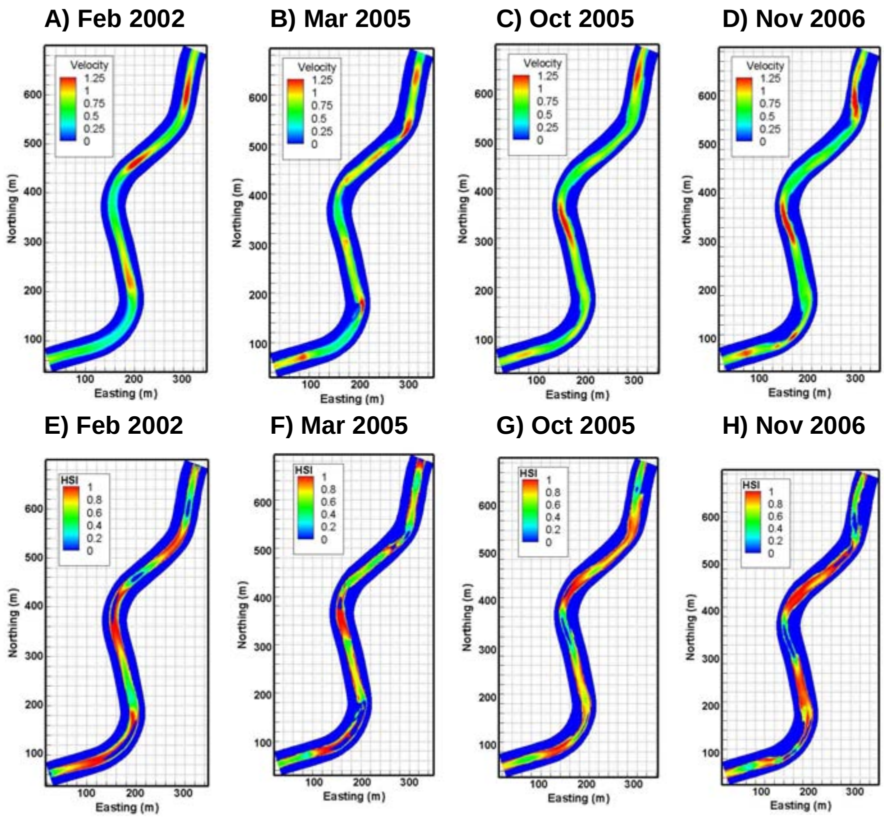

Figure 3. Model simulations of velocity (A-D) and the Habitat Suitability Index (E-H) for a discharge of 6.4 m^3/s.

Using the local HSI curves [10], habitat quality was predicted for each bed topography in order to investigate how changes in morphodynamics influence habitat availability. Results shown in Figure 3e indicate that high-quality spawning habitat was initially limited to riffle crests and the uppermost pool (XS-3). Habitat quality remained in the heads of riffles in March 2005, though is reduced by pool scour in the upper pool. Following the overbank flows of 2005 and 2006, the higher quality habitat gradually expands throughout the length of the riffles (Figures 3g – 3h), due to sediment storage and a reduction in the riffle slope. The predictive capability of the habitat modeling is validated by the percentage of redds found in each of the habitat quality types (Figure 4), as the large majority of redds are located in medium or high-quality habitat.

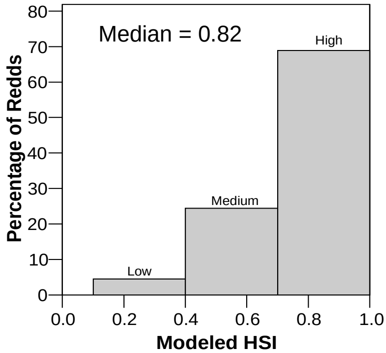

Figure 4. Biological validation of the modeled HSI values, using percentage of 2004 observed redds located in each of the modeled HSI habitat types.

3.3 Physical Processes and Habitat Development

The dominant morphologic responses to the design of a simplified channel were bar growth coupled with bank erosion, pool scour and riffle erosion and deposition, which occur more or less as proposed by Trush *et al.*, [6]. The initial channel evolved towards greater physical complexity with more diverse hydraulic and habitat conditions. The rates of channel migration and bar growth were greatest during periods of sustained overbank flow, highlighting the role of large floods in promoting channel change. The importance of overbank flow in driving channel change has been observed in recent flume experiments [22] and field studies [23] and is being explored through ongoing numerical model simulations.

The habitat modeling exercise illustrates how adjustments in channel morphology related to sediment storage can produce discernible changes in habitat quality. These results highlight the dynamic nature of river channels and the need to consider sediment storage and the role of large floods in driving the desired physical processes sought by many restoration projects. As shown here, these processes operate on multi-year time-scales emphasizing the importance of anticipating and planning for changes over time.

4.0 CONCLUSION

This study examined how a simplified, restored gravel-bed river evolved over time in terms of morphologic change, channel hydraulics and the availability of spawning habitat. Channel change at this site is driven by channel curvature and bed material storage especially during large over bank floods, which promoted bar growth, pool scour and enhanced cross-sectional asymmetry. The rate of bar growth was correlated with the migration of the outer bank. This process has important implications for the maintenance of actively migrating rivers. The erosion of the outer bank leads to downstream deposition on riffles and point bars. This in turn leads to the development of more favorable spawning conditions for Chinook salmon via reduced velocities and increased depths over the riffle. These results illustrate the importance of considering the role and magnitude of sediment transfer and storage in driving the physical processes necessary for maintaining dynamic river systems.

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