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Hydro- and morphodynamics of riffle-pool sequences in the middle Elwha River, Washington, USA

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ABSTRACT: Riffle-pool sequences are ecologically important features of mild-sloped gravel-bed rivers. They are composed of alternating vertical bed undulations and are often forced by variations in width. The natural formation and maintenance of riffles and pools remains poorly understood, as does their response to certain disturbances such as changes in sediment supply. The Elwha River restoration project and associated removal of Glines Canyon Dam provides a natural setting to explore how large increases in sediment supply affect downstream riffles and pools. Here we present results from bathymetric/topographic surveys conducted in fall 2014 and spring 2015 and two-dimensional hydrodynamic modeling associated with each of the surveyed surfaces. Riffle and pool units for each survey were classified using the hydrodynamic model results, and riffle areas increased by 33% while pool areas decreased by 50% over the winter 2014/2015 season.

1 INTRODUCTION

Many gravel-bed rivers exhibit downstream undulations in relative bed elevation termed riffles and pools. These alternating geomorphic units are present in both straight and meandering coarse-bed channels with slopes < 2% (Leopold et al. 1964, Knighton 1998). Riffles are defined as areas of higher relative elevation with a symmetrical cross-section and coarser bed material. Conversely, pools have relatively low topography and characteristically have finer bed material (Keller 1971, Richards 1976). Because riffles and pools provide important habitat to a number of aquatic organisms, their formation and/or maintenance are often the goal of restoration projects (e.g. Biron et al. 2012, Pasternack & Brown 2013).

The natural genesis and maintenance of riffle-pool features remain poorly understood, as does their response to certain disturbances (e.g. unsteady sediment supply). In some systems, the valley and/or channel width have been shown to exert an influence on the location of riffle and pool units. For example, White et al. (2010) found that valley width constrictions coincided with pools in the Yuba River. Through one-dimensional modeling of lower Bear Creek, de Almeida & Rodríguez (2012) showed that riffles and pools spontaneously emerged at channel expansions and constrictions, respectively. Brew et al. (2015) also showed how riffle-pool locations were controlled by variations in bankfull channel width during a large sediment pulse in the middle Elwha River (Fig. 1). This was corroborated with flume studies by Nelson et al (2015) where pool locations were controlled by width constrictions regardless of sediment supply.

The removal of Glines Canyon Dam as a part of the Elwha River restoration project provides a natural setting to further examine how a large increase in sediment supply may affect riffle-pool sequences and their associated hydrodynamics. This paper presents two topographic/bathymetric surveys, one immediately following full removal of Glines Canyon Dam (Sept 2014) and the other the

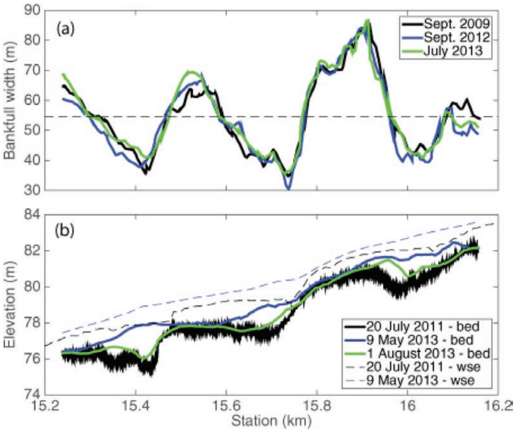

Figure 1. (a) Bankfull widths of the middle Elwha River measured from Google Earth imagery. (b) Thalweg elevation profiles from the middle Elwha River. From Nelson et al. (2015) with data from Brew et al. (2015).

following spring (June 2015). Our objectives are to characterize changes in morphology and hydrodynamics over winter 2014–2015.

2 METHODS

2.1 *Study site*

The Elwha River is situated on the northern part of the Olympic Peninsula in Washington State, USA. From its headwaters in Olympic National Park it flows north over 70 km to its outlet at the Strait of Juan de Fuca. Construction of Glines Canyon Dam began in 1925 and was completed the following year (Crane 2011). In 1992 the *Elwha River Ecosystem and Fisheries Restoration Act* (Public Law 102–495) was signed into law by President George H.W. Bush and gave authorization to the Secretary of the Interior to acquire the Glines Canyon Dam hydroelectric project, as well as the downstream Elwha Dam hydroelectric project, and execute whatever actions necessary "for the full restoration of the Elwha River ecosystem and native anadromous fisheries" (US Congress 1992). Consequently, removal of both Elwha and Glines Canyon dams began in September 2011. Elwha and Glines Canyon dams were completely removed in March 2012 and August 2014, respectively.

The site for our study is a fairly straight reach (sinuosity of 1.06) of the middle Elwha River, between the former Glines Canyon and Elwha dams (Fig. 2), which impounded Lake Mills and Lake Aldwell, respectively. Our reach is located from 5 km downstream of the former Glines Canyon Dam site to the Madison Creek confluence at the boundary of Olympic National Park, just upstream from the USGS McDonald Bridge stream gage. The upstream limit of the study reach is several hundred meters downstream of the "Boulder Garden". The study reach extends approximately 900 meters downstream and is composed of three riffle-pool sequences that are co-located with variations in bankfull width (Fig. 1).

2.2 *Hydrologic setting*

The first years of dam removal saw modest hydrology for the Elwha River. From September 2011 through September 2013 the average flow at the McDonald Bridge gage was 107–108% of the mean annual discharge and the largest peak-flow was 292 m³/s (Fig. 3a, Magirl et al. 2015). Because discharges remained below the two-year recurrence interval during this period, flows probably remained within the channel banks. Following complete removal of Glines Canyon Dam in August 2014 the flows increased during the wetter-than-normal winter of 2014–2015 (Fig. 3b). Two flood events during the period of interest resulted in flows greater than the two-year flow (Fig. 3c, d). Because of their magnitude these

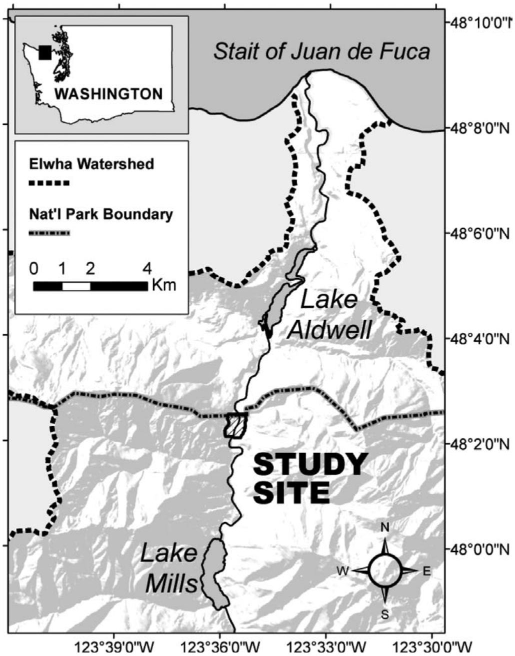

Figure 2. The location of our study site within Elwha National park, between the former dam/reservoir sites.

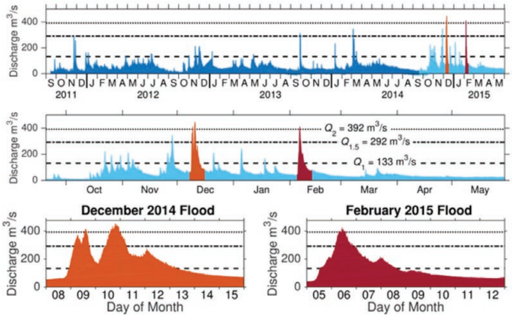

Figure 3. (a) Discharge data from the beginning of dam removal (Sept. 2011) through May 2015. (b) Discharge data between the two survey dates (Sept. 2014 and June 2015). (c) Flood hydrograph from Dec. 2014. (d) Flood hydrograph from Feb. 2015. The dashed line refers to the one-year flow recurrence interval (Q_1), the dash-dot line the one-and-a-half-year flow recurrence interval ($Q_{1.5}$), and the dotted line the two-year flow recurrence interval (Q_2). Discharge data from US Geological Survey (2015). Flow recurrence intervals from Brew et al. (2015).

floods likely resulted in flow depths exceeding the channel banks and discharges in excess of those required to be considered channel-forming.

2.3 *Field survey methods*

We conducted bathymetric/topographic surveys of the study reach before and after the winter 2014–2015 season. The first survey took place from 17 to 20 September 2014, and the second from 29 May to 2 June 2015. We collected elevation data using a Topcon GR-5 real-time kinematic (RTK) GPS system. Points were generally taken along perpendicular cross-sections spaced approximately 10 m apart, with lateral point spacings <1 m. Bars, banks, and wadable regions of the channel were surveyed using pole-mounted Topcon GR-5 receivers. Deeper in-channel elevations were obtained using a GR-5 in conjunction with a Seafloor Sonarmite (Hydrolite TM) single-beam echo sounder mounted to an inflatable kayak. The Topcon equipment reported horizontal accuracies varying from 0.001 m to 0.161 m with a mean of 0.009 and vertical accuracies ranging from 0.002 m to 0.265 m with a mean of 0.014 m.

Survey data were manually filtered to remove erroneous points, as well as points not classified as ground shots (e.g. large wood), from being used in the creation of Digital Elevation Models (DEM). Surveyed elevations from September 2014 and June 2015 were combined with aerial LiDAR data flown in October 2012 and February 2015, respectively, to create two continuous surface DEMs. The LiDAR point cloud was clipped to remove in-channel regions and areas coincident with those covered by the GPS surveying (e.g. point bars). The combined point clouds were interpolated using a natural neighbor technique to create DEMs with 1 m × 1 m spatial resolution. The September 2014 DEM was subtracted from the June 2015 DEM to create a DEM of difference (DoD), which represents the change in elevation that occurred between the two survey dates.

2.4 *Riffle-pool delineation*

Determination of riffle and pool units was completed using a combination of numerical modeling results and field experience. Two-dimensional hydrodynamic modeling was done using FaSTMECH (Nelson & McDonald 1996), which is available freely as a part of the International River Interface Cooperative (iRIC) modeling interface (www.i-RIC.org, Nelson et al. 2015). FaSTMECH uses a curvilinear orthogonal coordinate system to calculate depth-averaged, quasi-steady hydrodynamics (Nelson & McDonald 1996). The spatial grid used in FaSTMECH contained computational cells with an average size of 2 m × 2 m. Roughness was modeled using a constant drag coefficient value of 0.1, calibrated by comparing surveyed edge-of-water points to computed locations.

Computed flow depths and shear stress distributions at low discharge (8 m^3/s) were used along with experience at the field site to determine thresholds for riffle and pool delineation (Fig. 4), similar to the techniques used by Wyrick and Pasternack (2014). Hydraulic threshold values were iteratively tested against field experience until the associated geomorphic unit map conformed to field observations. The same metrics for morphological unit delineation were applied to the surfaces obtained by both surveys to compare the change in riffle and pool areas over time.

3 RESULTS AND DISCUSSION

3.1 *DEM differencing*

The DEMs resulting from the combination of GPS survey data and aerial LiDAR data are shown in Figure 5. The DoD has a minimum value of approximately –4.5 m, representing the maximum degradation, and a maximum value of approximately 3.5 m, representing the maximum deposition. The study reach and adjacent valley bottom showed an overall net degradation of over 20000 m^3, the majority of which occurred at the outside of bends with bank erosion. The channel bed itself shows net aggradation.

The bank erosion shown in Figure 5 does not necessarily mean that channel widening has occurred, although such a phenomenon has been documented for other situations of increased sediment supply and bed aggradation (e.g., Madej & Ozaki 1996). Rather, it seems to show an increase in

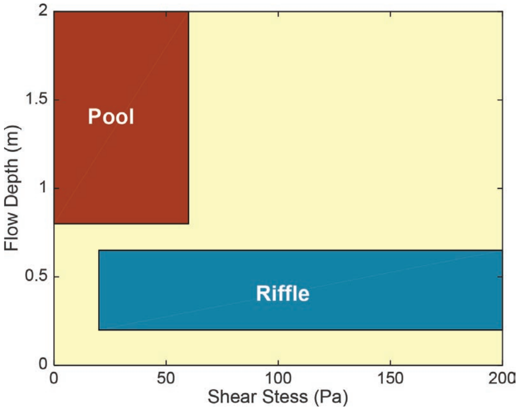

Figure 4. Hydrodynamic thresholds for delineating riffles and pools and low flow (8 m^3/s).

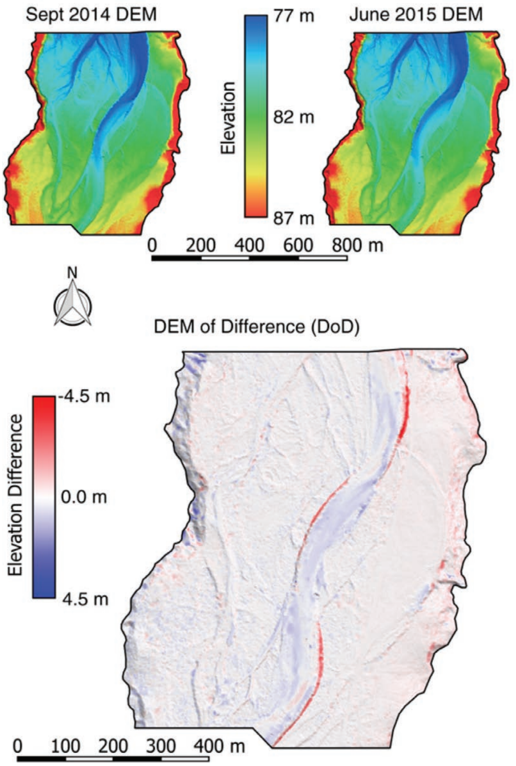

Figure 5. DEMs from Sept. 2014 and June 2015surveys and consequent DEM of difference (DoD) showing topographic change between the two survey dates. Flow is from bottom to top.

sinuosity as the outer bank degradation is generally coupled with point bar aggradation, keeping the channel width approximately the same. In looking at the entire middle Elwha River, defined as the length between the two former dam sites, East et al. (2015) found an increase in sinuosity over the first two years of dam removal as well.

3.2 *Riffle-pool morphology*

Some hydrodynamic results from FaSTMECH using both survey datasets for a discharge of 8 m^3/s are shown in Figure 6. The low flow hydrodynamics from September 2014show a maximum flow depth and shear stress of 1.72 m and 193 Pa, respectively. The same flow over the June 2015 topography/bathymetry results in a maximum flow depth and shear stress of 1.48 m and 93 Pa, respectively. Although the maximum values of flow depth and shear stress decreased from September 2014 to June 2015, their average values remained relatively close (Table 1).

Table 1. Maximum and average values for flow depth and shear stress between the two survey datasets.

	Maximum		Average	
Parameter	2014	2015	2014	2015
Flow Depth (m)	1.72	1.48	0.48	0.46
Shear Stress (Pa)	193.3	93.5	23.27	24.75

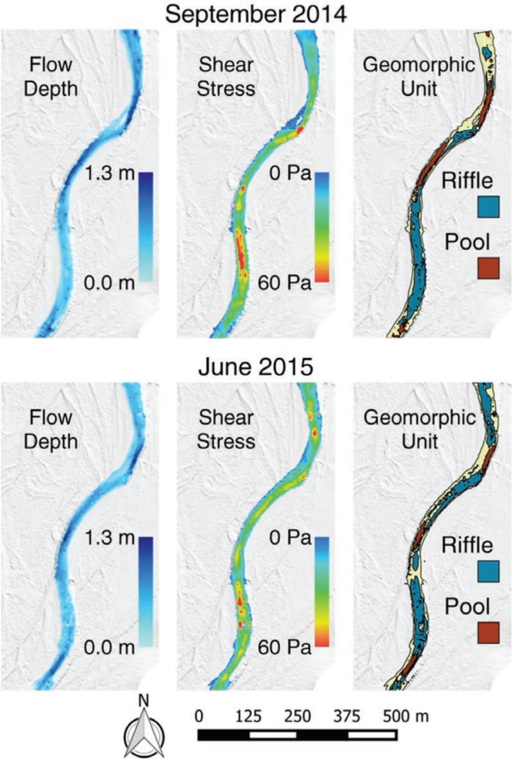

Figure 6. Two-dimensional hydrodynamic results from FaSTMECH and consequent geomorphic unit delineation.

Changes in the channel bathymetry and topography and the consequent changes in distributions of shear stress and depth resulted in differences in the spatial distribution of delineated riffle and pool units (Fig. 6). Riffles constituted about 36% of the area of the study reach in fall 2014 and pool made up about 14%. In spring 2015 the riffle area had increased to around 48% while the pool area decreased to 7% (Fig. 6).

Nelson et al. (2015) hypothesize that pool filling in riffle-pool sequences maintained by width variations is dependent on unsteady flow conditions. The pool filling, noted by a decrease in pool area, associated with overall aggradation of the channel bed is consistent with previous work on the middle Elwha showing that pools filled due to increased sediment load, but were subsequently re-excavated (Brew et al. 2015, East et al. 2015). Furthermore, the more plain-bed configuration associated with pool-filling is likely to increase stream power. An increase in both stream power and sediment supply were shown by Schumm & Khan (1972) to produce a more sinuous planform geometry. The sediment supply associated with the removal of Glines Canyon Dam, in the form of finer material likely transported through suspension, is consistent with observations made by Schumm (1985), that straighter channels are generally associated with bed load transport regimes while sinuous channels achieve transport chiefly through suspended load.

4 CONCLUSIONS

The two topographic/bathymetric surveys presented in this paper show that the channel bed of the middle Elwha River generally aggraded over winter 2014–2015. The outside banks of channel bends also showed degradation. Rather than causing channel widening, this aggradation and bank erosion led to increased sinuosity. The in-channel elevation changes over this period resulted in an increase to riffle area and a decrease in pool area. This may be a temporary effect as sediment pulses often fill pools that are later re-evacuated. Such has been the case in this reach previously in response to dam removal (Brew et al. 2015, East et al. 2015).

Understanding how channels with riffle and pool features adjust to disturbances such increased sediment supply can help river managers and restoration professionals determine best practices for management plans and restoration projects. Additional field, numerical, and laboratory work can help bridge this knowledge gap so that more effective management and restoration can be achieved.

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