BANKFULL WIDTH CONTROLS ON RIFFLE-POOL MORPHOLOGY UNDER CONDITIONS OF INCREASED SEDIMENT SUPPLY: FIELD OBSERVATIONS DURING THE ELWHA RIVER DAM REMOVAL PROJECT

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Abstract: Many gravel-bed rivers feature quasi-regular alternations of shallow and deep areas known as riffle-pool sequences, which in straight reaches are often forced by variations in channel width. The mechanisms responsible for the formation and maintenance of riffle-pool sequences are still poorly understood. There is also much uncertainty in the basic understanding of how fluvial systems respond and readjust to large sediment fluxes through time, as may occur during and after dam removal. Field observations have been made during a natural experiment on the Elwha River in Washington State, where the largest dam-removal project in history is providing riffle-pool sequences with greatly increased sediment supply. Analysis of aerial imagery and repeat bathymetric measurements indicate that prior to dam removal, pools on the Elwha were co-located with local decreases in bankfull width. During dam removal, a pulse of sediment temporarily filled in the pools, but eventually most of the pools reemerged at their prior location. During this time, the river did not experience large overbank flows. The persistence of the location of riffles and pools, even with large changes in sediment supply, suggests that channel width imposes an important local control on bed morphology and riffle-pool dynamics.

INTRODUCTION

Alternating vertical undulations in bed elevation, referred to as riffles and pools, are characteristic of both straight and meandering gravel-bed rivers with slopes less than 0.02 (Knighton, 1998). Areas of higher relative elevation with a symmetrical cross-section and coarser bed material are termed riffles. Conversely, pools have relatively low topography and characteristically have finer bed material (Richards, 1976). The diverse range of flows associated with riffle-pool sequences makes these features important for aquatic ecology and overall stream health (Allan and Castillo, 1995). Consequently, the creation or regeneration of riffles and pools is often a component of stream restoration projects (e.g. Pasternack and Brown, 2013).

The genesis and persistence of riffle-pool sequences is still not fully understood (Wohl, 2014). The velocity reversal hypothesis, first proposed by Keller (1971) and subsequently explored in numerous studies (e.g. Lisle, 1979; Keller and Florsheim, 1993; Clifford and Richards, 1992; Thompson et al., 1999; Thompson, 2011), suggests that at low discharge, flow velocities, and consequently sediment transport rates, are higher in riffles than in pools, but at high discharge this pattern reverses so that velocities and transport rates in pools exceed those in riffles. More recently, flow convergence routing (e.g., MacWilliams et al., 2006) has suggested that convergence of flow through constrictions is more important for riffle-pool maintenance than velocity reversal, an idea supported by Sawyer et al.'s (2010) observations and modeling of the Yuba River in California.

Downstream variations in valley and channel width have been shown to be important influences on the development and persistence of riffle-pool sequences. White et al. (2010) examined a rapidly incising, laterally-confined reach on the Yuba River and found that riffles were persistently located in areas of greatest valley width. One-dimensional numerical modeling by de Almeida and Rodríguez (2012) also suggests that riffles and pools can spontaneously emerge at wide and narrow locations in the channel, respectively, and that the relative grain size sorting between riffles and pools is dependent on unsteady flow. These studies have been valuable in demonstrating the importance of downstream width variations on the development and maintenance of riffle-pool morphology, but how riffle-pool sequences might respond to large changes in sediment supply remains poorly understood.

The Elwha River restoration project provides an opportunity to explore how dramatic changes in sediment supply interact with downstream variations in channel width to influence riffle-pool morphology. In this paper, we present field observations of river width and bathymetry collected during the first two years of the removal of Glines Canyon Dam. The objectives of this study are to characterize downstream patterns of bankfull width and to document changes in channel bed morphology in a relatively straight reach of the middle Elwha River before and after the release of a large amount of reservoir sediment. Our observations suggest that channel width can be an important control on the persistence of riffles and pools, even under conditions of large changes in sediment supply.

METHODS

Study Site: The Elwha River is located on the Olympic Peninsula in Washington State. It flows from its headwaters in Olympic National Park 45 miles to the Strait of Juan de Fuca in the Pacific Ocean. Historically, the Elwha river network has been very productive salmon system with typical annual spawning runs of 400,000 fish (Smillie, 2014). The Elwha was once a member of a select few Pacific Northwestern rivers that supported all five Pacific salmon species (Chinook, chum, coho, pink, sockeye) in addition to four species of anadromous trout (Steelhead, coastal cutthroat, bull, and Dolly Varden char). Beginning in 1910, Elwha Dam, the first of a series of two dams, was constructed at river mile 4.9 in the lower reaches of the river. The dam was poorly constructed and subsequently failed in 1912. However the dam was rebuilt and completed by 1913 (Crane, 2011). Twelve miles upstream, Glines Canyon dam was constructed at river mile 17 and completed by 1926. The dams provided the neighboring town of Port Angeles and its paper mill with inexpensive hydropower. The dams lacked fish passage, however, and it has been estimated that spawning returns were reduced to fewer than 3,000 fish annually (Smillie, 2014).

As decades passed it became clear that the dams were inefficient at generating power and it appeared that their costs to the ecosystem exceeded their economic benefits. In 1992, President George H. W. Bush signed the Elwha River Ecosystem and Fisheries Restoration Act into law. This transferred ownership of the dams to the federal government and allocated funds for dam mitigation. Following reservoir sedimentation modeling and laboratory experiments by Bromley et al. (2011), it was determined that the sedimentation issues could be managed by removing the dams in a controlled manner. It has been estimated that up to 34 million yd^3 of sediment had been trapped in the reservoirs with the majority (~28 million yd^3) behind Glines Canyon Dam in

Lake Mills (Draut and Ritchie, 2015). Beginning with Elwha Dam in Fall of 2011, both dams have gone through a stepped down removal process and periods of holding to allow reservoir sediments to stabilize and anadromous fish to move through the Elwha main stem and into tributaries. Elwha Dam was completely removed in March of 2012 and the final 30 ft. of Glines Canyon Dam was blasted away in August of 2014 completing the removal project. Turbidity issues due to increased reservoir sediment have occurred at a downstream water treatment plant, but overall the project has gone to plan and is viewed as a major success among large-scale dam removal projects.

The field site used for this study is a reach of the middle Elwha River located between the two former dams (Figure 1). This site has a relatively low sinuosity of 1.06, is close to the USGS stream gage at McDonald Bridge, and is far enough away from both dam sites that the local hydrologic regime is probably not significantly altered from backwater effects created by the former Elwha Dam. During the time period we are examining (from before dam removal until November 2013), approximately 7.8 million yd^3 of sediment was released from the former Lake Mills (East et al., 2015).

Bathymetric Boat Surveys: Throughout the Elwha restoration project, the U.S. Bureau of Reclamation (USBR) and National Park Service (NPS) have collected bathymetric data as part of their sediment management monitoring program, documenting the morphological evolution of the Elwha River (Bountry, 2014). Data sets are available from July 2011, before the dam removal, through their most recent survey in November 2013. Boat survey data has been refined to reduce the data set to points most representative of the channel thalweg (J. Bountry, personal communication, 2013). The reach we are using is located between river stations 50+000 and 53+000 (Figure 1). This stationing corresponds to the distance in feet upstream from the river mouth at the Strait of Juan de Fuca, with the "+" stationing analogous to a comma. In this analysis, we use bathymetric datasets collected by the USBR on July 20, 2011, May 9, 2013 and August 1, 2013.

Bankfull Width Mapping: To obtain an understanding of how channel width might interact with riffle-pool morphology in the Elwha system, a series of aerial images available on Google Earth were used to characterize downstream patterns of bankfull width in the study reach. Aerial photos from June 6, 2009, September 3, 2012 and July 5, 2013 were selected because of their temporal proximity to the bathymetric surveys of interest. For each aerial photo, bank lines corresponding to the bankfull discharge were estimated and digitized. Indicators such as sand bars, dense vegetation, and terraces were used to visually estimate bank locations. The channel centerline was also digitized by estimating the current thalweg under normal flow conditions. These geometric data were exported as KML files and converted to shape files in ArcGIS. The banks were used to develop a polygon containing both banks and the extents of the river reach. Cross-sections perpendicular to the centerline were created at 1-ft intervals and trimmed within the boundaries of this polygon.

Hydrologic Analysis: Flows in the study reach during the period of interest were characterized using streamflow data from USGS gage 12045500 at McDonald Bridge. Both daily average values and daily maximum 15 minute instantaneous peaks were gathered over the period of interest in this study (September 10, 2011 to June 28, 2014). These values were plotted against

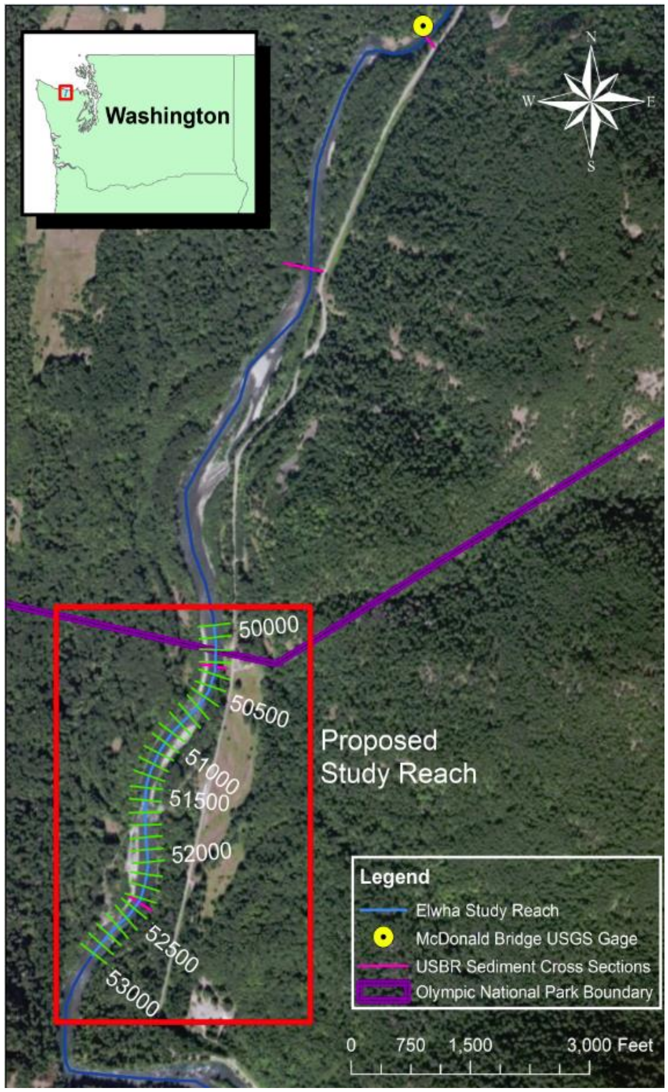

Figure 1 Elwha study reach between river stations 50+000 – 53+000 between former dam sites.

time to generate a hydrograph for the Elwha River below Glines Canyon Dam during dam removal. Annual peak flow values were collected as well, with hydrologic data available beginning in 1897. These data were then ranked from highest to lowest discharge. The recurrence interval for each flow in the annual maximum series were calculated using a Weibull plotting position technique

$$T = \frac{R}{n+1} \tag{1}$$

where R is the overall rank of that discharge in the annual maximum series, n is the number of peak flow values, and T is the return period of that particular flow in years.

RESULTS AND DISCUSSION

<u>Sequential Pool Filling and Evacuation on the Elwha:</u> Figures 2-4 show the evolution of the bed and water surface profiles in the study reach over the period of interest. The baseline dataset from July 20, 2011 (before dam removal) shows three clearly defined riffle-pool sequences within this reach as depicted with the brown line in Figure 2. At the time of the survey, the discharge was 2,340 cfs and the reach displayed a typical riffle-pool backwater profile. The average bed slope across the reach at this time was 0.0063.

By the May 9, 2013 survey, the pools had aggraded significantly, and the morphology approached a plane bed condition with a similar average slope of 0.0063 (Figure 3). At that time, Glines Canyon Dam had been partially removed and fine reservoir sediment was readily available to be transported. During the survey, the discharge was 3,390 cfs and the water surface profile was relatively flat and shallow, as would occur under quasi-normal flow conditions. This reduction of backwater effects induced by reduced riffle-pool relief suggests an increase in sediment transport capacity.

The August 1, 2013 profile has an average slope of 0.0064 and shows the reemergence of pools in their former locations (Figure 4). Up to 5 feet of incision took place between the May and August 2013 surveys. The water surface profile shown in Figure 4 indicates that the redeveloped riffles and pools produced locally-strong backwater effects under the summer low flow discharge of 851 cfs at the time of the survey. This morphodynamic adjustment suggests that there was a sharp reduction in upstream supply and the fine sediment that had filled the pools was evacuated.

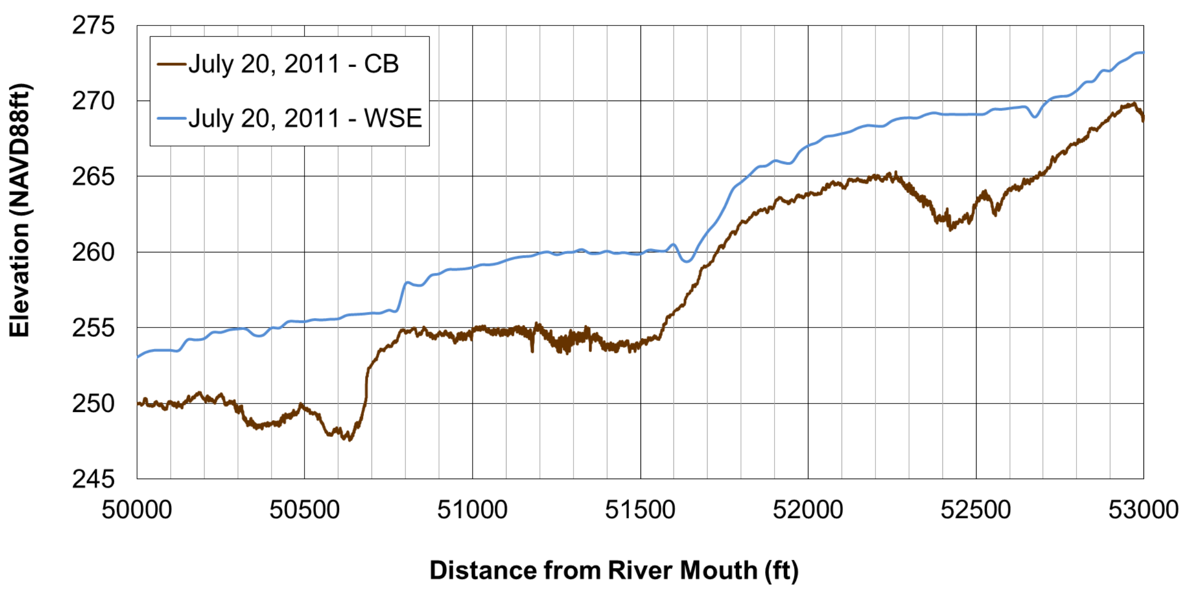

Figure 2 July 2011 channel bed and water surface profiles of the study reach before dam removal showing well developed riffle-pool morphology inducing a backwater profile (where CB is channel bed and WSE is water surface elevation).

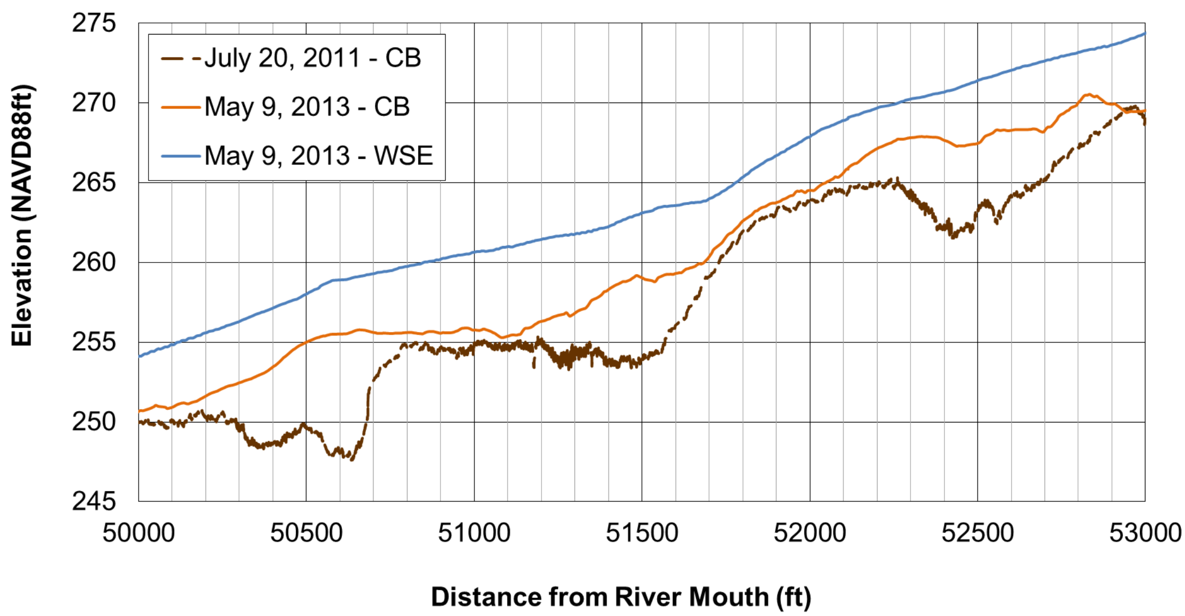

Figure 3 May 2013 channel bed and water surface profiles of the study reach during dam removal depicting temporary pool filling and a flattened water surface (where CB is channel bed and WSE is water surface elevation).

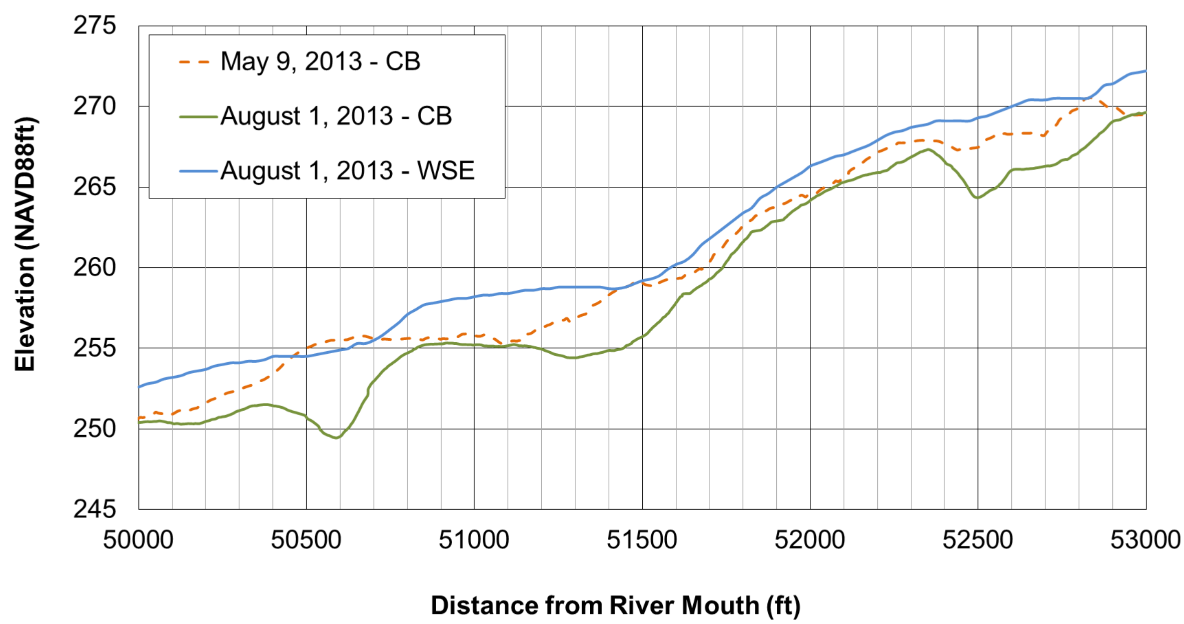

Figure 4 August 2013 channel bed and water surface profiles of the study reach during low flow conditions showing pool evacuation and the reemergence of riffle-pool morphology with reduced sediment supply (where CB is channel bed and WSE is water surface elevation).

<u>Downstream patterns of bankfull width:</u> The bankfull channel width of the study reach identified with Google Earth and spatially aligned with bed topography surveys is presented in Figure 5. The channel width ranged from about 100 to about 275 feet, with an average of approximately 180 ft. For each dataset, the channel showed a distinct downstream pattern of narrowing and widening with a wavelength of about 1000 ft, or 5-6 average bankfull widths. This pattern was consistent between 2009 and 2013, with relatively little change in bankfull width occurring during that time period.

The bathymetric survey data shows the three pools coinciding with the most constricted portions of the channel and riffles forming in the widest locations (Figure 5). Although the pools filled in temporarily, their reemergence at the same location suggests that channel width provides an important local control on pool persistence over a short time frame under conditions of dynamically changing sediment supply.

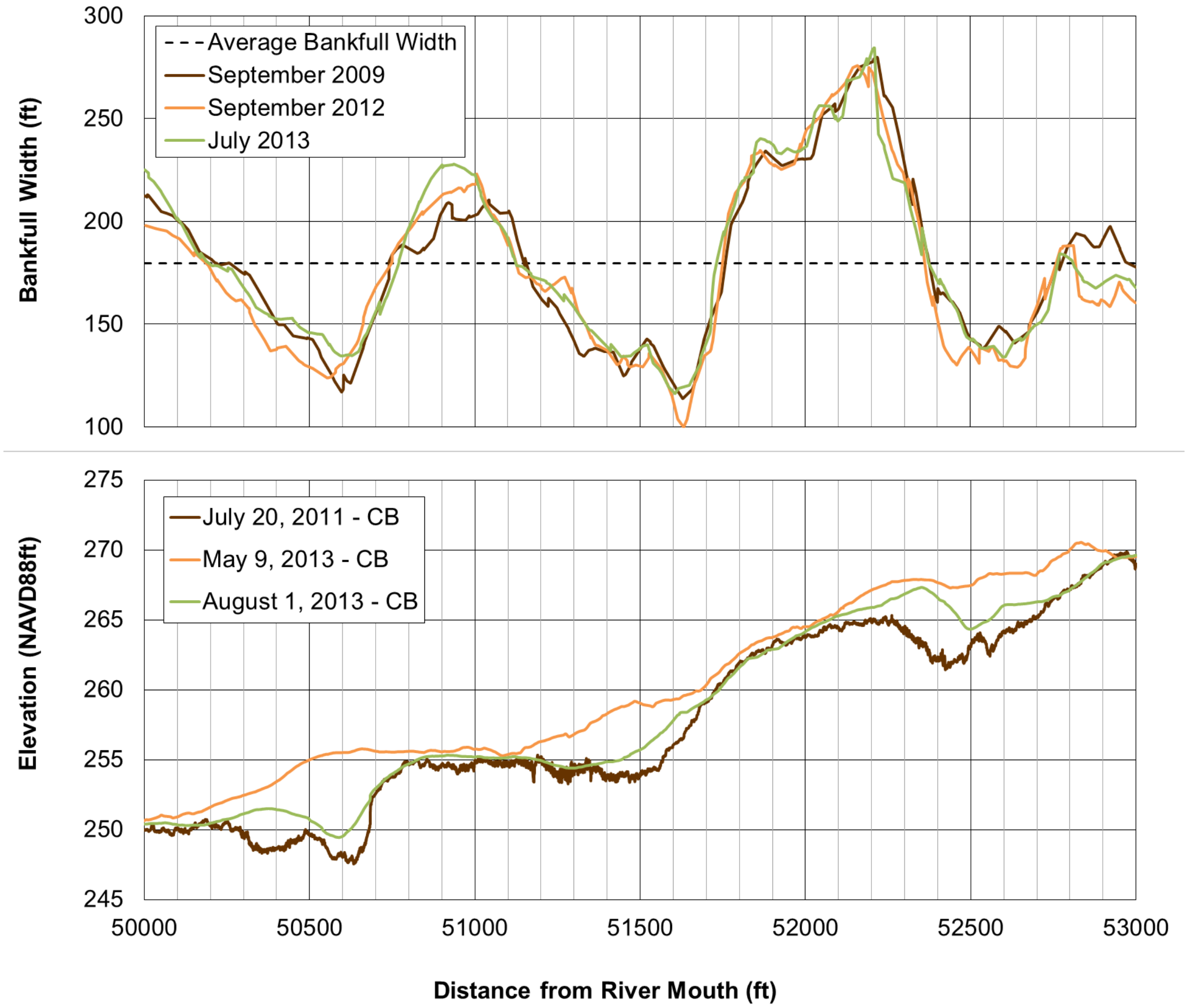

Figure 5 Coupling of bankfull channel width from Google Earth and bathymetry from in the Elwha Study Reach (where CB is channel bed).

Hydrologic Regime during Dam Removal: The flow record from the USGS gage at McDonald Bridge from September 10, 2011 to June 26, 2014 (Figure 6) shows a rain and snowmelt driven hydrologic regime typical of Pacific Northwestern watersheds at moderate elevations (Climate Impacts Group, 2014). In a typical water year there is a peak due to winter storms, a recession and then another peak in late spring or early summer due to snowmelt runoff and "rain on snow events". In addition, the overall magnitude of peak flows showed the lack of a major channel-forming flow event exceeding bankfull conditions (Figure 6). A bankfull flow is typically defined as the discharge that fills the main channel and begins to spill onto the floodplain (Leopold, 1994). It is considered very influential on geomorphic processes and often characterized as the discharge that has a recurrence interval of 1.5-2 years (Leopold, 1968; Williams, 1978; Andrews, 1980). Table 1 shows the computed 1-, 1.5-, and 2-year recurrence interval flows for the Elwha River at the McDonald Bridge gage. During the time period of interest only three instantaneous peaks reached the 1.5-year value and none exceeded the 2-year flow. This period of relatively mild hydrology suggests that there were likely no overbank flows and major channel forming discharges probably did not occur. Therefore, the channel width may have acted as an important driver in the geomorphic processes that did occur, such as the observed pool filling and evacuation.

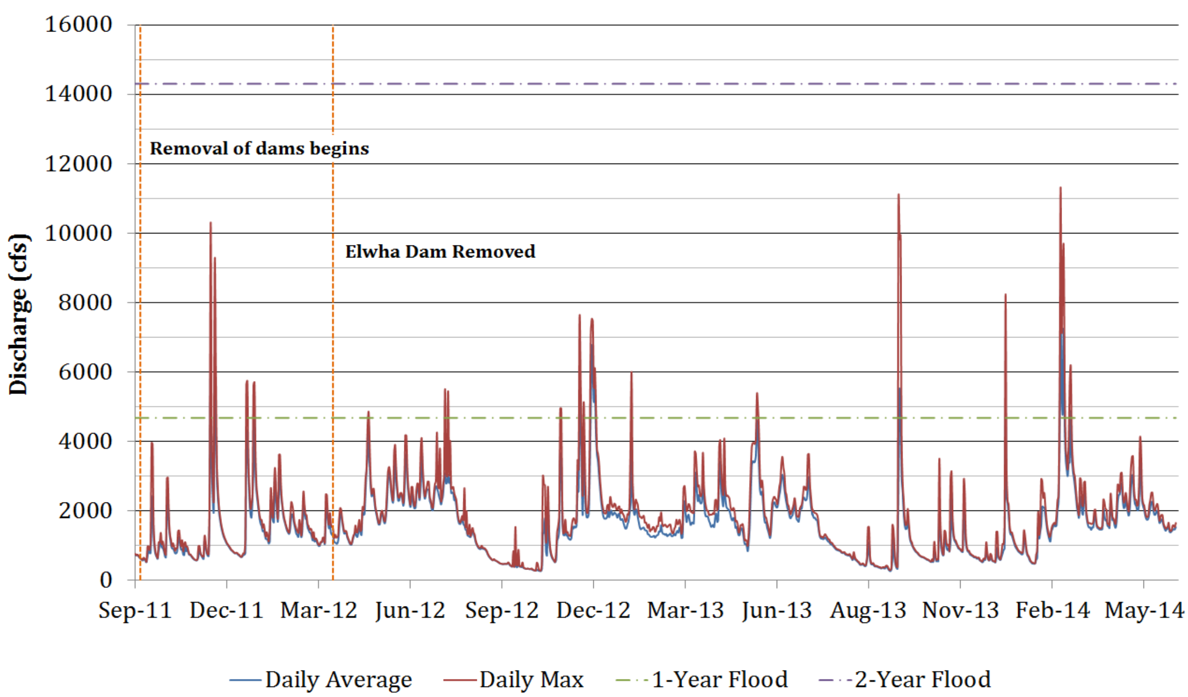

Figure 6 Hydrologic Record of the Elwha during the dam removal time period at the USGS stream gage at McDonald Bridge (Station 12045500).

Table 1 Discharge recurrence intervals on the Elwha River

Peak Flow Recurrence Interval (yrs)	Peak Flow (cfs)
1	4,680
1.5	10,300
2	13,848

CONCLUSIONS

Channel width has been shown to exert a local control on the development of riffle-pool morphology in certain environments (de Almeida and Rodriguez, 2012) and lead to pool maintenance through flow convergence routing (MacWilliams et al., 2006). Riffle-pool systems such as the Elwha develop and maintain riffle-pool topography due to this variable width condition. From the perspective of fluid momentum and sediment continuity, these expansions and contractions create variations in shear stress that induce preferential scour in pools and deposition across riffles.

Field results from the Elwha show that bankfull channel width imposed a local control on the locations of riffles and pools from 2011-2013, even when the system is undergoing dramatic changes associated with the removal of a large dam. The transient pool-filling apparent in the repeat longitudinal profiles and the re-emergence of the pools at the same locations, combined with the lack of large, channel-forming hydrologic events, suggests that the downstream changes in channel width provided an important control on the location and persistence of riffles and pools.

Understanding how and why pool filling after dam removal occurs will be important to salmon recovery efforts in coastal river systems. Pools provide critical holding locations for migrating fish to rest in as they navigate upstream to spawning grounds. If we can understand why temporary pool filling takes place and limit its occurrence during critical migratory time periods, this could enhance salmon recovery efforts.

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