

**Impacts of the sediment-laden Elwha River plume on light attenuation in the water column and kelp habitat**

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## **Abstract**

River dam removals are a form of sediment supply to the sub-tidal areas near river mouths. Suspended sediment in the sub-tidal water column can attenuate light, decreasing the amount of light available to seabed photosynthesizers, but not much is known about the effects of sediment plume light attenuation on kelp growth. During a recent dam removal project on the Elwha River, kelp densities in the sub-tidal region declined. In this study we evaluate trends in kelp growth since dam removal on the Elwha River began, using dive surveys from 2010 to 2013, and relate these trends to long-term river turbidity and light intensity data obtained during a 3-day study period in April 2014. The results suggest that the river plume attenuates light and has been at least partially responsible for decreases in kelp densities, but that this is not the sole determining factor in kelp growth. Another factor hypothesized to influence kelp growth is a difference in substrate size on either side of the river mouth.

## **1. Introduction**

The health and survival of kelp species depend on seabed grain sizes and low suspended sediment concentrations in the water column (Mumford, 2007). Kelp are photosynthetic organisms that attach to the sea bed in sub-tidal areas, generally shallower than 20-m water depth (Mumford, 2007). Kelp gametophytes live close to the ocean floor (Han and Kain, 2007) and kelp require relatively high ambient light, low concentrations of suspended sediment (which can block light and smother gametophytes), low water temperatures, and high water salinity (Mumford, 2007). They are unable to

attach to soft substrate in the sporophyte stage, and so require relatively large and hard substrate on which to fasten. Species that directly depend on kelp as a food source include sea urchins, mollusks, and other bottom grazers, and so kelp are considered to be an important part of the near-shore marine ecosystem (Mumford, 2007).

High suspended sediment concentrations (SSCs) in the marine environment are known to attenuate light in the water column, and the Elwha River Restoration Project provides a unique opportunity to study these effects in the sub-tidal area. Recent dam removals have dramatically increased the sediment supply to the downstream area, and have changed the morphology of the delta and sub-tidal region (Mackaay, 2014). Habitat restoration was a motivation for the dam-removal project (Duda et al., 2011), and studies have been conducted on the changes in grain size of the near-shore substrate that have potential implications for fish and kelp habitat (Lawrence, 2014 and Holman, 2014). However not much is known about the effects of increased SSCs in the water column, including the effects on light attenuation at the seafloor. The objective of this study is to investigate the impact of increased sub-tidal SSCs on light intensity at the seabed and the effect this has on kelp habitat near the Elwha River delta.

## **2. Background**

The Elwha River flows from the Olympic Mountains on Washington State's Olympic Peninsula into the Strait of Juan de Fuca, slightly west of the city of Port Angeles (Fig. 1). The Strait of Juan de Fuca is part of the Salish Sea and was carved by glaciers during the last glacial maximum, the Frasier Glaciation, which retreated about

16,420 cal yr B.P. (Porter and Swanson, 1998). Glacial deposits and eroded sediment from the Olympic Mountains make up the physical structure of the Elwha delta and the sediment supplied to and transported by the river (Warrick et al., 2011). The Elwha is a small, mountainous river, a majority of which lies within the Olympic National Park.

In 1910, construction began on the first of two dams built to harness hydroelectric power on the Elwha River: the Elwha and Glines Canyon dams. Over the past century, sediment built up behind the two dams and was estimated at a total of  $19 \times 10^6 \text{ m}^3$  (Bountry et al., 2010). This resulted in the sediment starvation of the lower reaches of the river, delta, and sub-tidal area, and coarsened the substrate of the area (Duda et al., 2011).

In 2011 deconstruction of the dams began in an effort to restore the Elwha River ecosystem and salmon habitat (Duda et al., 2011). Prior to dam removal it was estimated that between  $7$  and  $8 \times 10^6 \text{ m}^3$  of sediment would be transported downriver after dam removal (Randle et al., 1996, Bountry et al. 2010, Czuba et al. 2011), which was expected to alter the substrate size of the downstream reaches of the river and delta (Duda et al., 2011). Warrick et al. (2008) found that the majority of the substrate prior to dam removal in the west sub-tidal area was mixed, with mainly gravel- to cobble-sized sediment and boulders, which increased in abundance toward shore. Kelp canopies in the sub-tidal Elwha region corresponded to areas of hard substrate such as rock outcrops and coarse substrate with a high abundance of boulders. Such substrate was 2.5 to 3.5 times more likely to correspond to kelp canopies than was smaller-sized sediment (Warrick et al., 2008).

Prior to dam removal, a distinct sediment plume was observed at the interface of the river fresh water and the marine coastal waters (Warrick and Stevens, 2011). The tidal patterns and wave directions around the headland of the delta were found to influence the direction of plume movement, with the fresh water plume flowing predominantly toward the northeast (Warrick and Stevens, 2011).

### **3. Methods**

#### *3.1. Data collection*

Data were collected from two sites, one to the east and one to the west of the river mouth (Fig. 2). These sites were chosen to compare the east and west regions of the sub-tidal area, based on their proximity to the river mouth, their similar water depths, the likelihood that each would be in the plume at some point during the study period, and the presence of dive sites nearby where kelp abundance was measured in 2010-2013. At each site one HOBO Pendant Temperature/Light Data Logger was attached to a mooring and deployed on the seafloor at a water depth of eight to nine meters. Light intensity data in lumens/m<sup>2</sup> was collected at these sites in 5-minute intervals during 11-13 April, 2014. A HOBO Logger also collected light intensity data onshore near the river mouth, to serve as a control and to allow for subsequent differentiation between weather-driven light changes and changes due to suspended sediment concentrations (SSCs) in the water column.

During the same three-day period in which the Hobo Loggers were deployed (11-13 April), water-column profiles of depth and optical backscatter were taken using an

OBS at each site. Surface water samples were also taken during the cruise and subsequently filtered to allow for calibration of the OBS data. The SSC of the surface water samples was determined after the cruise by dividing the weight of the filtered and dried sediment by the total volume of filtered water. A linear relationship between OBS surface readings and filtered surface concentration was determined, allowing for the extrapolation of OBS readings throughout the water column. This procedure is described in greater detail in Ogston et al. (2000).

### *3.2. Additional data*

Tidal data was obtained from the NOAA station near Port Angeles, WA (station # 9444090; [tidesandcurrents.noaa.gov](http://tidesandcurrents.noaa.gov)) for 11-13 April. River turbidity data was obtained from the U.S. Geological Survey's water quality monitoring station Elwha River at Diversion near Port Angeles (station # 12046260; [waterdata.usgs.gov](http://waterdata.usgs.gov)) for 2011-2014, and river discharge was obtained at the U.S. Geological Survey's streamflow-gaging station Elwha River at McDonald Bridge near Port Angeles (station # 12045500; [waterdata.usgs.gov](http://waterdata.usgs.gov)) for 2011-2013.

Kelp densities at the two sites were determined annually from 2010 to 2013 during July or August, according to kelp growing season. Concentrations in stipes/m<sup>2</sup> were averaged over an area of 60 m<sup>2</sup> according to the procedure described in Rubin et al. (2011) using preliminary and unpublished data provided by I. Miller and S. Rubin (pers. comm.).

### *3.2. Data analysis*

Seafloor light intensities during the study period were compared to SSCs to determine a relationship between the location of the sediment plume and light attenuation in the water column. Intensities at both sites were differenced to determine relative light availability on either side of the river mouth, and this was compared to trends in kelp densities at the two sites. River turbidity during the study period was compared to turbidity values throughout the dam removal process to determine relative light intensities during dam removal compared to those during the study period, and to determine kelp habitat conditions during and after dam removal.

## **4. Results**

### *4.1. Light intensity*

Maximum surface-light intensities recorded during the study period were on the order of  $1.7 \times 10^5$  lumens/m<sup>2</sup> (Fig. 3b), while seafloor maximum light intensities were on the order of  $1 \times 10^3$  lumens/m<sup>2</sup> (Fig. 3c). In general, daily surface intensities began at ~6:00, increased to a maximum at ~14:00, and then decreased gradually until ~20:00. Intensities on 11 April were the most variable, with three peaks and two troughs, lasting ~1 hour each, between 11:40 and 15:20. The average amplitude between peak and trough was  $\sim 5.5 \times 10^3$  lumens/m<sup>2</sup> (Fig. 3c).

Seafloor intensities on the east side had a similar pattern, but with a higher degree of relative variability (Fig. 3c). During the first day the largest peak on record occurred at 13:20 during slack tide, and was followed by relatively variable low-light intensity periods during ebbing tide. An early peak on 12 April during slack tide was followed by

low intensities and a flood tide for the rest of the day. Two peaks occurred during slack tide on 13 April before noon. They were separated by a sharp trough and followed by intermittent periods of little to no light intensity during flood tide. Maximum values reached intensities on the order of  $2.5 \times 10^3$  lumens/m<sup>2</sup> (Fig. 3c).

West-side seafloor intensities showed a pattern similar to that of the east side, once the west study period started at 14:30 (Fig. 3c). On 11 April the intensity varied but showed a decreasing trend in the afternoon, and the last of the daylight occurred a half hour before the end of the surface daylight and half an hour after the last light on the east side. April 12 intensities were also relatively variable, with an increasing trend from 6:40 until 11:55 during slack and early flood tide, followed by a sharp drop in light intensity and an end to recorded daylight at 14:35 during slack and ebb tide. A sharp trough in the mid-morning reached zero intensity. The maximum intensity on the east occurred ~2 hours before the maximum on the west side and was only higher by 10.8 lumens/m<sup>2</sup>. The intensity on 13 April increased to a peak at ~12:00 during late slack tide and then decreased until the end of the west study period at 14:20 during flood tide. The maximum value on the west side occurred ~2 hours after that on the east side and had the exact same intensity value. Maximum values were on the order of  $1.4 \times 10^3$  lumens/m<sup>2</sup>, about 2 orders of magnitude smaller than surface intensities (Fig. 3c).

#### *4.2. Water-column properties*

Turbidity records for the Elwha River start in April 2011 and dam removal began on 17 September 2011; therefore limited turbidity data exists from before dam removal.

In the months before dam removal, turbidity values peaked at ~100 FNU (Formazin Nephelometric Units) and were relatively low (Fig. 4a). The first larger spike in turbidity occurred on 26 September after dam removal began and reached ~575 FNU, and between late September 2011 and late September 2012 turbidity values remained higher than pre-dam-removal values. From late September 2012 until mid-August 2013 turbidity values were consistently the highest on record since 2011, and values often reached ~1500 FNU (Fig. 4a.).

Turbidity values during and immediately prior to the April study period were similar to those recorded before dam removal, and reached ~175 FNU (~8% of the maximum turbidity during dam removal) with a mean of 67 FNU a few days before the study period (Fig. 5b). The maximum turbidity during the study period was 114 FNU and occurred during the first hours, after which a range of ~60 to 85 FNU was maintained. Water discharge also displayed little variability during the study period, with an average of ~42 m<sup>3</sup>/s, while the five days prior to the study period had discharge values of up to 57.8 m<sup>3</sup>/s (Fig 5a). During the year prior to the study period, discharge values peaked at ~311 m<sup>3</sup>/s and reached ~85 m<sup>3</sup>/s fairly regularly (Fig. 4a).

On 13 April at 13:30 the west side SSCs were between 3.2 and 6.0 mg/L (Fig. 6a). Concentrations decreased from 5.1 mg/L at the surface to 3.2 mg/L at ~2.4 m water depth, beneath which SSCs were consistently low at 3.4 mg/L to a water depth of ~7 m. The concentration increased again to a maximum of 8.8 mg/L at the seafloor. The SSCs on 12 May 2014 at 17:30 on the west side were fairly consistent throughout the water column, with a range of concentrations from 1.8 to 2.7 mg/L, with an average of 2.4 mg/L (Fig. 6a.).

On 13 April at 19:45 the east side SSCs ranged from 3.0 mg/L at ~2.3 m water depth to 22 mg/L at the surface (Fig. 6b). Below 2.3 m the SSCs remained fairly consistent, with an average of 3.0 mg/L. On 12 May at 19:35 the west side SSCs peaked at 7.2 mg/L near the surface and decreased sharply to 4.0 mg/L at ~2 m. At depths below 2 m the concentrations leveled off to an average of 3.7 mg/L (Fig. 6b).

#### 4.3. Kelp density

Total kelp densities on the west side remained constant from 2010 to 2011 at 0.87 stipes/m<sup>2</sup>, with a slight decrease in 2012 and a dramatic drop to 0 stipes/m<sup>2</sup> in 2013 (Table 1). No *Alaria marginata*, *Laminaria setchellii*, *Agarum fimbriatum*, or *Pleurophycus gardneri* were found at this site throughout the study period. *Desmarestia* sp., *Pterygophora californica*, and *Saccharina* spp were present during the first three years, while *Costaria costata*, *Cymathere triplicata*, and *Desmarestia* bushy were only present in 2010. *Nereocystis luetkeana* was only present during 2011 (Table 1).

On the east side total kelp densities rose from 2.3 stipes/m<sup>2</sup> in 2010 to 4 stipes/m<sup>2</sup> in 2011, but decreased sharply in 2012. The lowest density occurred in 2013, when densities reached a minimum of 0.77 stipes/m<sup>2</sup> (Table 1). No *Agarum fimbriatum* or *Pleurophycus gardneri* were found at this site throughout the study period. *Costaria costata* and *Nereocystis luetkeana* were only present in 2011, and the only species present in 2013 was *Pterygophora californica* (Table 1).

## 5. Discussion

### *5.1. Water-column suspended sediment concentrations versus light intensity*

The east-side SSC profile on 13 April indicates the presence of a strong surface plume to depths of 1.5 m at 19:45, which agrees with visual observations recorded during the cast period (Fig. 6b). This cast was taken after the seafloor light intensity study period was over, and so a direct comparison between SSCs and intensity cannot be made. However the time of day that the SSC cast was conducted corresponds to time periods during 11 and 12 April when intensity data were logged. At this time each day the east seafloor intensities were relatively low compared to surface intensities, suggesting the presence of the plume (Fig. 3c). These evening times correspond to an ebbing tide, which was shown by Warrick and Stevens (2011) to result under most conditions in the eastward location of the plume. Warrick and Stevens (2011) also found there to be an eastward plume during flood tide, which corresponds to low-light intensities on 11-13 April in the late mornings, and a radial plume during slack tide, which corresponds to the daily high-intensity peaks on 11-13 April when the plume was likely not located on the east side (Fig. 3c).

The SSC profile measured on 13 April on the west side indicates an “old” surface plume and a bottom plume (Fig. 6a). The cast was taken at 13:30 during late flood tide and a period of relatively high intensities. The relatively high surface concentrations—compared to those lower in the water column—were likely the remaining suspended sediment (the “old” plume) left by the earlier plume in the pre-dawn morning during ebb tide, which was shown by Warrick and Stevens (2011) to occasionally induce a westward-located plume. The bottom SSCs are most likely explained by wave action

observed during the study period, which was shown by Traykovski et al. (2000) to resuspend bottom-layer mud.

The relationship between high SSCs and low-light intensities indicates that light attenuation in the water column is at least partially caused by the sediment-laden river plume. Time periods of high surface light intensity and no seafloor light intensity, such as on the west side in the evening of 12 April (Fig 3c), are likely caused by the presence of the plume, either at the surface or the seafloor. High surface intensities during periods of relatively low seafloor intensities suggest the existence of the “old” plume. Sharp, short decreases in seafloor intensity, such as that at ~10:30 on 12 April at both sites (Fig. 3c), most likely correspond to a radial plume when the sites are on the edge of the plume and only covered for a short time before a slight movement of the plume exposes them again. The maximum seafloor intensity measurement at the east side (~2500 lumens/m<sup>2</sup> on 11 April) during a period of typical surface light intensities suggests that while there is a relatively high baseline of SSC at the two sites, short periods of decreased concentration and relative water clarity can occur. For ~1 hour on 11 April the incoming tide, a change in momentary river-water discharge, or a brief reduction in wave action brought clearer water from the strait over the east-side sensor.

River turbidity values during the April 2014 study period were relatively low and were similar to pre-dam-removal turbidity levels. During large dam-removal events, maximum river turbidity levels were more than ten times greater than those during the study period, and it follows that light intensities at these times were correspondingly much lower than we observed. The lack of seafloor-light-intensity data during these periods of higher turbidity prevents direct conclusions about the influence of mid-dam-

removal turbidity levels on light intensity. However a relationship between turbidity and SSCs developed by Curran et al. (2014) allows for the comparison between mid-dam removal SSC levels and those during the April 2014 study period. The SSCs used for the relationship were measured about 4 km upstream of the river mouth, while the data used for this study were collected in the sub-tidal region near the river mouth, so relative concentrations instead of actual SSC values are compared. River turbidity values during the April 2014 study period were similar to those during late July 2013, which Curran et al. (2014) corresponded to river SSCs of <100 mg/L (Fig. 8). After the draining of Lake Mills in late October 2012, river SSCs were consistently >5000 mg/L (Curran et al., 2014), indicating that mid-dam-removal light intensities were periodically much lower than those recorded during 11-13 April 2014 (Fig. 8).

### *5.2. Comparison between light intensity at the east and west sites.*

A Student's T-test performed on the seafloor intensity at the two sites shows a significant difference ( $p=0.00$ ) between the total light received at the two sites. Differencing the seafloor intensities shows that the west side of the river mouth received more light than did the east side (Fig. 7), with the east side receiving 13% less light during the study period. This is supported by Warrick and Stevens (2011), who found during a 96-day study period that the "new" plume frequented the east side ~50% and the west side ~10% of the time. It should be noted that both SSC profiles conducted at the east side indicated either a new or old surface plume, while the SSC profiles taken on the west side indicated either no plume or an old plume with a bottom plume (Fig. 6).

### 5.3. *Kelp density compared to SSC.*

The period of low river turbidity during 2011 occurred before dam removal (Fig. 4a), and corresponds to the highest densities of kelp at both sites (Fig. 4c and d). The 2012 period of increasing turbidity (during the first year of dam removal) corresponds to the most dramatic drop in kelp density on the east side, while the 2013 period of highest turbidity (during the second year of dam removal) corresponds to the sharpest drop in density on the west side. Higher river turbidity likely corresponds to higher SSCs in the river plume and lower light intensity at the seafloor (Section 6.1). It also potentially corresponds to high levels of fine-grained sediment deposition in areas frequented by the plume, as the plume is a mechanism for fine-grained sediment transport (Gelfenbaum et al., 2009). In addition to blocking light in the water column, this fine-grained sediment can coat kelp plants, preventing photosynthesis, and can create a fine-grained veneer on harder substrate, making it more difficult for kelp to attach (Airoldi, 2003 and references therein).

Han and Kain (1996) demonstrated the importance of episodic light and dark periods for kelp growth, as periods of dark can allow for the use of stored photosynthates. Growth was seen in kelp that were supplied light for only short increments of time, as young kelp are often surrounded by tall kelp forests which cause light levels to fluctuate (Han and Kain, 1996). However during extremely turbid events, such as those that occurred during dam removal, it is possible that light intensities dropped below a habitable level for extended periods of time. It should be noted that the light intensity data used in this study is a measure of brightness, and does not directly correspond to the

exact light necessities of kelp. Photosynthetically active radiation (PAR) is a measure of the exact wavelengths of light that are needed by kelp. For example, a critical level of blue light is required for kelp gametophytes to develop into sporophytes, and is a limiting factor in kelp development (Luning, 1980). Future studies should use long-term PAR data collection as a means of measuring available light at the seabed.

While many factors are clearly involved, the high SSCs during dam removal events, which attenuated light in the water column, are at least partially responsible for the observed decrease in kelp densities from 2011 to 2013. That the maximum kelp density on the east was more than four times higher than that on the west, and east side densities were consistently higher during 2010-2014 than were west side densities (Table 1) are potentially a reflection of more suitable initial substrate, rather than the higher frequency of the plume on the east side.

Substrate intensity data obtained by sonar during 2010 and 2013 suggests that substrate on the east side near the study site was coarse ( $> -2 \phi$ , or 4mm in diameter) and potentially suitable for kelp growth, while the substrate on the west near the study site was finer ( $< -2 \phi$ ) and potentially unsuitable for kelp habitat (Lawrence, 2014) (Fig. 9). This is consistent with the relative kelp densities at the two sites, as habitat on the east side was potentially more favorable. It should be noted that these study sites represent a relatively small portion of the east and west regions, and that substrate farther west in Freshwater Bay was found to be coarse with varying abundance of boulders (Warrick et al., 2008). Between 2010 and 2013 there was no major change in the coarseness of the substrate at either site (Lawrence, 2014), so it seems unlikely that a change in substrate size was the primary cause of the decrease in kelp densities during dam removal.

However, as the sonar data used in this study does not identify grain size changes other than changes close to 4 mm in diameter, changes in substrate size cannot be dismissed as a factor in kelp abundance. It is also possible that in such a turbid environment, seafloor scour played a role in decreasing kelp abundances at the sites. Future studies should examine the extent of seafloor scour during the gametophyte stage near the mouth of the Elwha River, and should conduct a more comprehensive survey of light intensity and grain-size changes on either side of the river mouth.

## **6. Conclusion**

Dam removal on the Elwha River has greatly increased the sediment supply to the sub-tidal area and has increased SSCs in the river plume. In this study the plume was found to attenuate light, decreasing the light intensity available to kelp at the ocean floor. During the study period, the plume was found to frequent the east side of the river mouth more than the west side, and so seafloor light intensities were found to be higher on the west side. Despite higher light intensities during the study period, there were lower densities of kelp on the west side than on the east side before and throughout the dam removal process. This indicates that another factor, such as the suitability of the substrate, was responsible for initial differences in kelp abundance between the east and west sites. However, while the substrate remained relatively uniform at both sites throughout the dam removal process, high concentrations of suspended sediment in the water column were observed during major dam removal events, which suggests that light attenuation is at least partially responsible for the decrease in kelp densities at both sites. Future studies of the sub-tidal kelp habitat at the Elwha River should investigate the

availability of specific light wavelengths during times of high SSCs, as well as the extent of seafloor scour during such conditions. A more detailed categorization of suitable substrate size for kelp habitat should also be considered. However this study provides a valuable contribution to existing knowledge of river plume light attenuation in the water column and its effects on kelp habitat suitability in the sub-tidal area of the Elwha delta.

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### **References**

- Acker, S., T. Beechie, P. Shafroth. 2008. Effects of a natural dam-break flood on geomorphology and vegetation on the Elwha River, Washington, U.S.A. Special Issue on Dam Removal and Ecosystem Restoration in the Elwha River Watershed, Washington State, Northwest Science, 82:210-223
- Airoldi, L., 2003. The effects of sedimentation on rocky coast assemblages. *Oceanography and Marine Biology: an Annual Review*, 41, 161-236.
- Bountry, J., Ferrari, R., Wille, K., Randle, T.J., 2010. 2010 survey report for Lake Mills and Lake Aldwell on the Elwha River, Washington. Bureau of Reclamation. Technical Report No. SRH-2010-23, 73.
- Curran, A.C., Magirl, S.C., Duda, J.J., 2014. Suspended-sediment concentrations during dam decommissioning in the Elwha River, Washington: U.S. Geological Survey Data Set, <http://wa.water.usgs.gov/pubs/misc/elwha/ssc/> doi:10.5066/F7M043DB.

- Czuba, C.R., Randle, T.J., Bountry, J.A., Magirl, C.S., Czuba, J.A., Curran, C.A., Konrad, C.P., 2011. Anticipated sediment delivery to the lower Elwha River during and following dam removal, in Duda, J.J., Warrick, J.A., Magirl, C.S., (Eds.), Coastal habitats of the Elwha River, Washington-Biological and physical patterns and processes prior to dam removal, U.S. Geological Survey Scientific Investigations Report 2011-5120, 28-46.
- Duda, J.J., Warrick, J.A., Magirl, C.S., 2011. Coastal and Lower Elwha River, Washington, prior to dam removal—History, status, and defining characteristics, in Duda, J.J., Warrick, W.A., Magirl, C.S., (Eds.), Coastal Habitats of the Elwha River, Washington—Biological and Physical Patterns and Processes Prior to Dam Removal, U.S. Geological Survey Scientific Investigations Report 2011-5120, 1-26.
- Gelfenbaum, G., Stevens, A., Elias, E., Warrick, J., 2009. Modeling sediment transport and delta morphology on the dammed Elwha River, Washington State, USA. *Coastal Dynamics*, 109, 1-15.
- Holman, C., 2014. Grain-size distribution analysis of the Elwha upper intertidal zone: impacts of dam removal and implications for Pacific sand lance (*Ammodytes hexapterus*) spawning habitat. FHL Marine Sedimentary Processes Research Apprenticeship Spring 2014.
- Lawrence, K., 2014. Use of seafloor substrate classification to estimate kelp habitat suitability following Elwha Dam removals. FHL Marine Sedimentary Processes Research Apprenticeship Spring 2014.
- Luning, K., 1980. Critical levels of light and temperature regulating the gametogenesis of three *Laminaria* species (Phaeophyceae). *Journal of Phycology*, 16, 1-15.
- Mackaay, M., 2014. Comparison of grain-size and delta morphology east and west of the Elwha River mouth. FHL Marine Sedimentary Processes Research Apprenticeship Spring 2014.
- Ogston, A.S., Cacchione, D.A., Sternberg, R.W., Kineke, G.C., 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. *Continental Shelf Research*, 20, 2141-2162.
- Porter, C.S., Swanson, T.W., 1998. Radiocarbon Age Constraints on Rates of Advance and Retreat of the Puget Lobe of the Cordilleran Ice Sheet during the Last Glaciation. Quaternary Research Center and Department of Geological Sciences, 50, 205-213.
- Randle, T.J., Young, C.A., Melena, J.T., Ouellette, E.M., 1996. Sediment analysis and modeling of the river erosion alternative. Bureau of Reclamation. Elwha River Ecosystem and Fisheries Restoration Project, Washington, Elwha Technical Series, PN-95-9, 136.
- Rubin, S.P., Miller, I.M., Elder, N., Reisenbichler, R.R., Duda, J.J., 2011. Nearshore Biological Communities Prior to Removal of the Elwha River Dams, in: Duda, J.J., Warrick, J.A., Magirl, C.S., (Eds.), Coastal habitats of the Elwha River,

Washington-biological and physical patterns and processes prior to dam removal, USGS Scientific Investigation Report, 2011-5120, 131-174.

Taejun, H., Kain, J.M., 1996. Effect of photon irradiance and photoperiod on young sporophytes of four species of the Laminariales, *European Journal of Phycology*, 31, 233-240.

Traykovski, P., Geyer, W.R., Irish, J.D., Lynch, J.F., 2000. The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. *Continental Shelf Research*, 20, 2113-2140.

Warrick, J.A., Draut, A.E., McHenry, M.L., Miller, I.M., Magirl, C.S., Beirne, M.M., Stevens, A.W., Logan, J.B., 2011. Geomorphology of the Elwha River and its Delta, in Duda, J.J., Warrick, W.A., Magirl, C.S., (Eds.), *Coastal Habitats of the Elwha River, Washington—Biological and Physical Patterns and Processes Prior to Dam Removal*, U.S. Geological Survey Scientific Investigations Report 2011-5120, 47-73.

Warrick, J.A., Stevens, A.W., 2011. A buoyant plume adjacent to a headland—Observations of the Elwha River plume. *Continental Shelf Research*, 31, 85-97.

## Figures

Table 1. Concentrations of kelp growth on the east and west sides between 2010 and 2013. Annual kelp densities of each species at both sites were totaled. (Data obtained from I. Miller and S. Rueben)

Site	Date	<i>Alaria Marginata</i>	<i>Costaria Costata</i>	<i>Cymathere Triplicata</i>	<i>Desmarestia Bushy</i>	<i>Desmarestia Flat Bladed</i>	<i>Laminaria Setchellii</i>	<i>Nereocystis Luetkeana</i>	<i>Pterygophora Californica</i>	<i>Saccharina Spp</i>	<b>Total</b>
West	8/30/2010	0	0.033	0.033	0.067	0.40	0	0	0.033	0.30	<b>0.87</b>
	8/6/2011	0	0	0	0	0.20	0	0.033	0.067	0.57	<b>0.87</b>
	7/25/2012	0	0	0	0	0.40	0	0	0.033	0.23	<b>0.67</b>
	8/12/2013	0	0	0	0	0	0	0	0	0	<b>0</b>
East	8/31/2010	0.20	0	0.37	0.30	0.067	0.37	0	0.77	0.27	<b>2.3</b>
	8/6/2011	0.53	0.033	1.5	0.067	0.033	0	0.47	1.3	0.067	<b>3.9</b>
	8/8/2012	0.033	0	0	0	0	0.033	0	1.2	0.067	<b>1.4</b>
	7/29/2013	0	0	0	0	0	0	0	0.77	0	<b>0.77</b>



Figure 1. Map of the study area: the Olympic Peninsula in Washington State, USA. The red box indicates the location of the Elwha delta (Image from Bountry et al. 2010).



Figure 2. Study sites on the west and east of the delta, at depths of 9 and 8 m respectively (Image obtained from Google Earth).

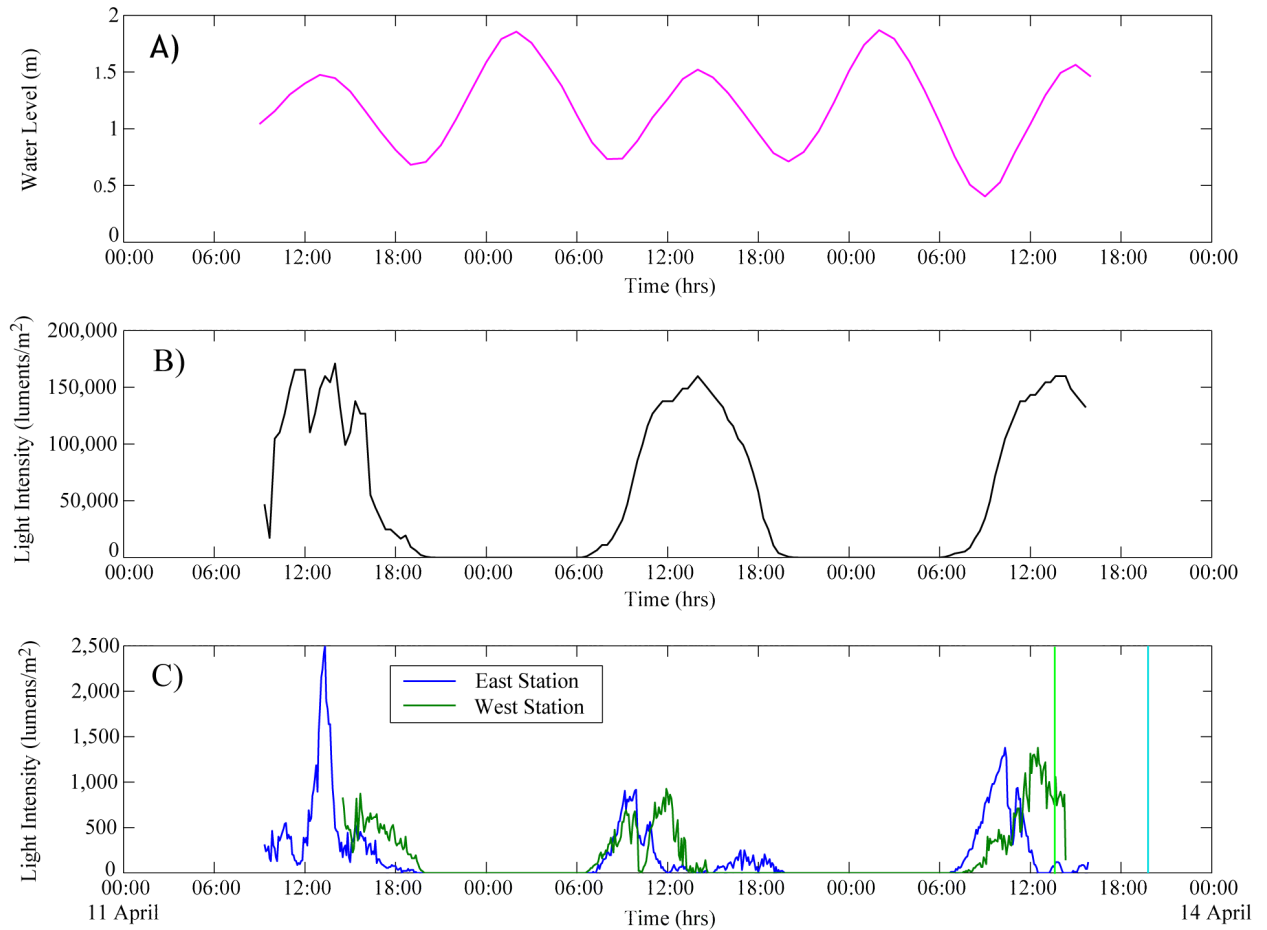


Figure 3. A) Time-series of water level, B) surface light intensity and C) seafloor light intensity at both the east and west station. Note the scale difference between B and C of 2 orders of magnitude. The light blue line on C indicates the SSC cast on the east side on 14 April at 19:45 and the light green line indicates the SSC cast on the west side on 14 April at 13:30.

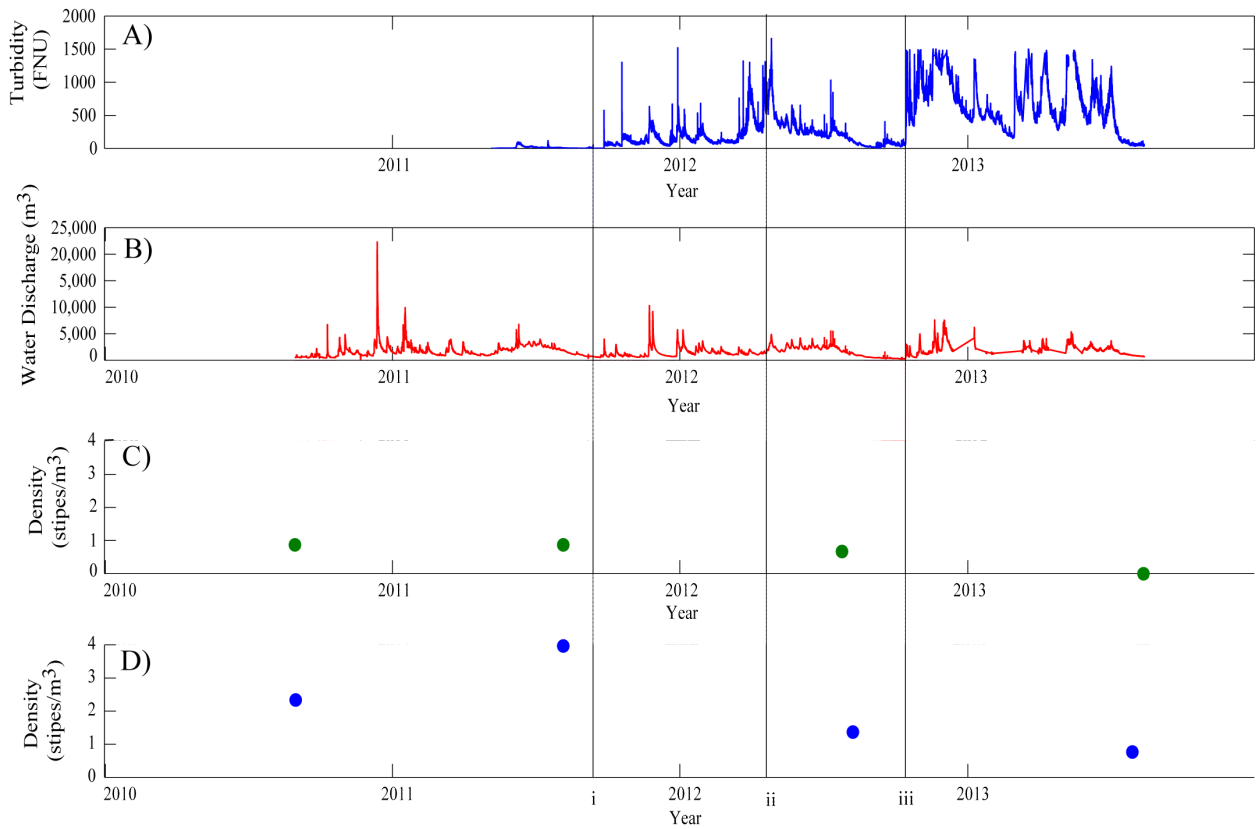


Figure 4. Time series from 2010 to 2013 of: A) turbidity of the Elwha River, B) water discharge, C) kelp stipe densities at the west site, and D) kelp stipe densities at the east site (kelp densities were collected by I. Miller and S. Ruben). The grey lines indicate major dam removal events, including the i) start of dam removal, ii) removal of the Elwha Dam, and iii) draining of Lake Mills.

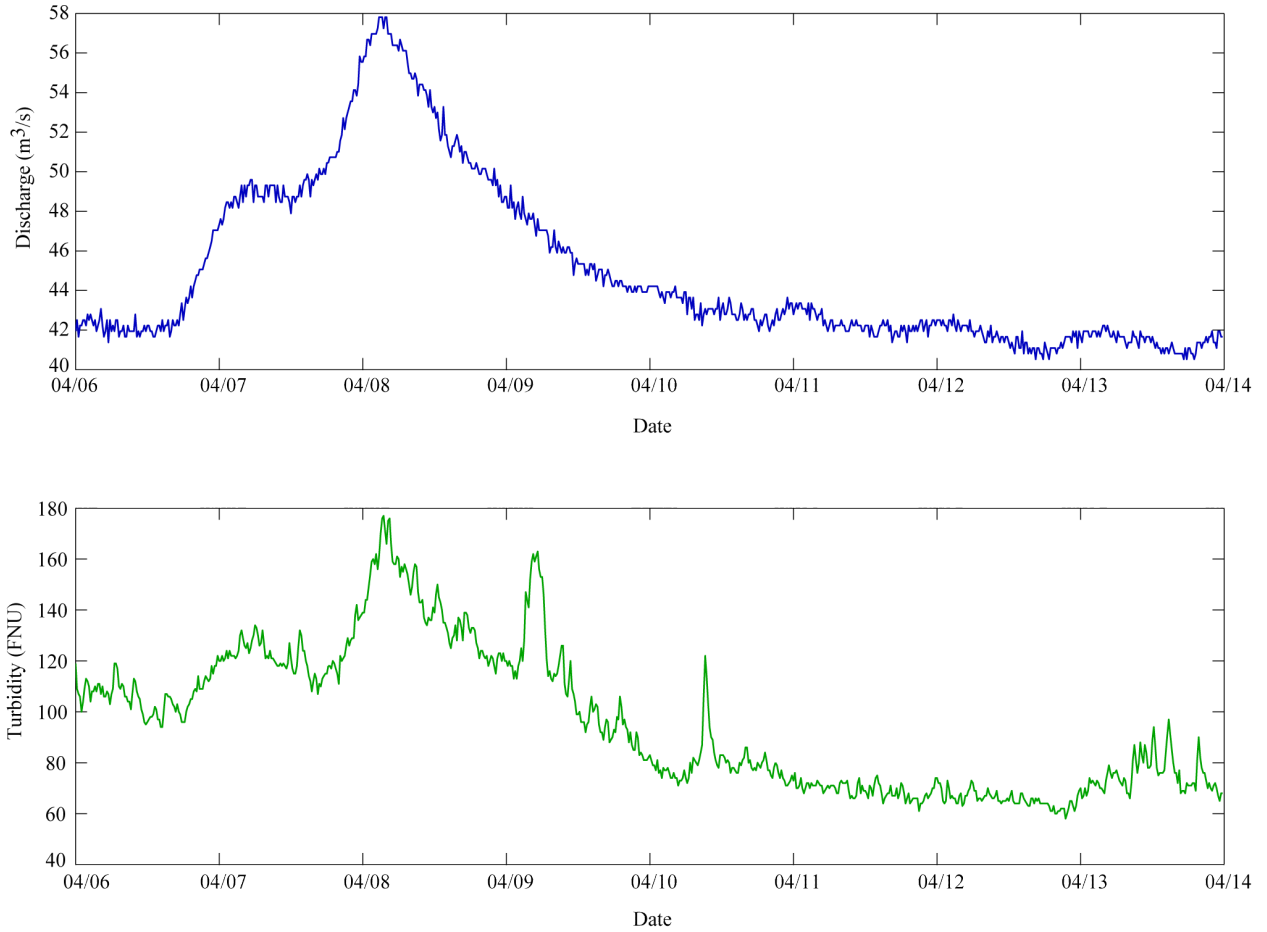


Figure 5. Time series from 5 days prior to the study period through the last day of the study period of A) river discharge of the Elwha River. The river discharge peaked on 8 April, 3 days prior to the start of the study period and B) water turbidity of the Elwha River. The maximum turbidity occurred on the same day as did the peak in discharge.

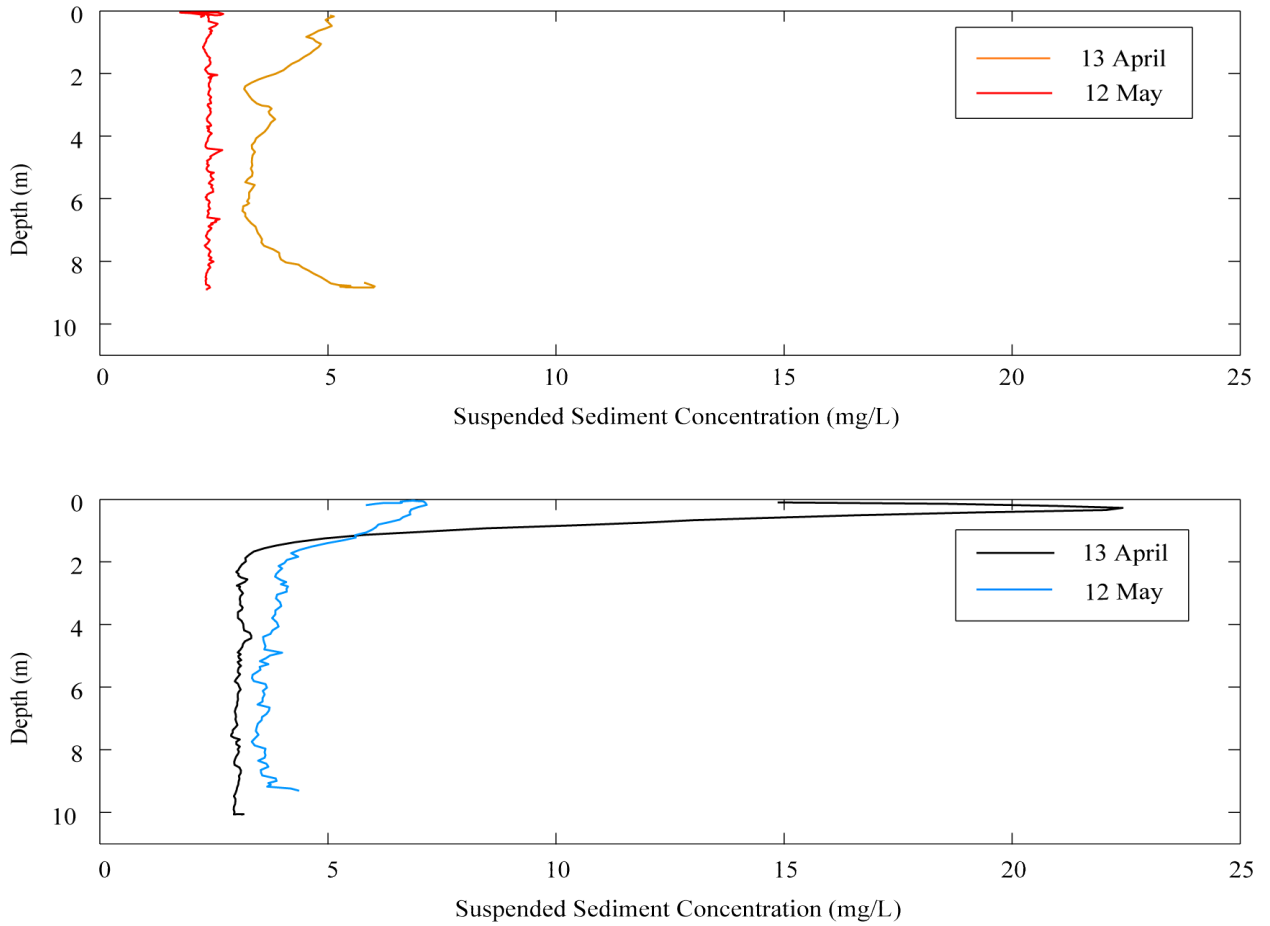


Figure 6. Suspended sediment concentrations on A) the west side; the dark green line is the SSC cast at 13:30 on 13 April and the light green line is the SSC cast at 17:30 on 12 May, and B) the east side; the black line is the SSC cast at 19:45 on 13 April and the dark blue line is the SSC cast at 19:35 on 12 May.

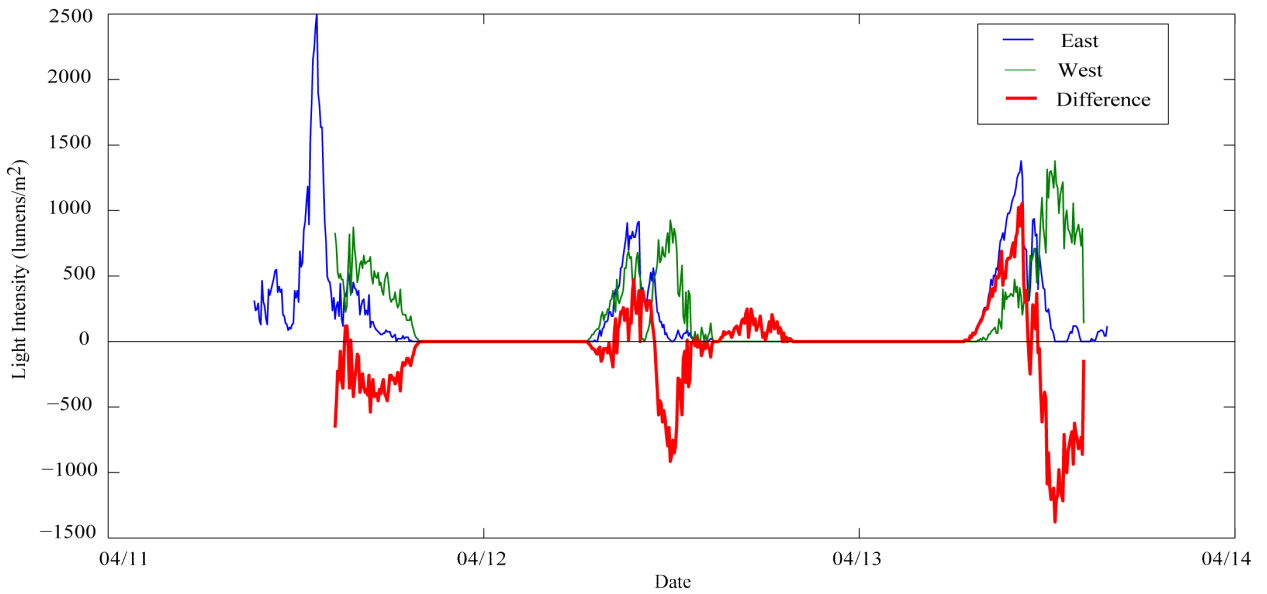


Figure 7. The difference in seafloor light intensity on the west and east sides of the river mouth. Note that negative difference values correspond to higher light intensity on the west side.

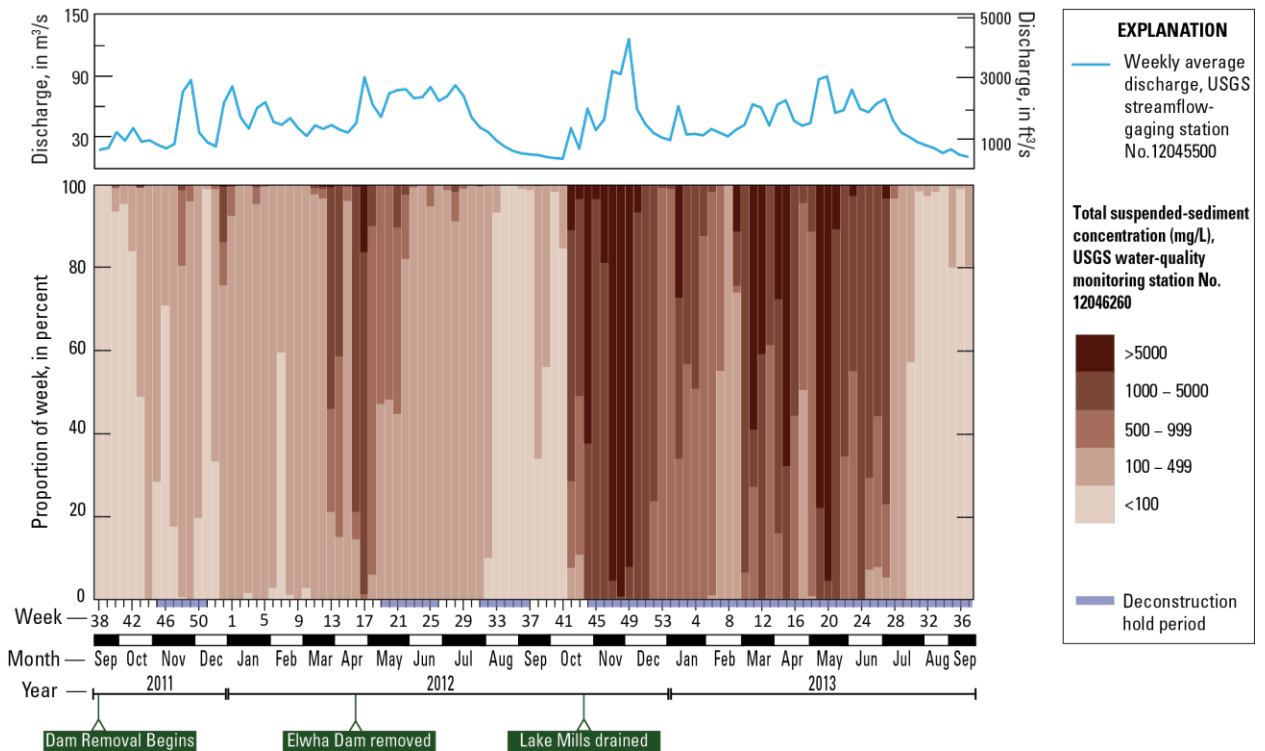


Figure 8. Suspended sediment concentrations in the Elwha River during dam removal (2011-2013). (Figure from Curran et al., 2014)

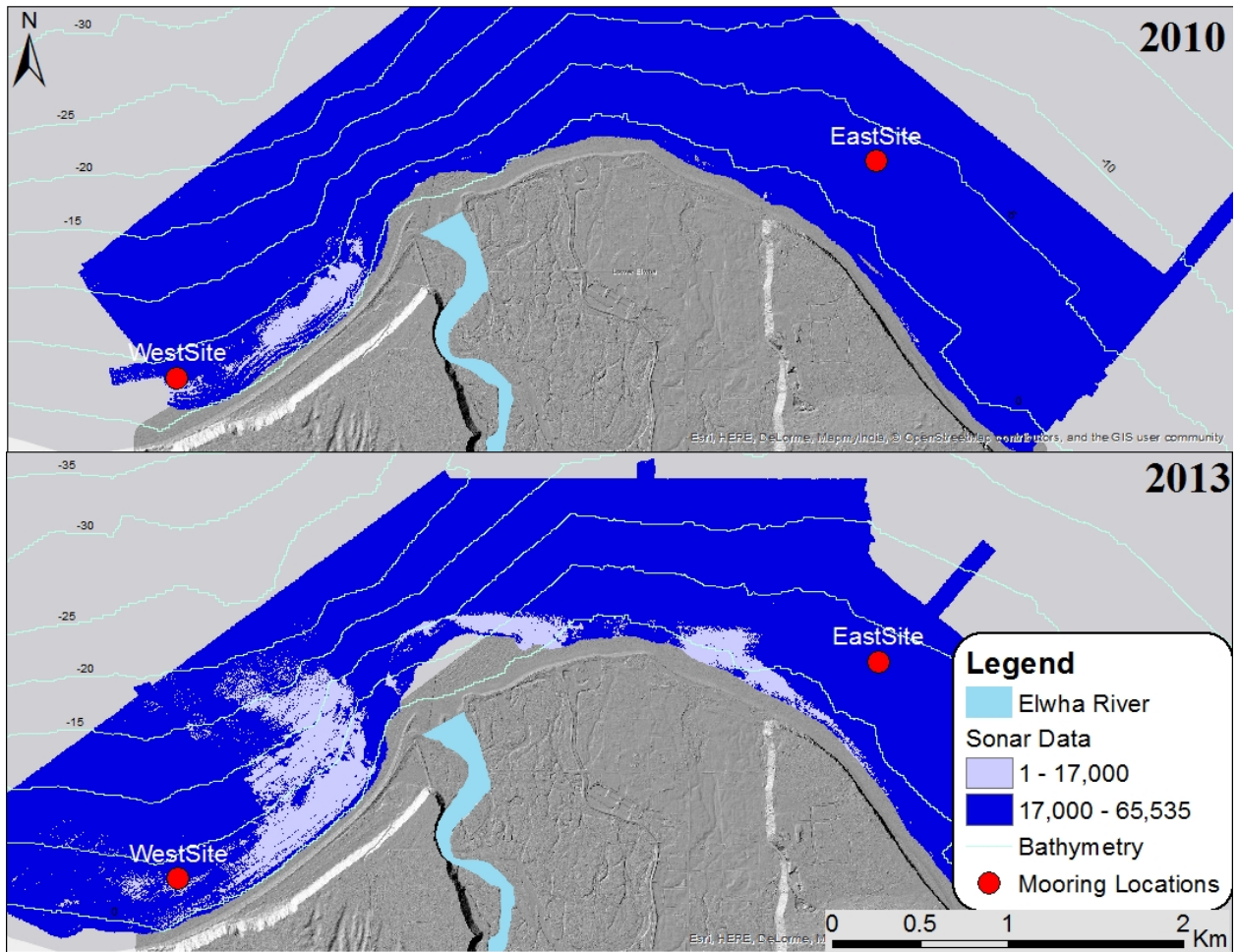


Figure 9. Sonar backscatter data of the subaqueous delta near the mouth of the Elwha River in 2010 and 2013. Dark blue corresponds to harder substrate (> 4 mm in diameter) and light blue corresponds to softer substrate (< 4 mm in diameter). (Image from Lawrence, 2014)