



Effects of fluvial and marine processes on nearshore suspended-sediment concentrations off the Elwha River

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NONTECHNICAL SUMMARY

The goal of this project was to determine whether river or marine processes had a stronger effect on the suspended-sediment content of water off the mouth of the Elwha River. This was done in the context of the ongoing Elwha dam removal project in order to understand how sediment released from the reservoirs will affect the nearshore environment. River discharge and sediment content were measured to find out how much sediment the river was transporting and whether or not reservoir sediment pulses after demolition events were identifiable. An instrument on the seafloor measured suspended-sediment concentrations (SSCs) and wave energies off the river mouth. The two data sets were compared to determine the main influence on nearshore SSC. Peaks in river sediment transport were coincident with floods and dam removal events, but the river had little influence at the marine study site. Nearshore SSC didn't respond to river sediment input but increased in response to strong wave activity. These observations match the dynamics of the Strait of Juan de Fuca. The sediment supplied by the river is too fine to settle in the high-energy nearshore environment, and net sediment transport in the Strait is to the east. By the time the sediment settles it has been transported east of the river. SSC at the instrument site responds to resuspension of seafloor sediment by strong waves, not input from the river. Due to this eastward sediment transport the greatest morphological effects from the dam removal will likely be east of the river.

ABSTRACT

Suspended-sediment concentrations (SSCs) in the Elwha River and nearshore environment off the river mouth were observed in order to determine the effects of the Elwha dam removal project on sediment supply to the river and marine environment. River gauge data over a period of dam removal from November 2011 to June 2012 was analyzed to identify deconstruction-caused SSC increases. Nearshore SSC was measured with an instrumented tripod over the same period and was compared to oceanic and river data to determine controls on nearshore SSC levels. The river had a background SSC level of 40-100 mg L⁻¹ with a maximum observed concentration of 4000 mg L⁻¹. Nearshore SSC had a background level of 10-12 mg L⁻¹ during the study with periodic events reaching levels of 20-40 mg L⁻¹ and a maximum of 110 mg L⁻¹. Peaks in river SSC were not coincident with peaks in nearshore SSC; the highest recorded river SSC levels corresponded with major deconstruction events, while the highest recorded nearshore SSC levels corresponded with strong wave orbital velocities. Nearshore SSC varied much more and reached higher levels during the second tripod deployment, but it was difficult to explain these increases on the preceding major river sediment releases due to a gap in the data. Fine river sediment from the dam removal supplied to the nearshore environment in a buoyant plume was probably

transported east of the mouth, prevented from settling by the high energy environment of the Strait of Juan de Fuca.

The Elwha River, a small mountainous river located in Washington State that drains into the Strait of Juan de Fuca (Fig. 1), has been the site of two hydroelectric dams for a century. Small mountainous rivers like the Elwha are significant sources of sediment flux to the ocean, but dams block much of a river's sediment transport (Milliman and Syvitski, 1992). Instead of contributing to river and marine morphology, sediment accumulates in the reservoirs. The Elwha and Glines Canyon dams, completed in 1913 and 1917 respectively, have trapped $19 \times 10^6 \text{ m}^3$ (a block approximately the size of a football field and 3.5 km tall) of sediment in the century since their construction (Bountry et al., 2010). The sediment has accumulated in Lake Aldwell, behind the Elwha Dam, and in Lake Mills, behind the Glines Canyon Dam. The reduction of sediment supply to the nearshore environment has resulted in significant erosion of the subaerial delta and Ediz Hook, the spit sheltering Port Angeles (Fig. 1) (Duda et al., 2011). In 1992 Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, allocating funds to purchase the dams and develop a plan for removal, which began in September 2011. Dam removal supplies a large amount of sediment to the river, with $7\text{-}8 \times 10^6 \text{ m}^3$ of the trapped sediment expected to eventually erode and be transported downstream (Czuba et al., 2011).

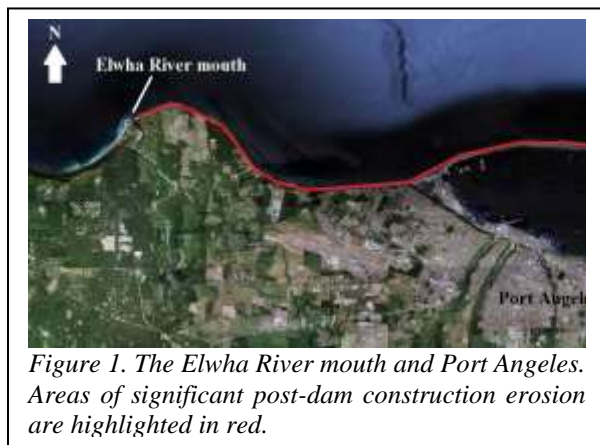


Figure 1. The Elwha River mouth and Port Angeles. Areas of significant post-dam construction erosion are highlighted in red.

Rivers transport sediment as bedload or suspended load (Garcia 1999). Bedload consists of sand and coarser sediments that travel downriver by skipping or hopping (saltation) near the bed. Suspended load consists of silts and clays that remain suspended in the river and can be quantified by a simple ratio of suspended-sediment mass per volume of water. This suspended-sediment concentration (SSC) is useful in determining a river's instantaneous sediment transport as suspended load travels at the same speed as the flow while bedload travels more slowly. The Elwha River supplies this suspended load to the Strait of Juan de Fuca in a 1 m-thick buoyant plume of suspended sediment and river water (Warrick and Stevens, 2011). Sediment advected by the plume settles out as the plume mixes with seawater, and can either be deposited immediately or resuspended by wave energy and currents and accumulate elsewhere (Wright and Nittrouer, 1995). Nearshore SSC therefore results from two sources: advected and resuspended sediment.

Numerous studies of river systems have found that the main factors in river SSC are total precipitation and river discharge (Lopez-Tarazon et al., 2010; Nu-Fang et al., 2011; Gao and Josefson, 2012). The Elwha dam removal project is a chance to study the effect of sustained high river SSC levels on the marine environment in the absence of high river discharge. Understanding this process is vital as the Elwha project is the largest dam removal project to date; many more dams will be removed in the coming years to restore river systems and as older dams become too expensive to maintain, some with reservoirs containing high levels of pollutants (Doyle and Stanley, 2003; Eyrolle et al., 2012). The ultimate fate of the sediment has consequences for the geomorphology of the nearby marine environment, and understanding the nearshore SSC response to sediment input from the river and physical marine processes on the subaqueous delta helps determine whether the sediment will accumulate near the river mouth or be transported elsewhere.

METHODS

River discharge and turbidity measurements were collected from river gauges maintained by the USGS. The gauges record every 15 minutes. Discharge records were taken from USGS gauge 12045500 and turbidity records were taken from gauge 12046260 for November 2011–June 2012, the dates of the tripod deployment (<http://waterdata.usgs.gov/WA/nwis/>). The turbidity gauge collects data in formazin nephelometric units, so a relationship developed by the USGS between river SSC samples and concurrent gauge turbidity measurements was applied to convert from turbidity to SSC (mg L^{-1}) (Fig. 2). The river SSC data was examined to see how the dam removal has influenced sediment levels in the river. Increases in river SSC that do not correspond to increases in river discharge were the result of dam removal activities.

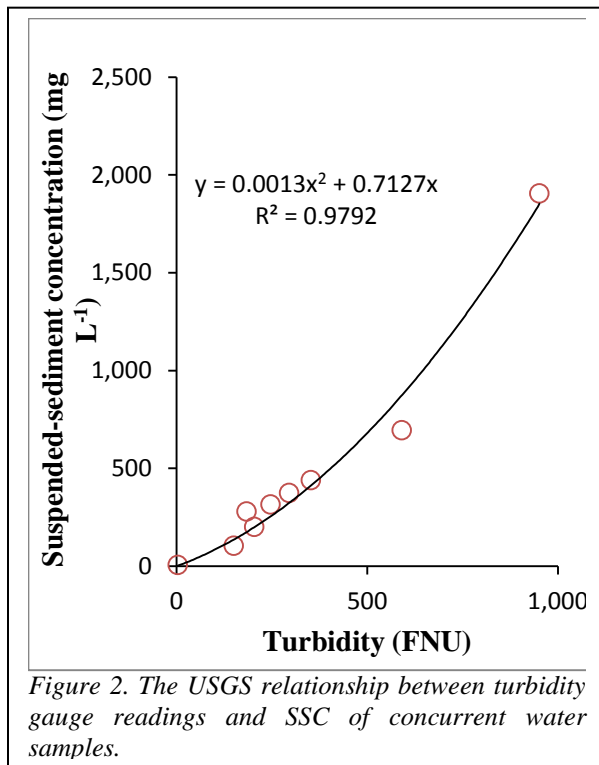


Figure 2. The USGS relationship between turbidity gauge readings and SSC of concurrent water samples.

Marine processes were studied using an instrumented tripod submerged off the mouth of the Elwha River at a depth of 15 m. Sensors on the tripod include an optical backscatter sensor (OBS)

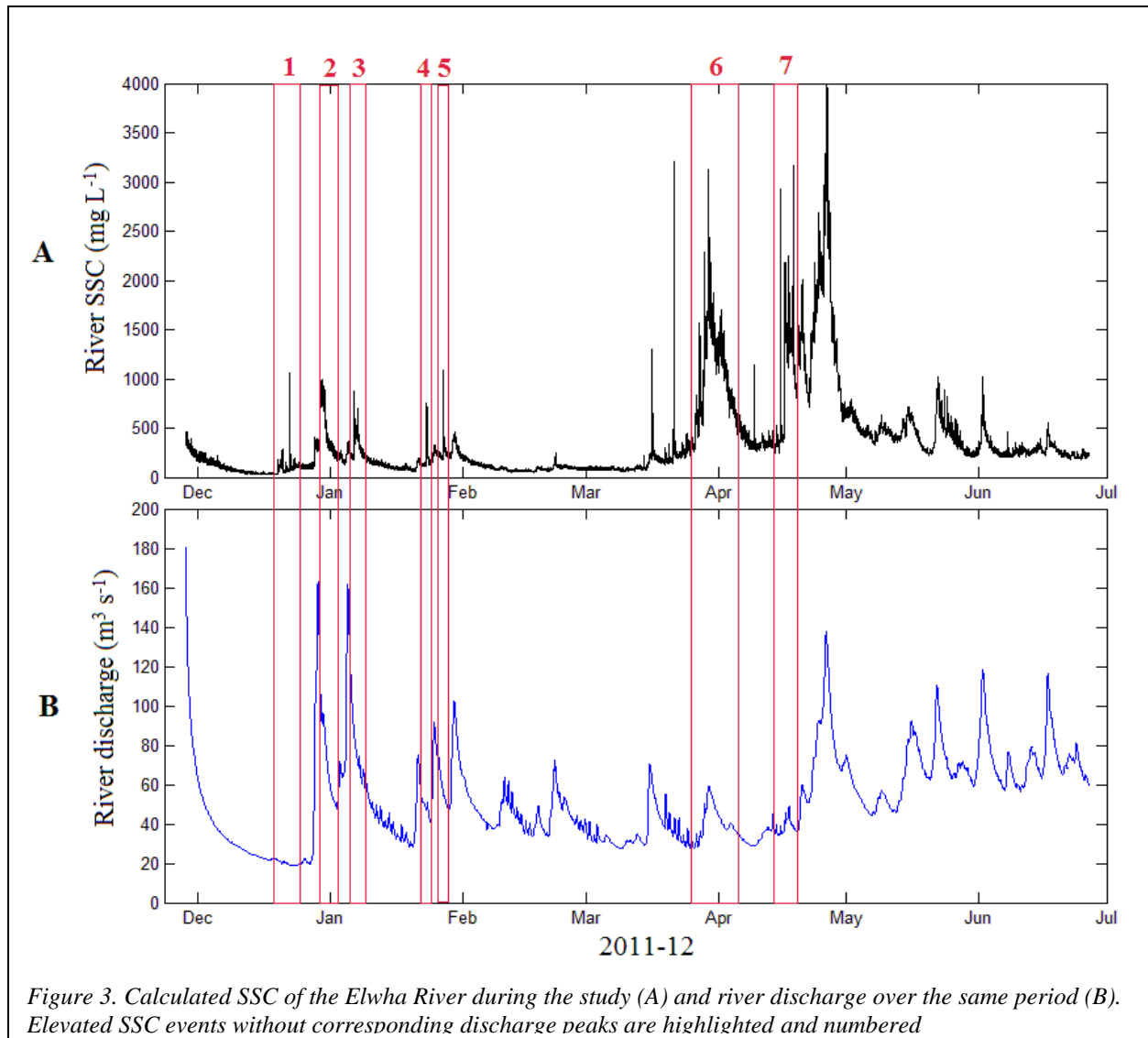
and an Ocean Probe acoustic Doppler velocimeter (ADV). These sensors measured every hour during the deployment. The tripod was first deployed in November 2011 and was raised every 3–4 months for refurbishment and data retrieval. Data from the first two deployments, from November 2011 through June 2012, were examined.

The OBS on the tripod measured the infrared backscatter off of solid particulate matter in the water at a height of 0.5 m off the seafloor. To convert these backscatter readings into SSC readings (units of mg L^{-1}) the OBS was calibrated with three water samples of known SSC to determine the linear relationship between backscatter and SSC. The calibration samples used sediment collected from the study area. The backscatter data was converted to SSC readings using this relationship, giving a record of the marine SSC over the study period. The ADV recorded near-bed wave orbital velocity 1 m off the seafloor at the study site.

The bottom wave-orbital velocity and river sediment input were compared to nearshore SSC at the tripod to determine river sediment or marine processes had the most significant effect on nearshore SSC. This comparison was used to determine whether sediment from the plume was being deposited near the mouth of the river or transported elsewhere and also to determine if the pulses of sediment resulting from dam removal had any immediate effects on the seafloor at the mouth of the river.

RESULTS

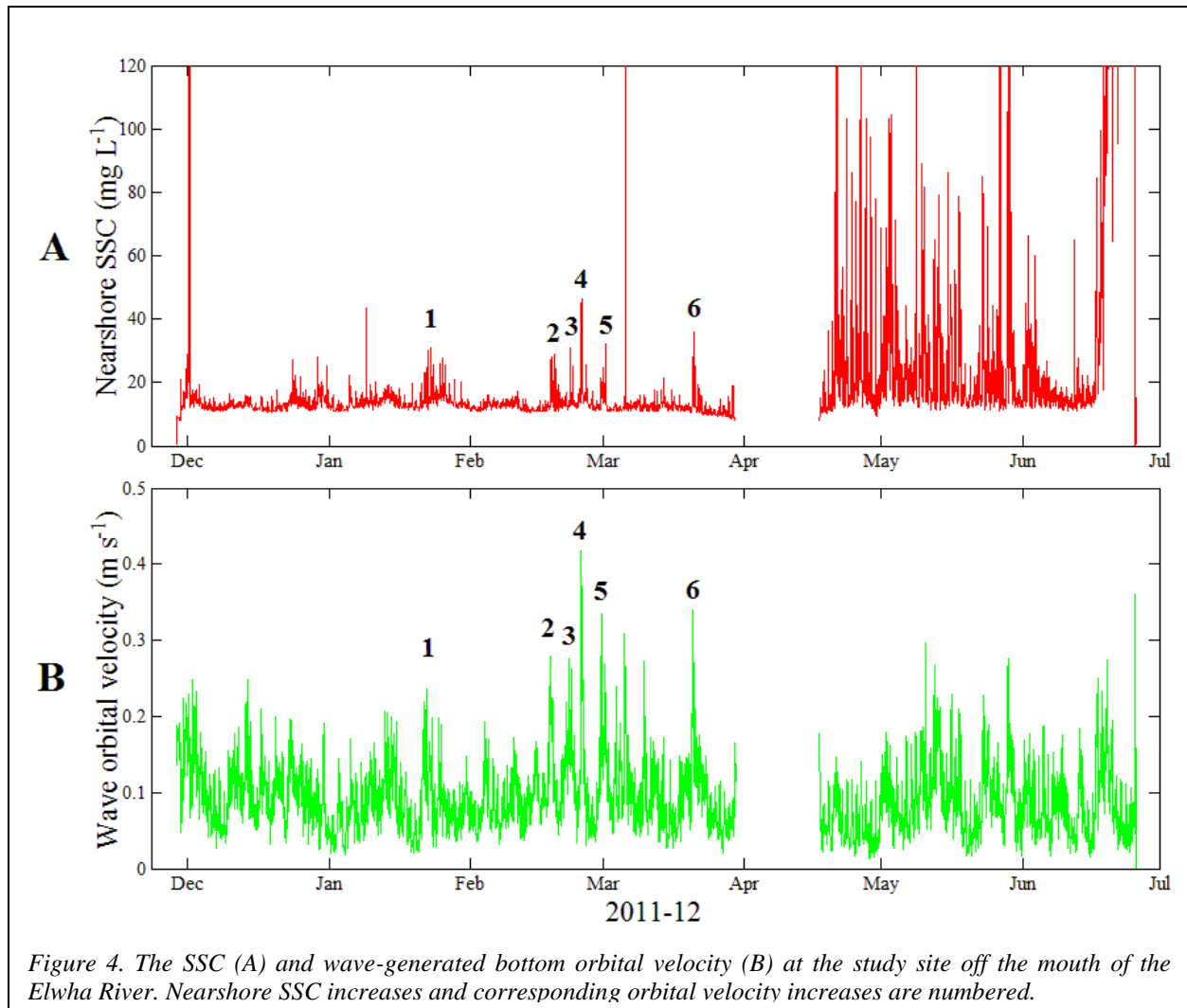
Background river SSC during the study period was 40–100 mg L^{-1} (Fig. 3A). Prior to mid-March multiple river suspended-sediment events had maximum SSCs of 200–500 mg L^{-1} . A large event (labeled as event 2) at the end of December had sustained concentrations of 800–900 mg L^{-1} and a peak concentration of 990 mg L^{-1} . Beginning in mid-March SSC increased over several weeks to a peak of 3100 mg L^{-1} on March 29 (event 6). The maximum concentration observed during the study period was 4000 mg L^{-1} on April 26. After the large March increase SSC never dropped below 200 mg L^{-1} .



River discharge peaked at $180 \text{ m}^3 \text{ s}^{-1}$ during the first measurement of the study period (Fig. 3B). Floods on December 28 and January 6 had maximum discharges over $160 \text{ m}^3 \text{ s}^{-1}$. Flood events from mid-January through mid-April had peak discharges of $60\text{-}100 \text{ m}^3 \text{ s}^{-1}$, while flood events from mid-April to the end of the study had peaks of $110\text{-}140 \text{ m}^3 \text{ s}^{-1}$.

Nearshore SSC varied over the first tripod deployment with a background level of $10\text{-}12 \text{ mg}$

L^{-1} (Fig. 4A). From November through March nearshore SSC increase events had maximum values of $20\text{-}40 \text{ mg L}^{-1}$. Variations in the second tripod deployment were greater, with many peaks of $70\text{-}100 \text{ mg L}^{-1}$. Large, short-duration spikes apparent in the time series as well as the large increase to over 1000 mg L^{-1} at the end of the second deployment were attributed to organic activity or other interference and were not evaluated in this study.



From November through mid-February the wave-generated bottom orbital velocity varied from 2 to 25 cm s^{-1} (Fig. 4B). Velocity peaks increased through the end of the first deployment with maximum velocities of 42 cm s^{-1} on February 25, 33 cm s^{-1} on February 29, and 34 cm s^{-1} on March 20. Orbital velocities during the second deployment generally remained below 20 cm s^{-1} and reached maximums of 30 cm s^{-1} on May 11, 28 cm s^{-1} on May 28, and 27 cm s^{-1} on June 19.

DISCUSSION

Increased river discharge resulted in higher SSCs, but several periods of elevated river SSC did not correspond with significant increases or peaks in river discharge (Fig. 3). These periods were likely instances of trapped reservoir sediment

being washed down the river after major demolition events. The National Park Service maintains a dam removal blog (<http://www.nps.gov/oly/naturescience/damremovalblog.htm>). Comparing these elevated SSC periods to the removal process reveals that each of the periods corresponded to a major Elwha Dam removal event, specifically periods of channel switching at the Elwha Dam and draining of Lake Aldwell (Table 1). The final drawdown of Lake Aldwell also exposed lake sediment that was easily transported by the river. The first major flood after the final lake drawdown resulted in the highest observed river SSCs, 4000 mg L^{-1} at the end of April, and baseline SSCs of 200 mg L^{-1} versus 40-100 mg L^{-1} before the final drawdown (Fig. 3). No major deconstruction events happened

from May 1 through the end of the study in order to protect several fish runs on the river.

Table 1. River SSC events and corresponding Elwha Dam removal milestones.

Date	River SSC Event (Fig. 3)	Major Deconstruction Event
12/20/2011	1	River flow moved into its natural channel at the Elwha Dam
12/30/2011	2	River flow switched back into its natural channel at the Elwha Dam
1/6/2012	3	Period of Lake Aldwell drawdown
1/23/2012	4	River flow switched back into its natural channel at the Elwha Dam and Lake Aldwell drawn down 1 m
1/27/2012	5	Lake Aldwell drawn down 1 m
3/28/2012	6	Final Lake Aldwell drawdown
4/10/2012	7	Excavation of channel at Elwha Dam site

This dam removal influence does not obviously extend to the nearshore study site. River SSC event 4 (Fig. 3) appears to be correlated with an increased nearshore SSC on January 22-23 (event 1, Fig. 4), but wave orbital velocity at that time was also high (24 cm s^{-1}) and might explain the increase. The gap in the nearshore measurements between the tripod deployments missed the transition from relatively steady SSC levels to the highly variable nearshore pattern seen in the second deployment. Without those measurements it is difficult to explain the change in nearshore SSC variability at the study site as the result of the large sediment input from the rivers during April.

The lack of direct influence of river sediment on nearshore SSC fits with the sediment transport characteristics of the Strait of Juan de Fuca. Due to the long fetch and strong Pacific Ocean swells longshore transport is strongly eastward (Wallace 1988). The Elwha supplies fine sediments to the Strait in a buoyant plume, which takes time to mix with the seawater and settle out the sediment. The plume predominantly flows to the east of the river mouth and longshore sediment transport is also eastward (Warrick and Stevens, 2011). By the time fine sediment settles out of the plume and reaches the seafloor it will be to the east of the river delta, while the tripod is immediately off of the mouth (Fig. 5).

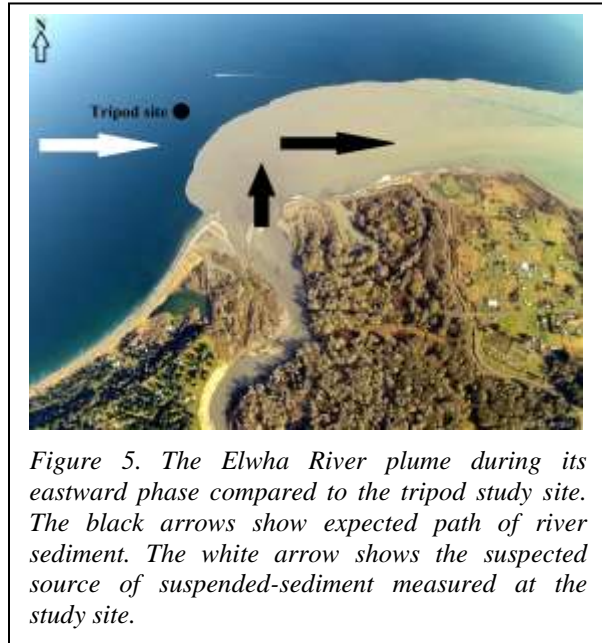
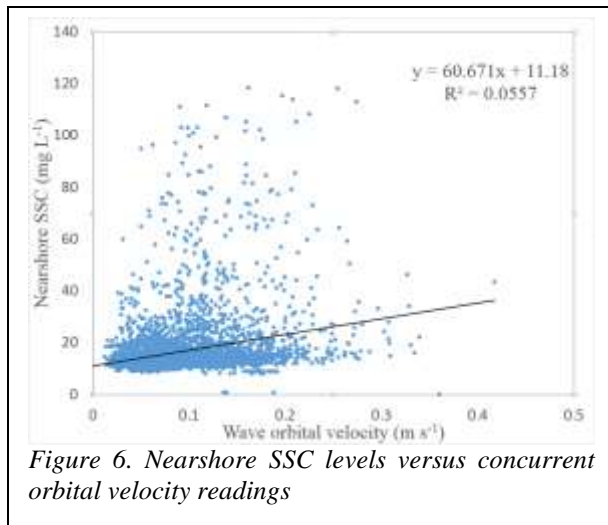


Figure 5. The Elwha River plume during its eastward phase compared to the tripod study site. The black arrows show expected path of river sediment. The white arrow shows the suspected source of suspended-sediment measured at the study site.

Several orbital velocity events (2-6) showed that strong wave energies could resuspend enough sediment to significantly affect SSCs (Fig. 4). However, SSC at the study site was not significantly correlated with wave orbital velocities (Fig. 6). This suggests that besides during strong wave events SSC at the study site is controlled by another source of suspended sediment. Due to the Strait's eastward sediment transport this source is likely west of the river mouth (Fig. 5), possibly the bluffs in Freshwater Bay (Shaffer et al., 2005).



Better data on the effects of the dam removal on the nearshore environment could have been collected at a different study site. The main goal of the tripod deployments is to study hyperpycnal river plumes, and they are located with that goal in mind. A deployment to the east of the river delta would be better situated to pick up the sediment signal from the river.

This study did not take into account the river's bedload transport. Sand and coarser sediments travelling as bedload take longer to wash down the river but have a larger effect on local morphology, their larger masses requiring more energy to wash away. Understanding the river's bedload transport would give a better idea of how the dam removal is going to reshape the shoreline and affect the erosion that has occurred since the dams were constructed.

CONCLUSIONS

- The dam removal process released pulses of sediment to the river, the largest increasing river SSCs to 3-4 g L⁻¹.
- Nearshore SSC levels increased in magnitude and variability after the large sediment releases of April, but a gap in the data conceals the transition period and makes it difficult to explain as a consequence of dam removal.
- Significantly higher than normal wave orbital velocities at the study site increased SSCs, but at lower energies waves were not correlated with SSCs at the study site.

- The eastward sediment transport of the Strait of Juan de Fuca and results of the study suggest that fine river sediments are moving east of the river and that SSC at the study site is controlled by sources to the west of the river.

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