

**Resuspension and Advection as Sediment Transport Processes in the Elwha Delta
Nearshore Environment**

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Marine Sedimentary Processes Research Apprenticeship

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Abstract

The largest dam removal project in U.S. history began on the Elwha River in 2011. A large quantity of sediment was expected to enter the marine environment, but where this sediment would end up and how it would get there were unknown. This study investigated currents and sediment transport at a study site offshore of the Elwha Delta over two winters during the dam removal process. Trends between Acoustic Doppler Current Profiler (ADCP) data and oceanographic conditions were examined. Suspended sediment concentrations at the study site were obtained by calibrating ADCP backscatter data, and were found to be most strongly correlated with river discharge. These data indicated that advection was the primary mechanism of sediment transport at the study site. Currents were found to be predominantly eastward, indicating the direction of advection. This study provides a foundation for future work examining the transportation of sediment in and around the Elwha Delta, and how this transport will impact the area in the future.

1. Introduction

Suspended sediment in the marine environment has typically arrived at its current location through either resuspension on site or advection from elsewhere. When measuring sediment transport we typically rely on Eulerian measurements from tripods and/or moored instruments. Using this measurement technique with an ADCP does not immediately reveal the presence of resuspension or advection in the collected data. Further analysis must therefore be performed in order to detect resuspension and advection. This project helps understand sediment transport processes in the Elwha

Delta's nearshore environment. By understanding transport, the questions of where new sediment entering the system post-dam removal will go and how it will affect the marine environment can be examined. This investigation is accomplished by comparing ADCP velocity and backscatter data to tides, waves, river discharge, and water velocities at a study site offshore of the Elwha Delta in approximately 15 m of water.

2 Background

2.1 Elwha Dam removal project

The Elwha River restoration and the associated dam removal project are significant contemporary issues in Washington State, USA. Emptying into the Strait of Juan de Fuca via the northern shore of the Olympic Peninsula (Figure 1), the Elwha River is 72 km in length, with 83% of its watershed inside Olympic National Park (Duda et al., 2011). Two run-of-river dams once blocked the 72 km Elwha River, at 7.9 and 21.6 km upstream from its mouth, and inhibited the downstream transport of sediment. In 1992 Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, which led to the removal of both the 1913 Elwha and 1927 Glines Canyon dams (NPS, 2010). Deconstruction of the dams began in September 2011, and as of March 2012, the Elwha Dam had been completely removed. A small portion of the Glines Canyon Dam remains, scheduled to be removed by summer 2013 (NPS, 2012). The deconstruction of these dams should allow approximately one third (Warrick, 2012) of the approximately $26 \times 10^6 \text{ m}^3$ of sediment trapped in the dam reservoirs to move downstream (NPS, 2013). This influx of sediment is expected to have a profound impact on the Elwha Delta and its nearby coastline (Duda et al., 2011).

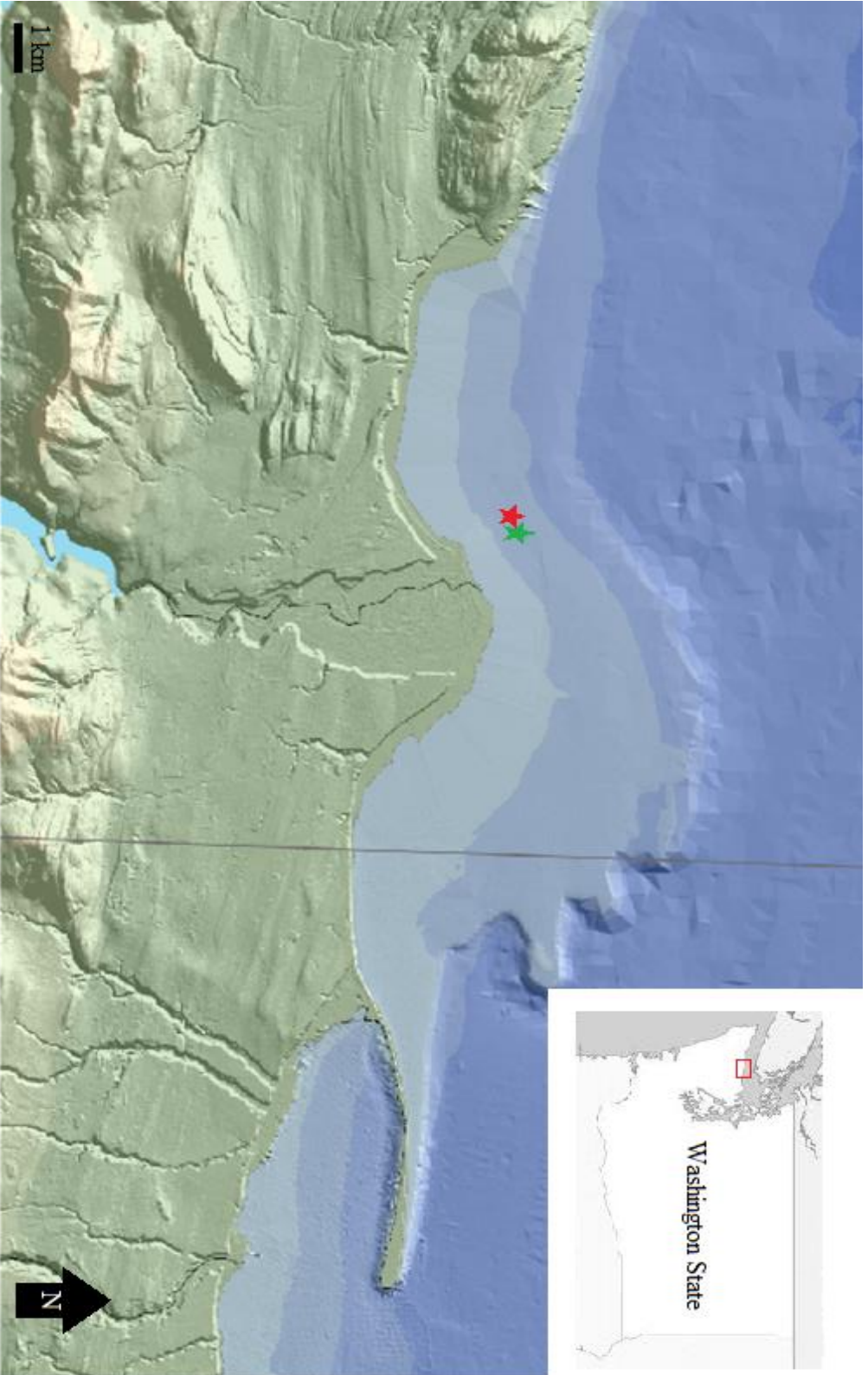


Figure 1. Map of the study site. Tripod locations are denoted for both Deployments A and B. Deployment A is depicted by the red star, whereas Deployment B is depicted by the green star. Images were obtained from <https://catalyst.uw.edu/workspace/efe/37528/260439> and <http://kootation.com/tanzania-outline-map.html>

2.2 Physical processes

Sediment transport near the Elwha Delta is controlled primarily by waves and nearshore currents, which serve to resuspend and advect sediments. Resuspension typically occurs in areas where currents are strong enough to overcome the critical stress of the bed and displace sediment from the bottom into the water column. This resuspension therefore requires the area to be subject to forces that can create the amount of current required to resuspend sediment. As a result, resuspension is more prevalent in shallower areas with strong tidal currents or large waves. Advection, on the other hand, typically occurs near areas of higher sediment concentration such as a large nearby sediment source, as the advected material must be moved from one place to the next. The turbid Elwha River provides ample source for this transport. Due to its strong tides, large waves, and abundant sediment, it is likely that both resuspension and advection are present at the Elwha Delta, although the exact extent is unknown.

Wave patterns play an important role in transporting sediment near the Elwha Delta. A littoral cell offshore of the Elwha Delta stretches from Freshwater Bay east to Ediz Hook, and receives sediment from the Elwha River and the bluffs east and west of the river mouth (Warrick et al., 2009). Swell entering the region from the Pacific Ocean dominates wave patterns both in the littoral cell and on the Elwha Delta, and creates eastward longshore drift that supplies Ediz Hook with sediment (Galster and Schwartz, 1990). This swell occurs consistently throughout winter and spring, and carries with it large sediment pulses discharged by the Elwha during those times (Warrick et al., 2009). The same swell generates an eastward surfzone current, whereas currents farther offshore experience influences from factors beyond Pacific swell such as tidal forcing, and are not

consistently eastward (Warrick et al., 2011). Because of its location in the Strait of Juan de Fuca, the Elwha Delta experiences relatively small amounts of wave energy compared to open ocean beaches, although waves are still a dominant process on the delta.

Tidal currents near the delta vary over both space and time, and are strongly influenced by the shape of the delta. The tides, which are mixed semidiurnal with a mesotidal range (NOAA Buoy 9444090; tidesandcurrents.noaa.gov), create currents primarily in the east-west direction in the Strait as they move water in and out of the Salish Sea. The protruding Elwha Delta forces nearshore flow to move around it, resulting in currents that flow around the delta in an arc. Tidal currents on the east side are typically twice as strong as those on the west side (Warrick and Stevens, 2010). These tidal currents result in residual currents that cause convergence and offshore transport of sediment and water (Warrick and Stevens, 2010). During flood tides an eddy is created to the east of the delta, and during ebb tides an eddy is created to the west of the delta (Warrick and Stevens, 2010). These tides are an important force driving currents near the Elwha Delta.

2.3 River discharge

River processes have an important impact on the Elwha nearshore environment. Elwha River discharge generally peaks in late spring and early winter, although winter discharge peaks are greater than those in spring (USGS River Gauge Station 12045500; waterdata.usgs.gov/nwis). These peak events are generally due to the large amount of precipitation received between October and January and spring snowmelt (WRCC Station 452548; www.wrcc.dri.edu). The freshwater of the Elwha River creates a plume that rises over the saltwater of the Strait, spreading in a very wide, shallow, and occasionally

visually distinct layer (Warrick and Stevens, 2011). These river processes significantly alter the marine environment near the Elwha Delta.

3. Methods

3.1 ADCP data

Both velocity and backscatter data were collected via upward-facing 600 kHz Acoustic Doppler Current Profilers (ADCP) at two locations in depths of 12-20 m. A tripod was deployed from the R/V Clifford A. Barnes at stations near the delta and river mouth from 28 Nov to 23 Dec 2011, and from 12 Oct 2012 to 8 March 2013 (Figure 1). These ADCPs were mounted approximately 2 m above the seafloor on tripods. Measurements were taken every half hour at a frequency of 2 Hz for 1 min in 100 0.25 m bins, with the average value recorded. Due to a 0.88 m blanking distance, the first bin was 1.36 m above the ADCP and roughly 3.36 m above the seafloor. ADCP backscatter data was calibrated using a calibration factor found in an Ogston et al., 2008 study of the Gulf of Papua, Papua New Guinea. This calibration factor was derived for fine-grained sediments in a tidal environment, which is similar to the Elwha nearshore environment. Increasing or decreasing the magnitude of the calibration factor by as much as an order of magnitude merely altered the magnitude of the suspended sediment concentration (SSC) obtained through calibration while leaving the relative measurements proportionately equal. Due to this proportional accuracy, the calibration factor from Ogston et al., 2008 was used to calculate relative SSC throughout the upper water column over changes in time.

3.2 Other data

Supplemental data sets were assembled from external sources. River discharge data were acquired from the USGS station at McDonald Bridge, WA (USGS River Gauge Station 12045500, waterdata.usgs.gov/nwis). Wave data were acquired from the NOAA buoy at New Dungeness, WA (NOAA buoy 46088, www.ndbc.noaa.gov). Tidal data were gathered from the NOAA station in port Angeles, WA (NOAA station 9444090, tidesandcurrents.noaa.gov).

3.3 Data analysis

ADCP data analyses were the primary focus of this study. Velocity was investigated throughout the water column to within approximately 3 m of the seafloor. A low-pass filter was applied to ADCP data to remove tidal forcing signature. The same velocity investigations were conducted on the filtered data. Backscatter data was converted to scattering volume (Sv) and then SSC, and used as to compare relative SSC values at different points in space and time. River discharge and wind data were compared to changes in the velocity profile to look at the effects of storm events on nearshore water movement.

4. Results

Results were based upon Acoustic Doppler Current Profiler (ADCP) and oceanographic condition data from two deployments. Deployment A took place from 28 Nov 2011 to 23 Dec 2011, while Deployment B took place from 12 October 2012 to 8 March 2013. These time-series data included tides, river discharge, river turbidity,

significant wave height, water column velocity, water column backscatter, and SSC.

Time-series data of both conditions and SSC for both deployments A and B are shown in Figures 2A and 2B. Typical examples of both unfiltered and low-pass filtered velocities taken from Deployment A are shown in Figures 3 and 4, with positive velocities corresponding to northward and eastward movement. Up-down velocities during Deployment B, both filtered and unfiltered, are shown in Figure 4.

4.1 Oceanographic conditions and suspended sediment concentration

Oceanographic conditions at the tripod sites displayed some observable patterns over the two deployments (Figure 2). The tides varied from a maximum of 2.73 to a minimum of -1.14 m MLLW, a mesotidal range, and were mixed semidiurnal. River discharge had a maximum recorded value of $124 \text{ m}^3 \text{ s}^{-1}$, although Deployment B had several periods during October 2012 where correct data were missing and could have been greater. Similarly, accurate river turbidity data for Deployment B was missing in several places, although valid readings generally varied from 200 to 900 FNU. River turbidity was generally related to river discharge. The highest observed significant wave height was 2.67 m, but waves were typically around 0.5 m high. Significant wave height tended to vary in bursts between large and small heights, as exemplified by early February 2013. SSC varied between 0.01 and 0.6 g L^{-1} , although values were typically at the low end of that range and greatest during November and December (Figure 5). Throughout the water column SSC tended to be uniform, although spikes associated with the river plume were occasionally observed in the upper 0.5 m. SSC was much greater during Deployment B than Deployment A.

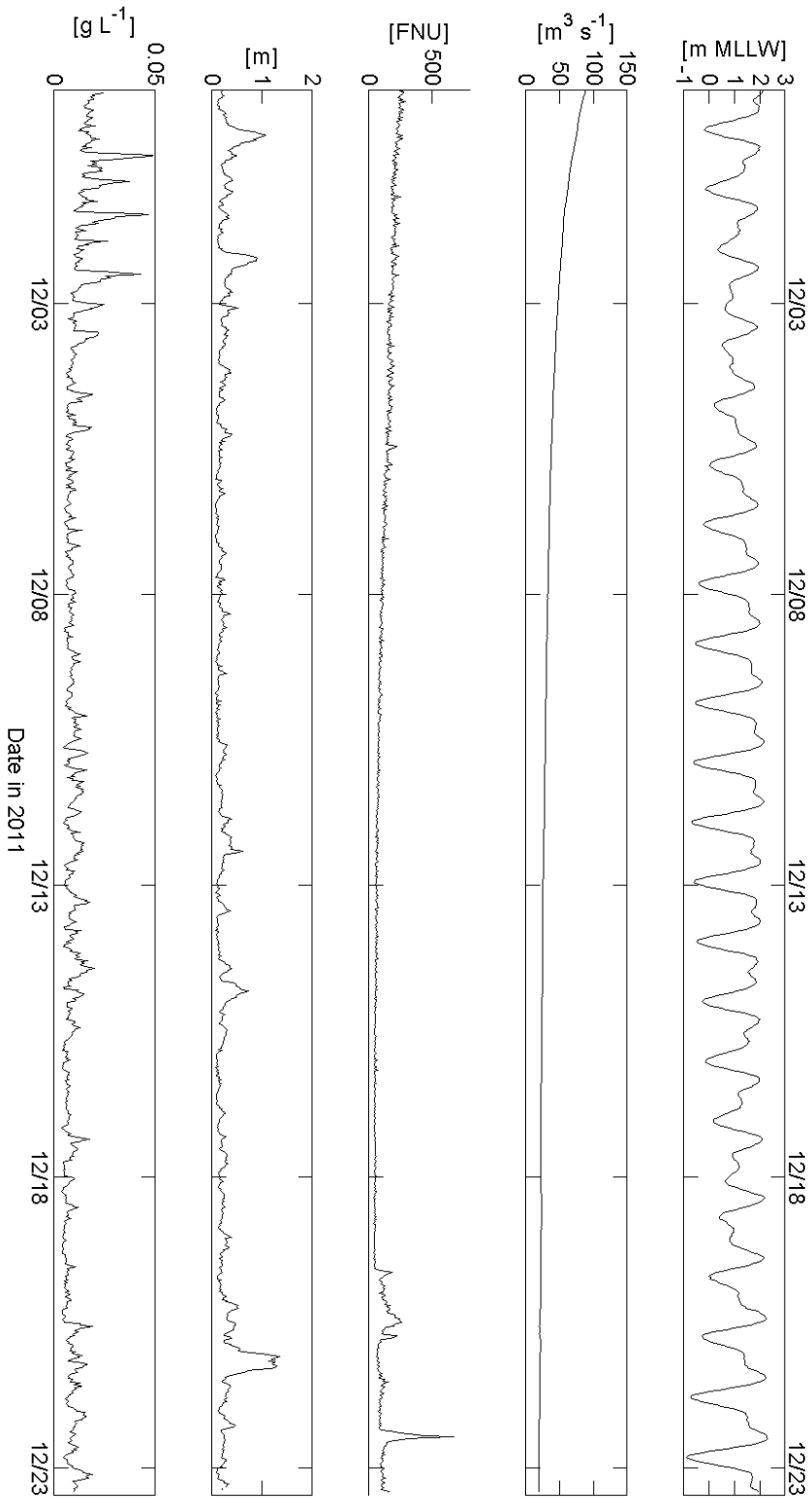


Figure 2A. Time-series data of oceanographic conditions and SSC data from Deployment A near the Elwha Delta. From top to bottom: tidal elevation, Elwha River discharge, Elwha River turbidity, significant wave height, average SSC value for the entire water column as calculated from calibrated ADCP backscatter data.

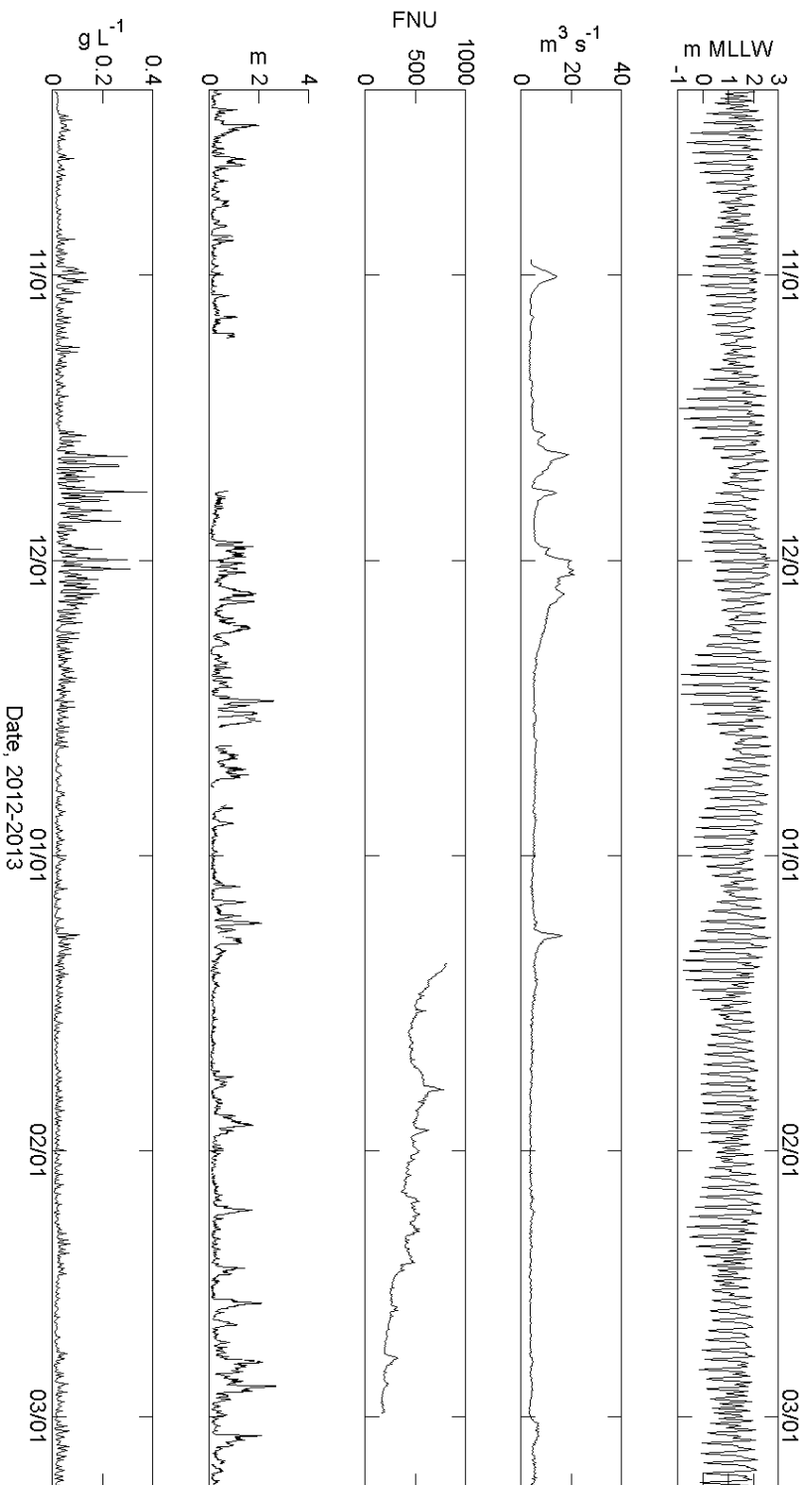


Figure 2B. Time-series data of oceanographic conditions and SSC data from Deployment B near the Elwha Delta. From top to bottom: tidal elevation, Elwha River discharge, Elwha River turbidity, significant wave height, average SSC value for the entire water column as calculated from calibrated ADCP backscatter data.

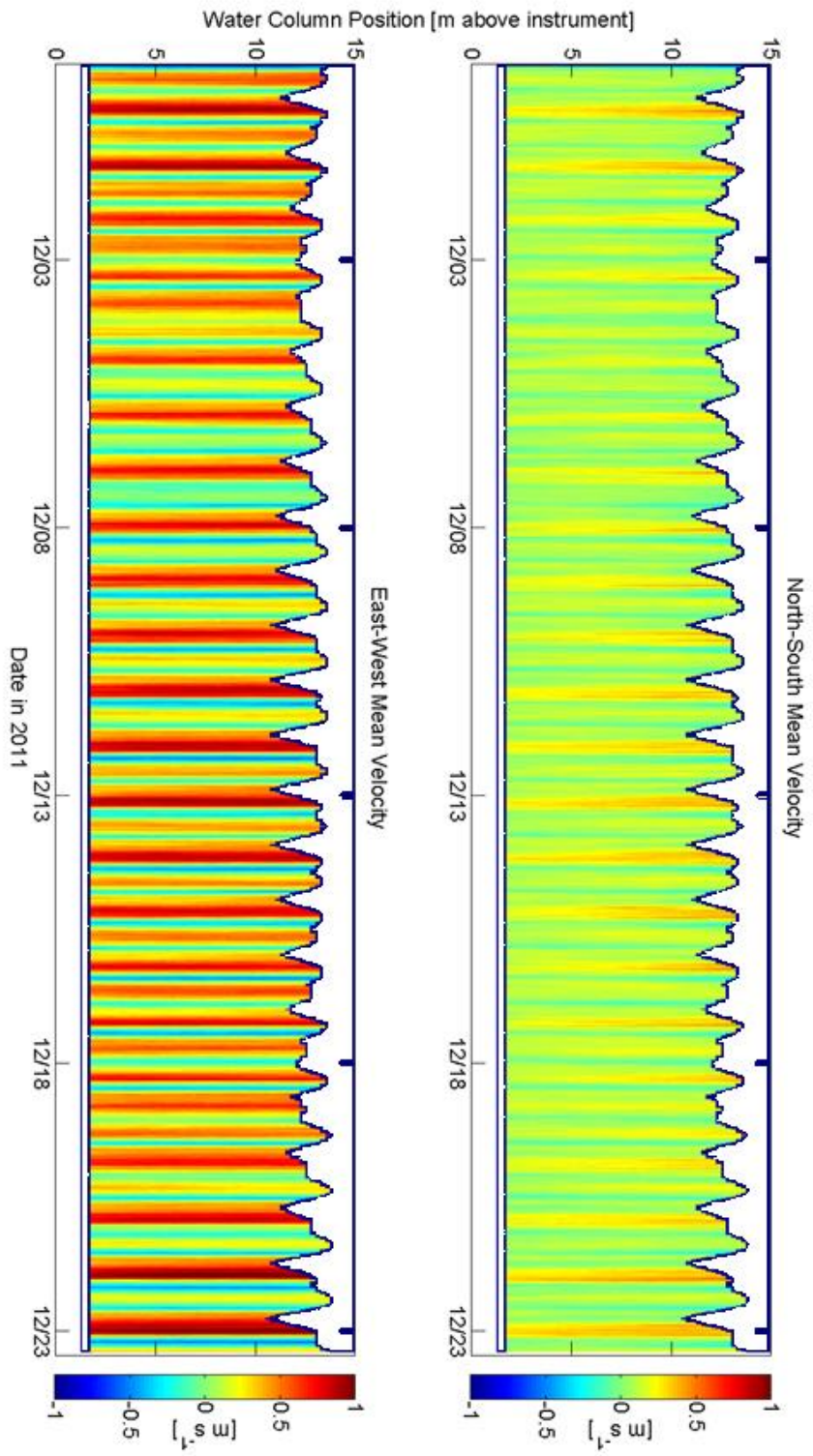


Figure 3. Time-series data of current velocity from ADCP measurements during Deployment A. The entire deployment is shown. This data is representative of the currents throughout both deployments.

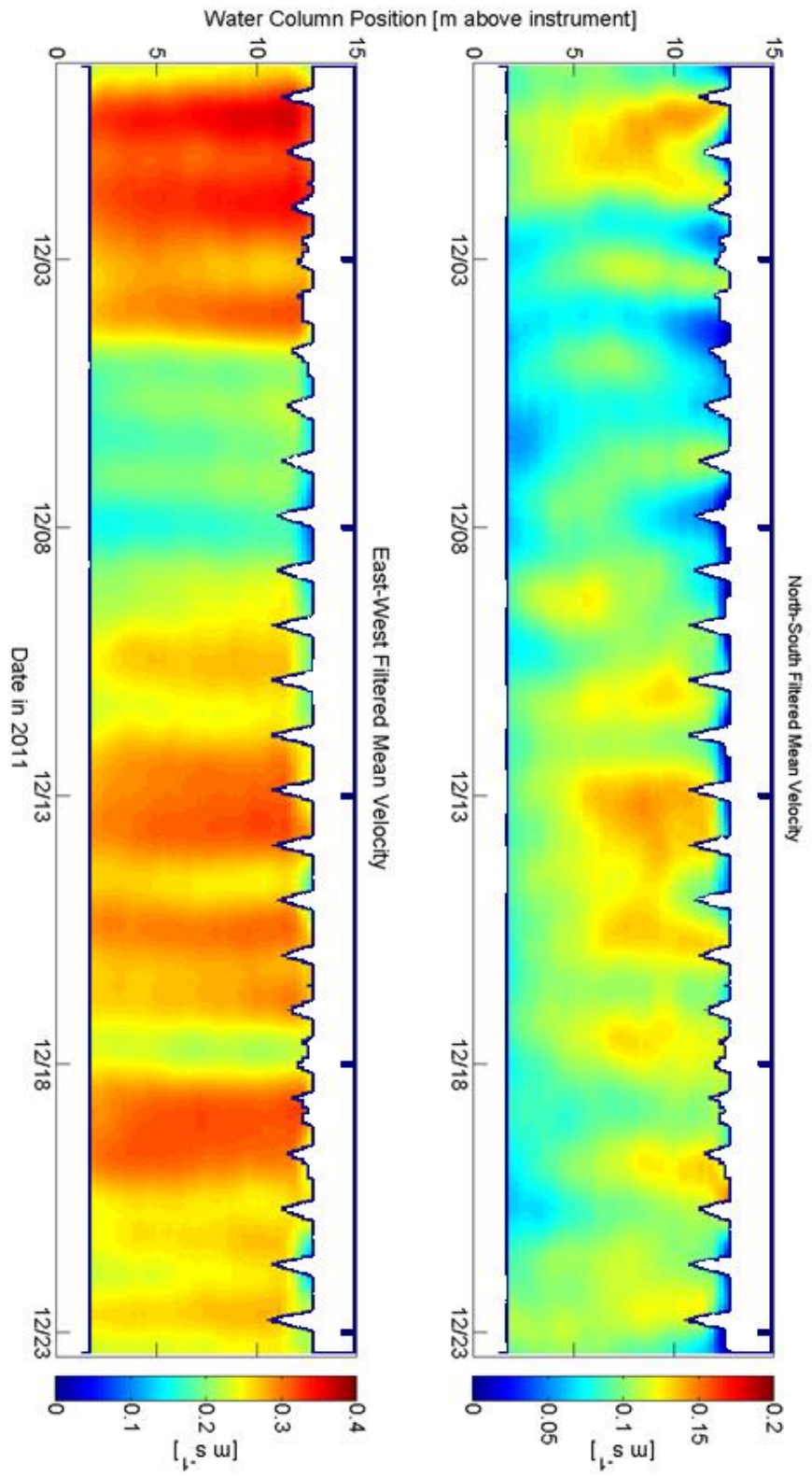


Figure 4. Time-series data of current velocity from ADCP measurements during Deployment A. The entire deployment is shown. This data is representative of the currents throughout both deployments.

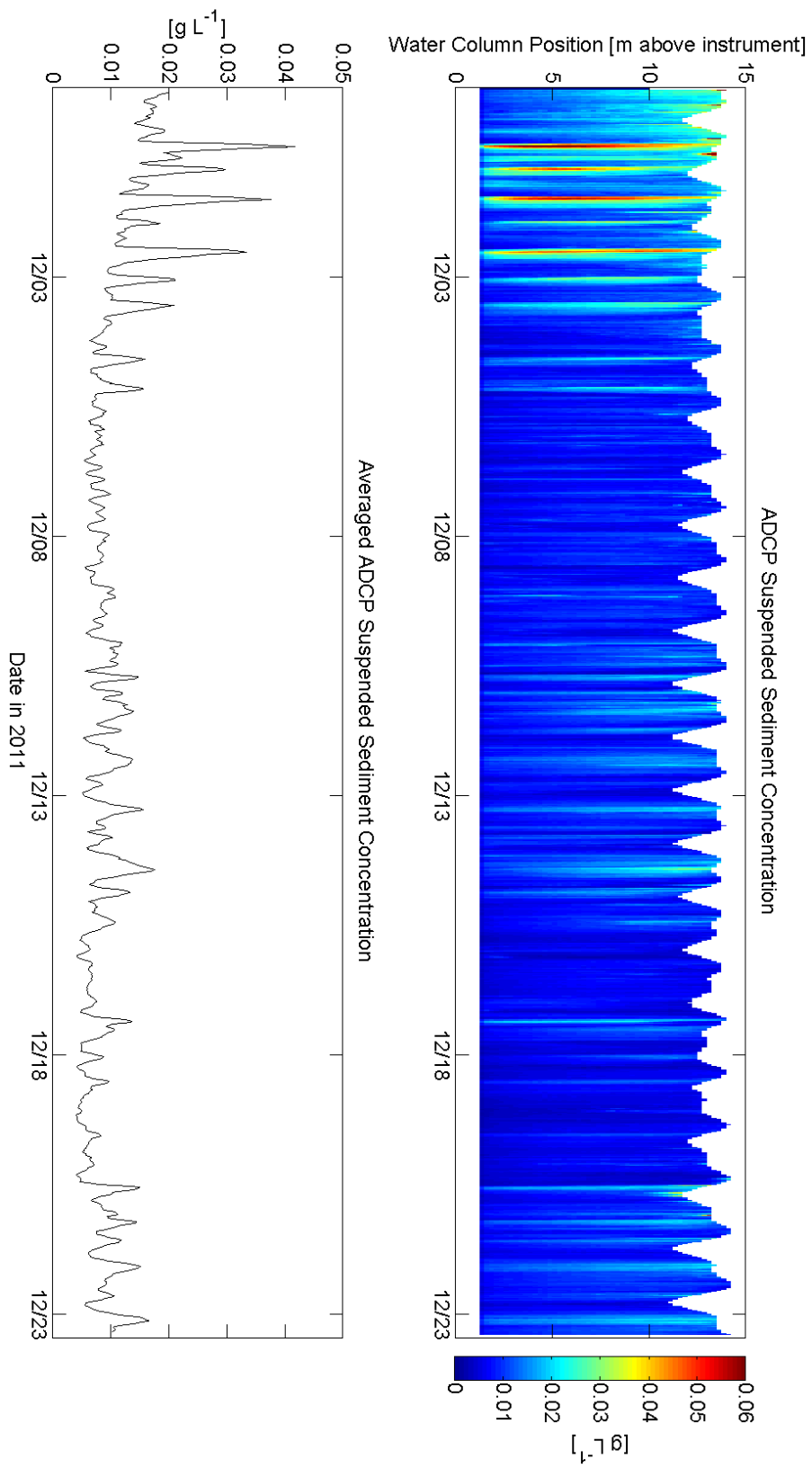


Figure 5A. Suspended sediment concentrations for the duration of Deployment A. The upper graph shows SSC throughout the water column. The lower graph shows the value of average SSC in the water column at a given time.

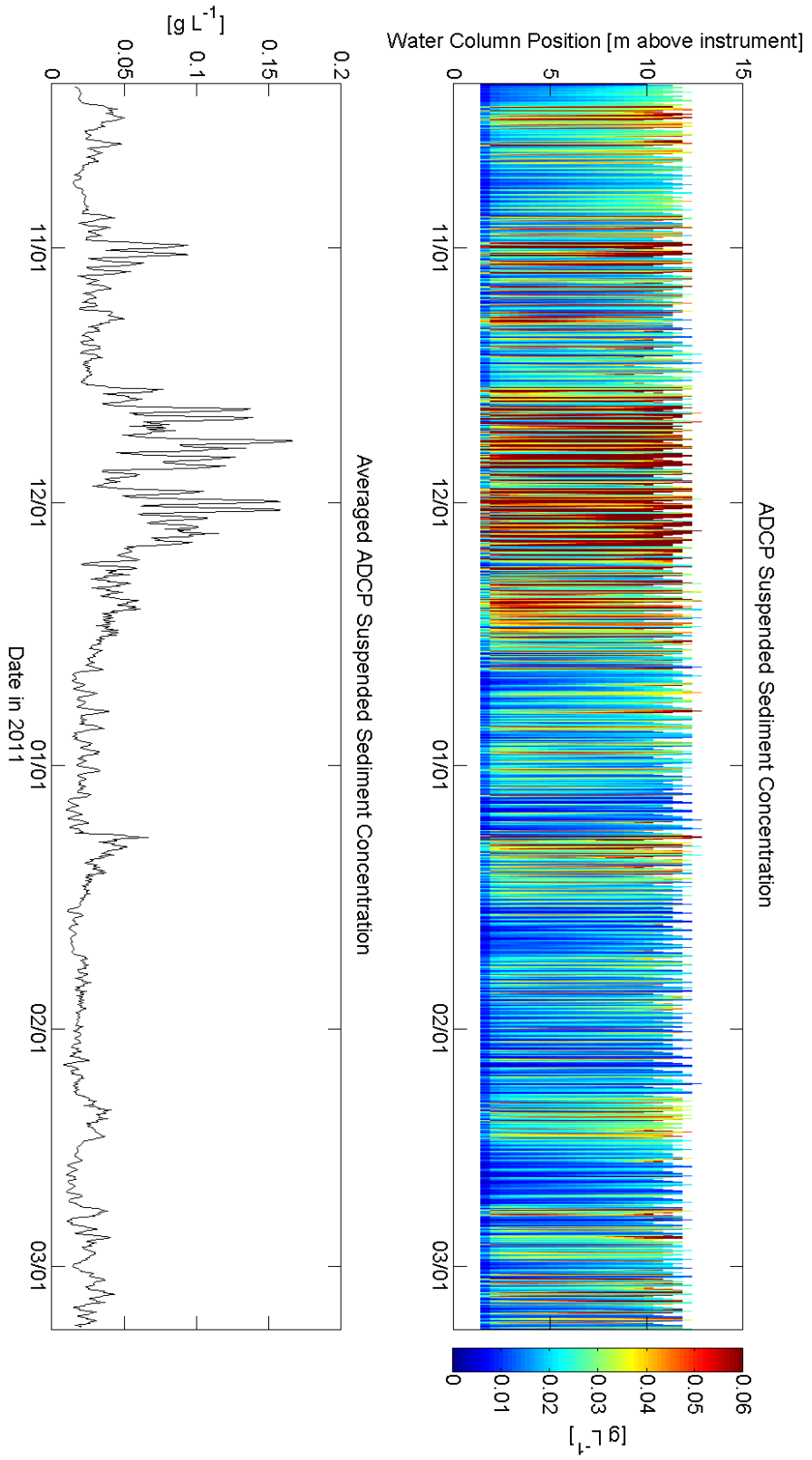


Figure 5B. Suspended sediment concentrations for the duration of Deployment B. The upper graph shows SSC throughout the water column. The lower graph shows the value of average SSC in the water column at a given time.

4.2 Velocity

Currents at the tripod site displayed daily tidal signatures. East-west currents were very uniform throughout the water column, with eastward flow during flood tides and westward flow during ebb tides, although eastward currents were stronger. North-south currents were weaker than east-west, although a shear in the vertical was consistently observed in north-south currents during large flood tides (Figure 3). During these periods of shear, water in the upper layer flowed northward $0.25\text{-}0.5\text{ m s}^{-1}$ faster than the water below it. Flood tides were associated with strong northward flow, while ebb tides were associated with weaker southward flow, although during some ebb tides no north-south flow was observed. Up-down velocities were typically below 0.05 m s^{-1} and almost exclusively upward, although a specific tidal pattern did not appear to exist. Filtered up-down currents showed periodic areas of upward velocities close to 0.1 m s^{-1} , which reoccurred every 2-4 days.

Low-pass filtering velocity data to remove daily tidal signatures revealed further patterns. East-west flow varied from 0.1 to 0.3 m s^{-1} about every two weeks, with spring tides corresponding to greater velocities. The water column was generally uniform in both the east-west and north south direction, although there were times at which shearing in the vertical on the order of 0.05 m s^{-1} was present. North-south velocities varied from 0 to 0.05 m s^{-1} in the same spring-neap manner, again with spring tides corresponding to greater velocities. Up-down velocity patterns were more evident when low-pass filtered, with velocities of close to 0.1 m s^{-1} present in the upper water column during neap tides (Figure 6). Up-down velocities were weaker during spring tides, and were typically between 0 and 0.03 m s^{-1} .

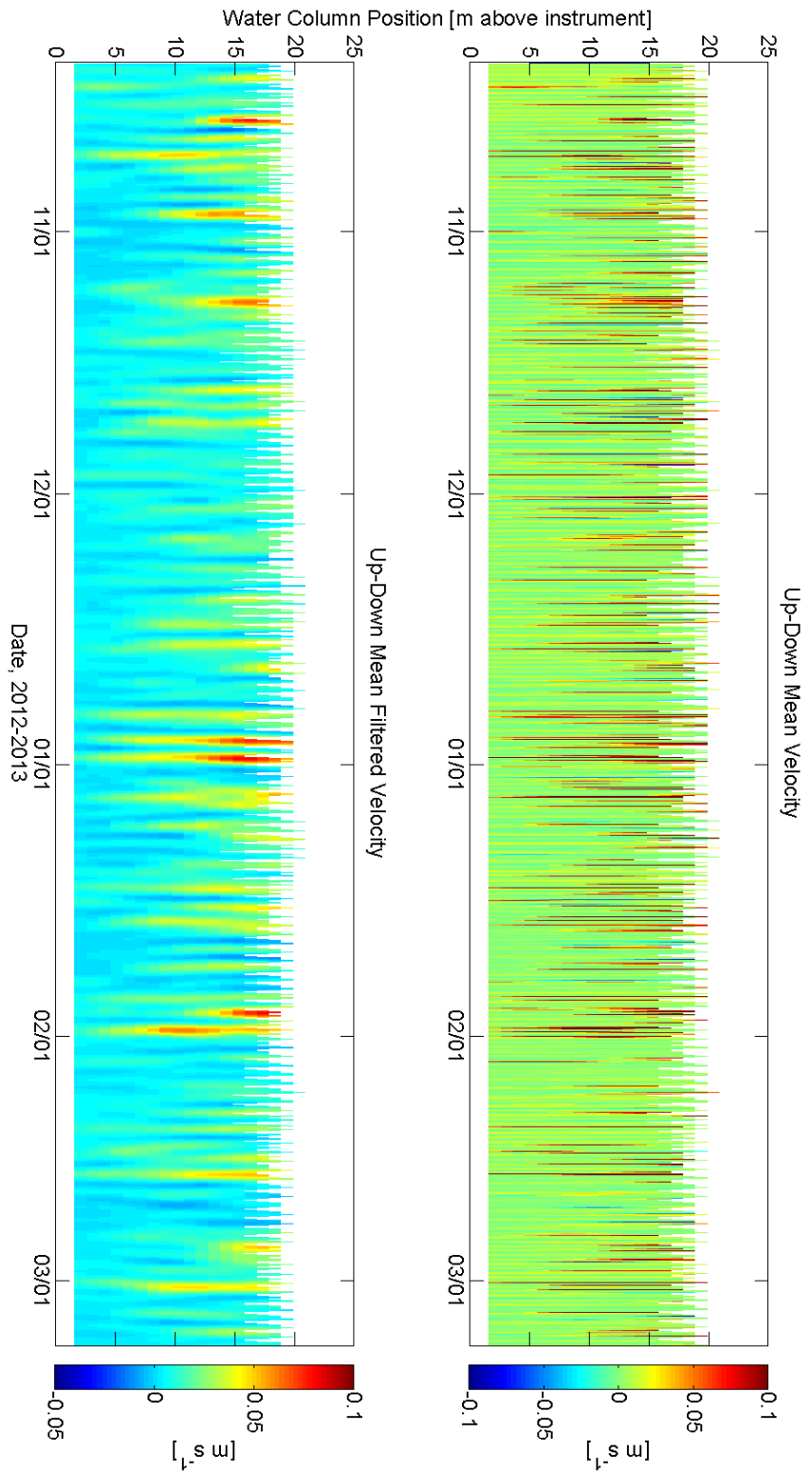


Figure 6. ADCP upward velocity measurements during Deployment B. The upper graph shows upward velocities, while the lower graph shows low-pass filtered upward velocities.

5. Discussion

5.1 Velocity trends

Upward velocity trends were observed during Deployment B (Figure 6). In low-pass filtered current data we can see periodic upward velocities of up to 0.10 m s^{-1} that reoccur in a cycle of 2-4 days. This indicates that ignoring the ebb and flood of tides, there is a net upward movement of water in the water column at the study site. These filtered upward velocities were strongest following lower low water (LLW), and reoccurred to some extent every other LLW. While the upward velocity was not uniform throughout the water column, this provides some evidence of periodic upwelling occurring at the Elwha Delta. A similar upward velocity was also seen in unfiltered velocity measurements, where it was repeated more frequently and less regularly, indicating that it was partially due to high frequency processes such as daily tidal variations, and partially due to low frequency processes, such as spring-neap cycles and larger circulation trends.

5.2 Resuspension

In order to analyze resuspension in the water column, the relationship between SSC and forces that move water locally was examined. This study examined waves, tides, and currents as the primary water-moving forces at the study site. A subtle trend between significant wave height and mean SSC was observed. Figure 7 shows that as significant wave height increased above 0.4 m, SSC also increased. This relationship was approximately linear, although at wave heights above 1 m this relationship seemed to disappear. Below wave heights of 0.4 m there may exist a steeper relationship between wave height and SSC, but there was enough noise in this data to conceal any definitive

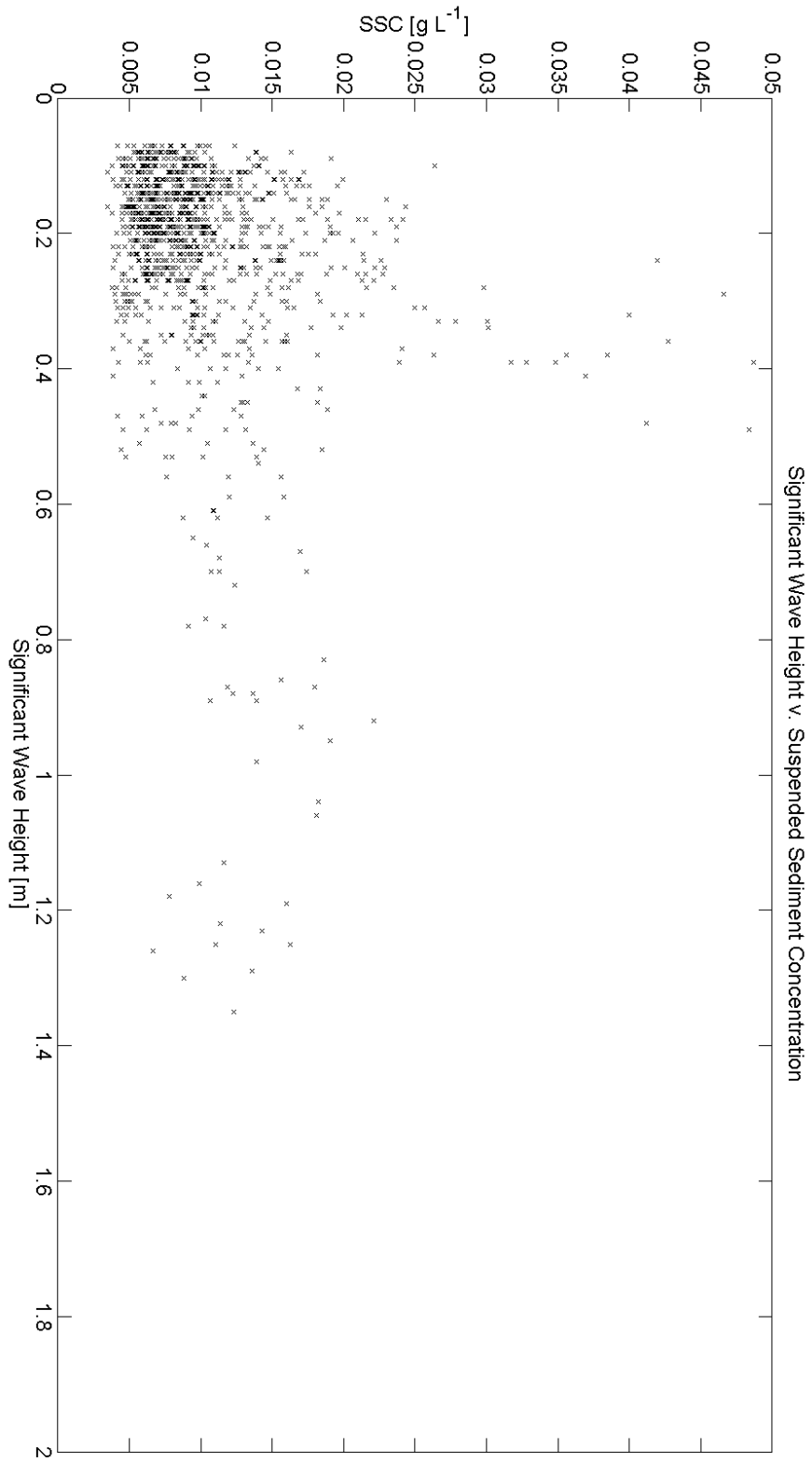


Figure 7. the relationship between significant wave height and suspended sediment concentration. Only data from Deployment A is shown. No significant trend is observed.

trend. A relationship between significant wave height and SSC was not present in the data from Deployment B. Based on these two deployments, a trend does not exist between significant wave height and SSC at the study site.

A subtle trend also existed between tidal elevation and SSC, although this trend varied between Deployment A (Figure 8A) and Deployment B (Figure 8B). For both deployments SSC had a narrow range at low tides (below 0 m MLLW), whereas at high tides (above 2 m MLLW) SSC had a wider range. The low end of the SSC range was the same regardless of tidal elevation. In Deployment A the greatest range in SSC existed at mid-tides (between 0 and 2 m MLLW), which suggests that the tidal exchange resuspends a significant amount of sediment. However Deployment B had the greatest range in SSC at high tides. Tides and SSC are weakly linked, with high tides generally correlated to SSC values that are equal to or greater than those at low tides.

Current magnitude did not seem to be directly linked to SSC. Figure 9A has some evidence of a trend, although it is weak at best. At velocities close to 0.5 m s^{-1} SSC had a range from 0.003 to 0.014 g L^{-1} , whereas at velocities of 1 m s^{-1} SSC ranged from 0.007 to 0.02 g L^{-1} , showing that SSC increased as current magnitude increased. There was a lot of noise in this trend at velocities below 0.5 m s^{-1} , however, which shows that the relationship between current magnitude and SSC is not always present. Figure 9B has a similar trend for current magnitudes above 0.5 m s^{-1} , although the SSC values are higher. This is evidence that some resuspension occurs due to the action of currents, but that currents are not always the driving factor of SSC at the study site.

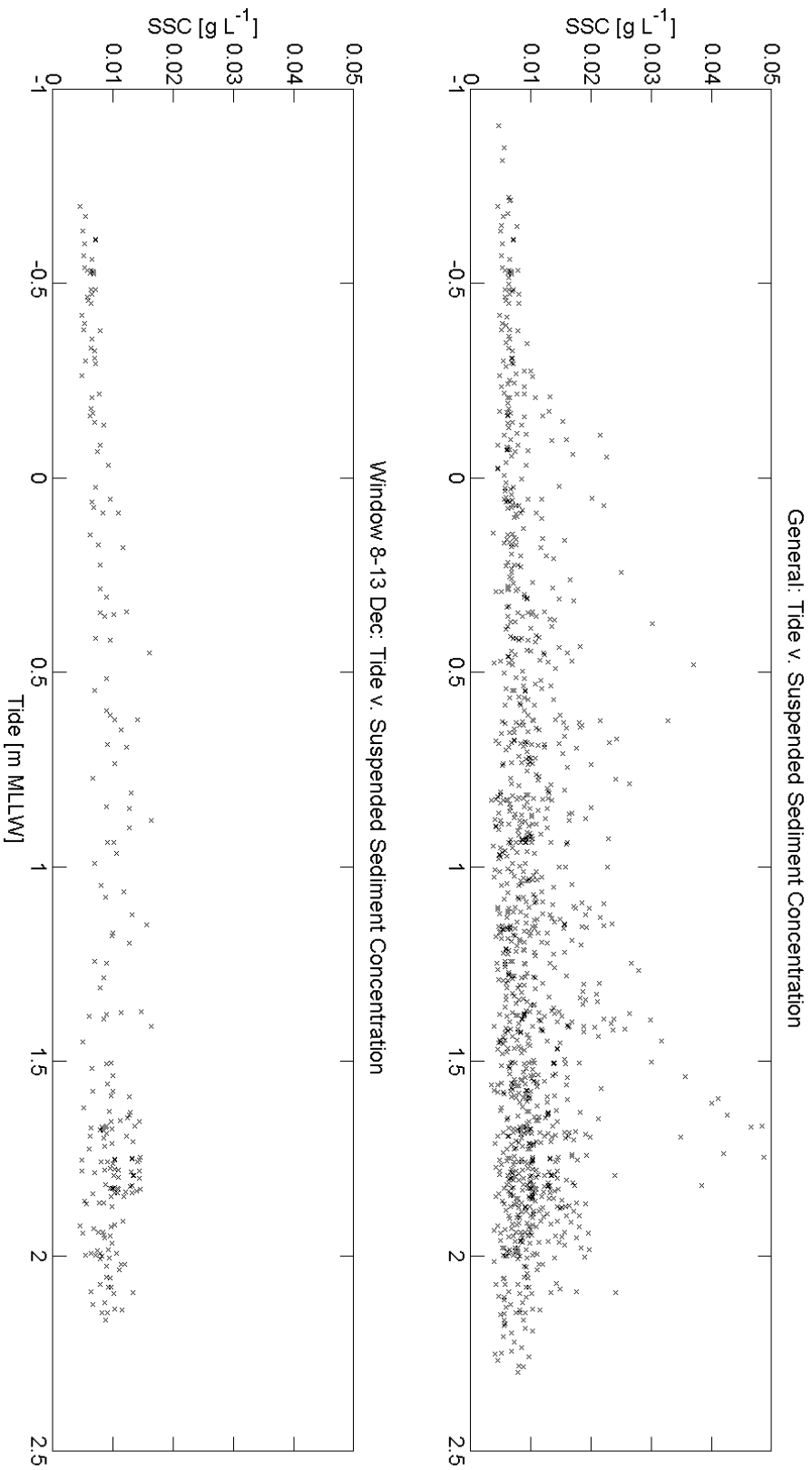


Figure 8A. The relationship between tidal elevation and suspended sediment concentration. The upper graph uses the full dataset from Deployment A. The lower graph uses only the data from Deployment A between 8 Dec and 13 Dec, 2011.

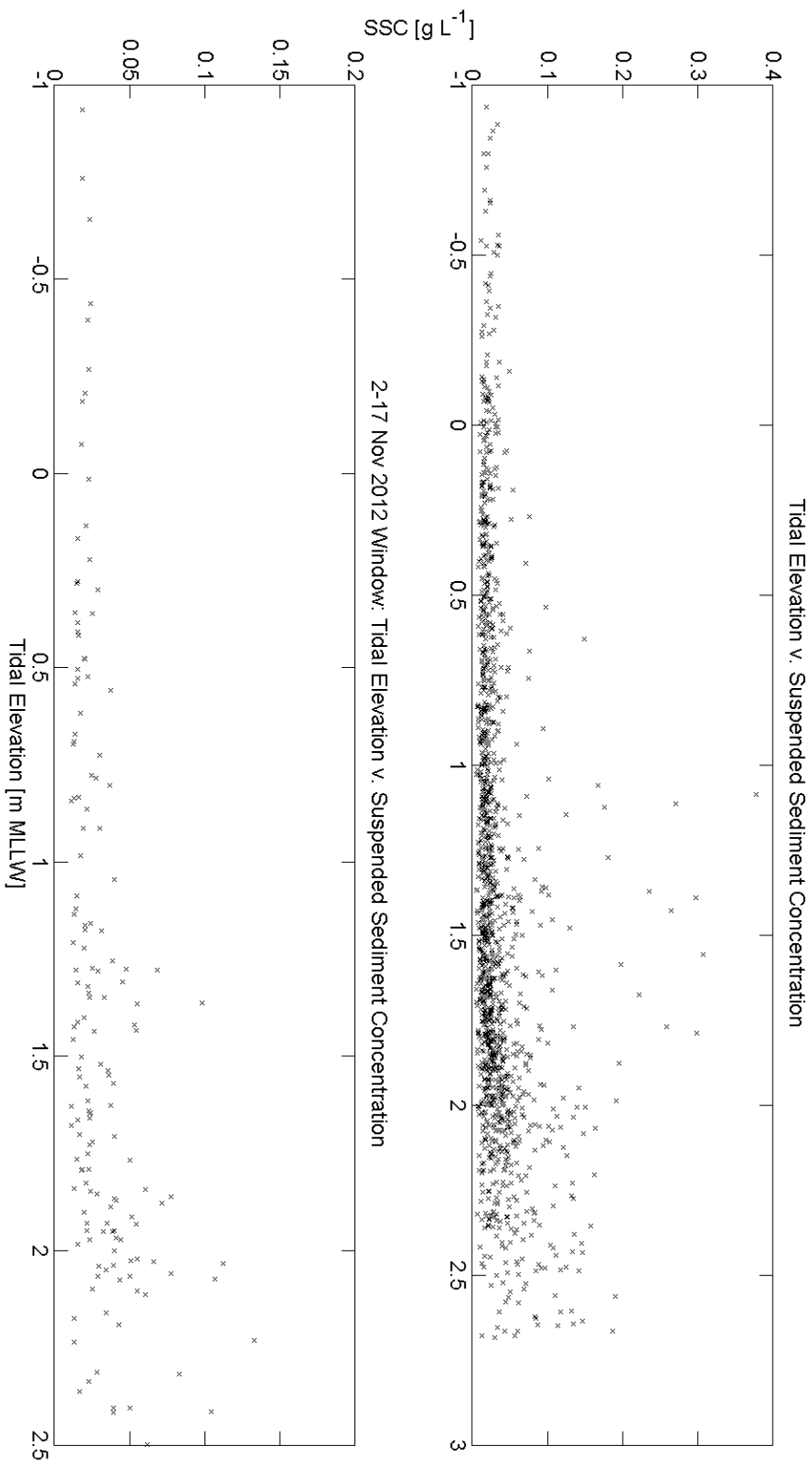


Figure 8B. The relationship between tidal elevation and suspended sediment concentration. The upper graph uses the full dataset from Deployment B. The lower graph uses only the data from Deployment B between 2 Nov and 17 Nov, 2012.

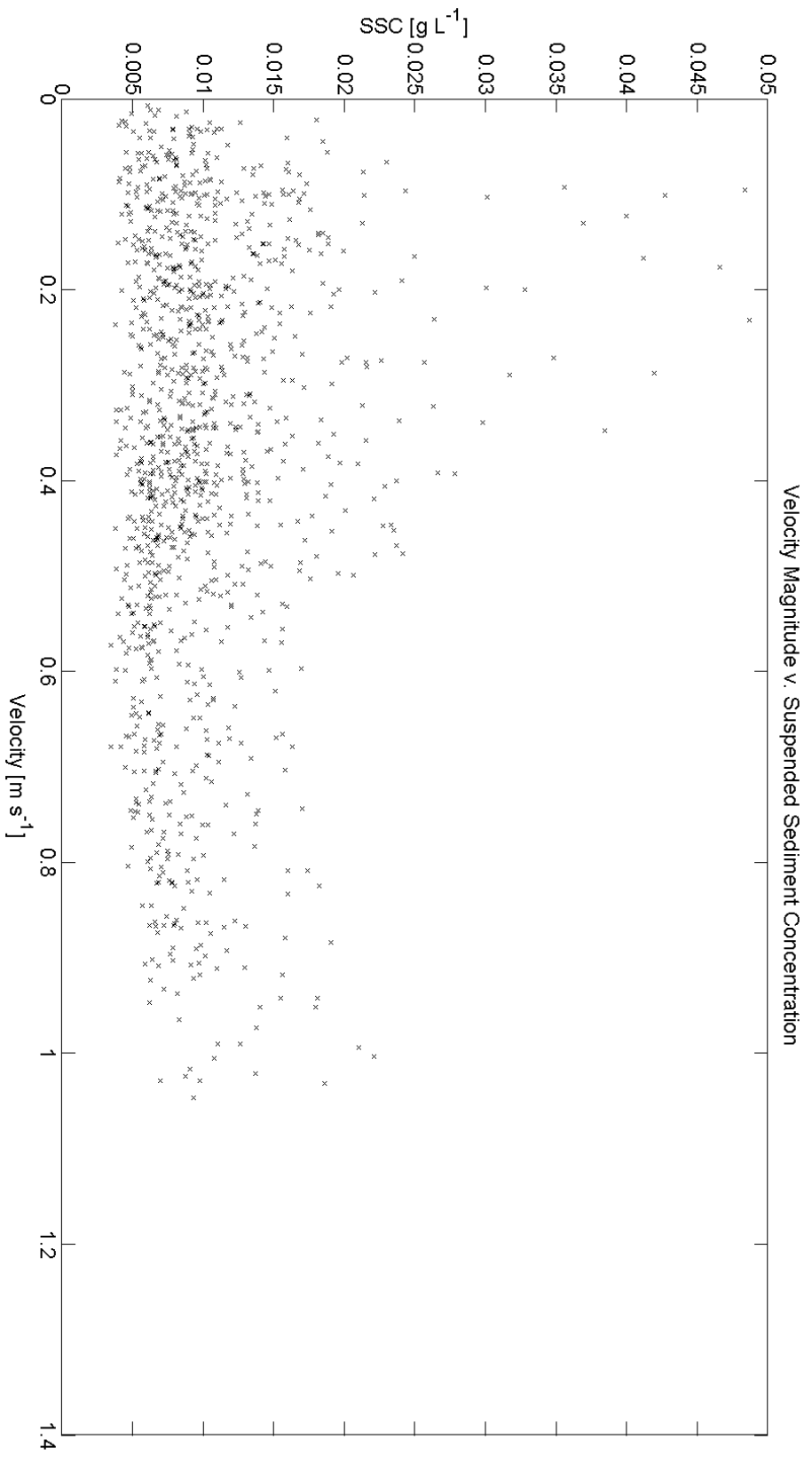


Figure 9A. The relationship between current velocity and SSC during Deployment A. A trend is observed for velocities above 0.5 m s⁻¹.

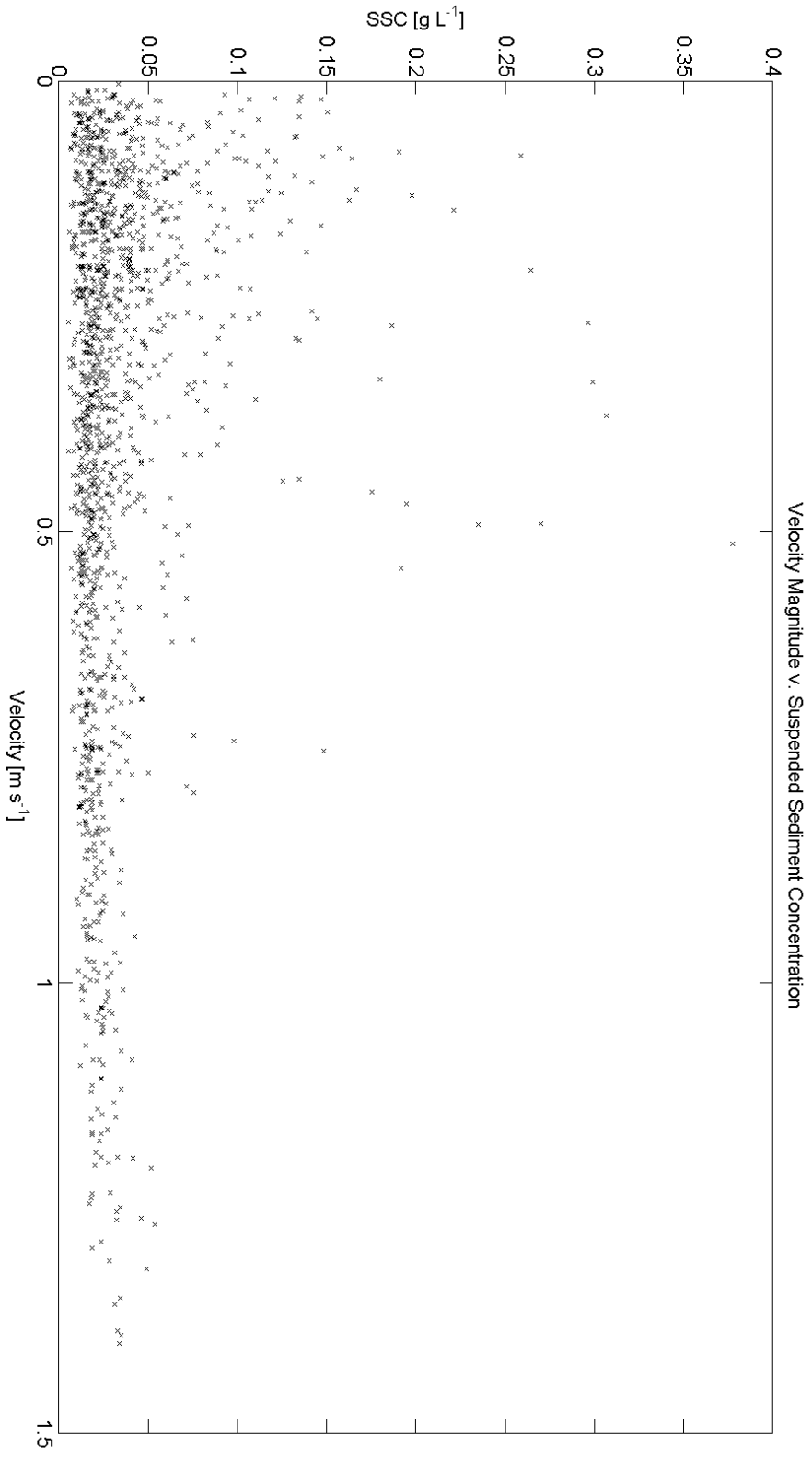


Figure 9B. The relationship between current velocity and SSC during Deployment B. A trend is observed for velocities above 0.5 m s⁻¹.

5.3 Advection

River discharge and SSC were strongly linked. Figure 10A shows that as river discharge increased, SSC increased in a linear fashion. There was some variation in this trend, but not nearly as much as there was when comparing waves, tides, or currents to SSC. Figure 10B does not support this link as strongly, as a direct linear relationship is not readily observed, but the discharge during Deployment B was much less than that in Deployment A. This decreased discharge may not have been great enough to enter the region where the linear relationship applies.

When SSC is low-pass filtered to remove tidal and wave signatures, however, the relationship becomes clearer. Figure 10A shows a continuous relationship between river discharge and filtered SSC that increases linearly up until discharges of about $65 \text{ m}^3 \text{ s}^{-1}$, at which point SSC begins to decrease by the rate at which it was previously increasing. This relationship makes some sense. Over the majority of Deployment A river discharge decreased continuously, so when plotted against SSC a function should have been plotted, that is to say for most river discharge values there should have been only one corresponding SSC value. When plotted it is observed that as river discharge decreases, SSC also changes continuously. Figure 10B shows a less clear relationship between discharge and filtered SSC, but we still see a general linear relationship between the two datasets. These figures indicate that river discharge is directly linked to SSC when we ignore the effect of tides. If the study site was an amphidromic point, we should therefore see a closer relationship between SSC and river discharge, as there would be no interference from the tides, although other high frequency processes such as waves could still have an effect.

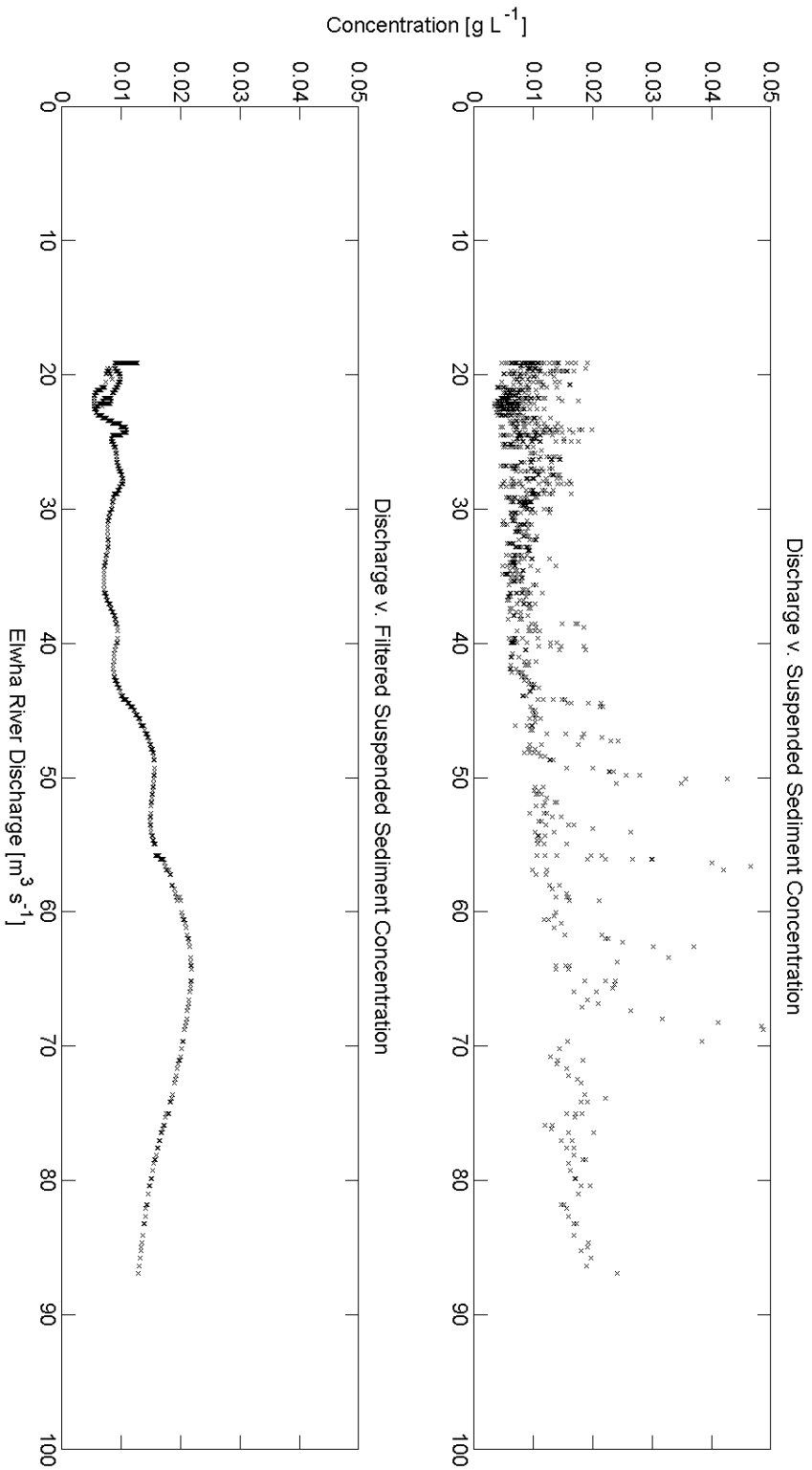


Figure 10A. The relationship between river discharge and SSC during Deployment A. The upper graph shows river discharge versus SSC with a linear relationship, while the lower graph shows river discharge versus low-pass filtered SSC, with a similar linear relationship.

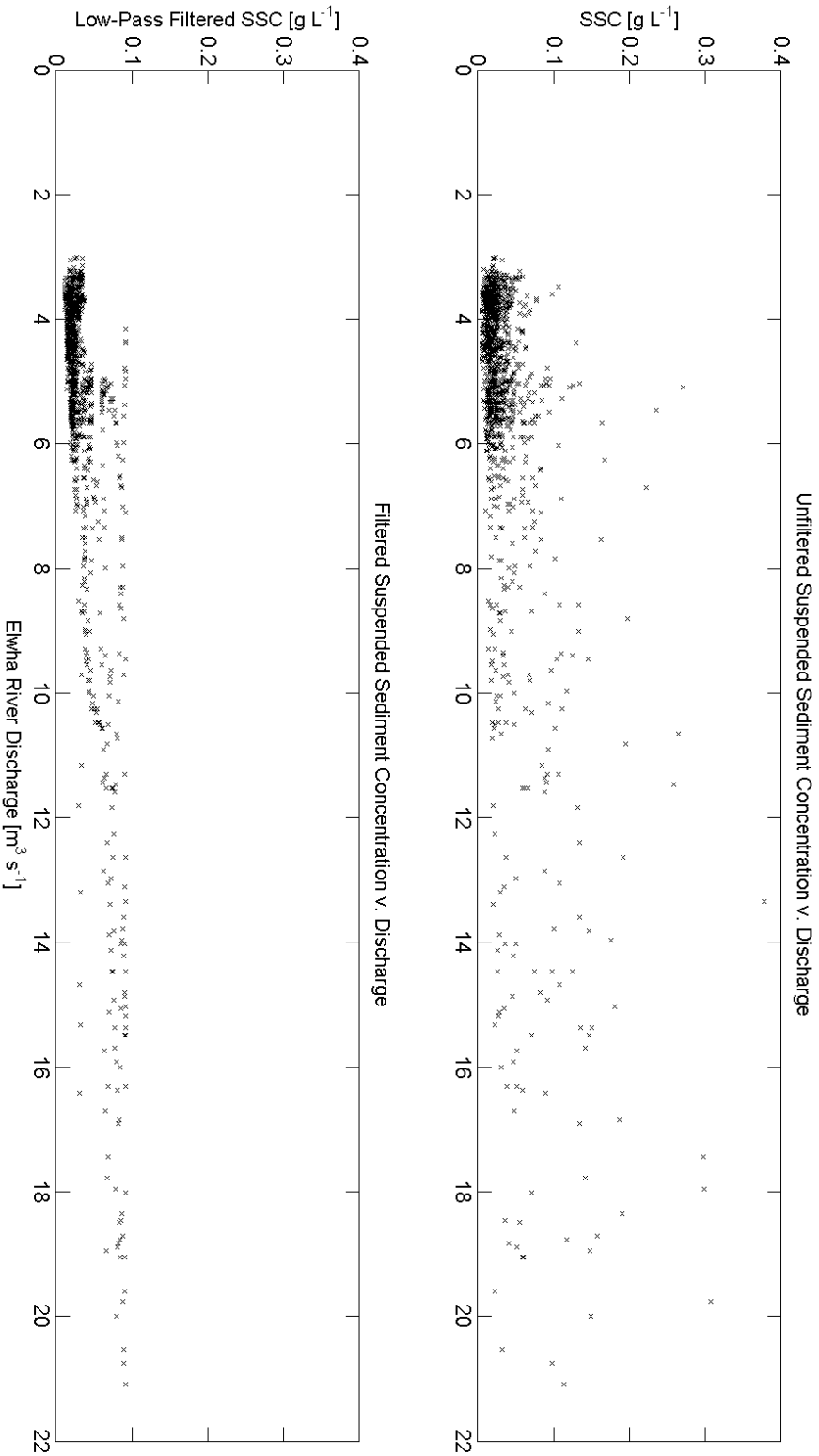


Figure 10B. The relationship between river discharge and SSC during Deployment B. The upper graph shows river discharge versus SSC with a subtle linear relationship, while the lower graph shows river discharge versus low-pass filtered SSC, with a similar linear relationship.

5.4 Implications

Nearshore circulation patterns are an important part of the Elwha Delta's ecological and littoral properties. Upwelling by definition advects sediment, nutrients, and other properties from lower in the water column to the surface. Currents within the entire water column act to transport sediment via advection and/or resuspension, which could have an important impact on ecology and coastal erosion (Warrick 2009). These relationships could be replicated in other parts of the world in order to examine nearshore processes. This investigation described important sediment transport processes at a study site and provides a basis for further studies into the movement of sediment in the Elwha Delta nearshore and marine environment.

Future studies could further explore the processes investigated by this project. Only the portion of the water column above approximately 3 m was investigated by this study, as that was the zone that the tripod-mounted ADCP could measure. The lower 3 m of the water column may contain a significant amount of suspended sediment, however, so excluding it from the study may have altered the results that were obtained. Resuspension is also more prevalent at the seafloor, so by excluding the lower 3 m it was possibly more difficult to see any sort of resuspension signal in the data. In addition, only one study site was used, which could have been subject to local forces that were not present elsewhere near the Elwha Delta. Furthermore, tidal elevation was used as a proxy for tidal flow, which was not always accurate. If one were to replicate this study in the future, then by taking more complete measurements of the water column, measuring at multiple study sites, and using a more accurate measure of tidal flow one could gain a

more complete understanding of the sediment transport mechanisms in the Elwha Delta nearshore environment.

6. Conclusion

Comparison of oceanographic conditions with ADCP data allowed for analysis of sediment transport mechanisms near the Elwha Delta. Currents at the study site were found to display a strong tidal signal that oscillated between periods of strong east by northeast flow during flood tides and periods of weak westward flow, weak eastward flow, or no flow during ebb tides. A weaker residual northeast flow was detected, which acts with the tidal currents to move the majority of suspended sediment at the study site northeastward along the shore. Advection was found to play a primary role in the supply of sediment to the study site. Resuspension was also found to be important, but it had more of a secondary effect. This means that most of the sediment in the water column at the study site arrived from another location, specifically the Elwha River, which shows that sediment is escaping from the river mouth and making it at least as far as the study site.

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