

Effects of Tides on Suspended Sediment Concentration in the Elwha River After Dam Removal.

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Abstract

River plumes are a form of sediment transport from the river to the sea. In the Elwha River, Washington, suspended sediment forms a river plume that is released into the Strait of Juan de Fuca. Here, we evaluate the suspended-sediment concentration in water-column profiles and sensor calibration to determine the location of the plume in the Strait. The results suggest that in general, suspended-sediment concentrations were higher on the west side of the delta than to the east side, and a bottom plume was observed in the east. Based on changes in salinity and tides, we suggest that tides control the movement of suspended sediment in the vicinity of the Elwha River mouth, and that low salinity and suspended-sediment concentration are correlated.

1. Introduction

Small mountainous river plays an important role in supplying sediment to the ocean. Sediment is transported to the ocean where it accumulates and transported to other regions (Nittrouer and Wright, 1994). The subaqueous delta is a region that is located below water and it controls the sediment deposited in the area such as the ocean (Drexler and Nittrouer, 2008).

According to Warrick (2011), river plumes are also a means of sediment transport in form of suspended-sediment in the low salinity water. River plumes are important to study, because they can affect river and marine ecosystem, parameters of water quality and processes in the ocean such as upwelling and stratification.

Hickey, 2010 made a study on river plume in a simple physical setting. This study, made exploration of river plumes possible without the complication of the landscapes surrounding it. Some geographical settings, make observations of river plume complicated, one of the example of this is the Elwha River, which is also a small mountainous river.

The objective of this paper is to observe the river plume from the Elwha River off of the Strait of Juan de Fuca and make comparisons between turbidity, tide, and surface salinity. Profiles of water columns will be used to analyze the river plume and to compare the suspended-sediment concentrations in and out of the plume.

2. Regional Settings

The Elwha River is a small mountainous river on Washington State's Olympic peninsula. The region was largely not impacted by human activity with 83% of the Elwha basin protected in Olympic national park except for upstream where two hydroelectric dams were (Phillips and Donaldson, 1972). The Elwha River drains to the Strait of Juan de Fuca, and is characterized by strong tidal currents and swells generated in the Pacific Ocean. The Elwha and Glines Canyon dam blocked fish passage and prevented majority of the sediment transport, trapping $19 \times 10^6 \text{ m}^3$ of sediment reservoirs behind the dams during their existence (Bountry et al, 2010).

The Strait of Juan de Fuca is known for its tall swells and high exchange of oceanic water from the Pacific Ocean. Tides in the Strait of Juan de Fuca are mixed semi-diurnal with a strong spring-neap variation. Currents on the delta are dominated by tidal forcing, with tidal harmonics accounting for 90% of the variance (Gelfenbaum, 2009).

The Strait of Juan de Fuca features mixing over shallow sills, which is an important mechanism. After entering the Strait of Juan de Fuca, sediment will be dispersed by waves and tidal currents and deposited on the beaches and seafloor of the delta (Warrick, 2011).



Figure 1. Map of Elwha River (Gelfenbaum, 2009)

3. Methods

3.1 Field Data

Sampling took place off the Elwha River in the Strait of Juan de Fuca, in two research cruises from April 10 to April 13, 2014. The majority of the survey was within 2 km off shore and along 3 transects in and near the Elwha River plume. The first transect occurred on April 10, at 5 PM, consisting of three stations. The second transect consisted of two stations. The remaining cast was made throughout on the April 13 consisting of 23 stations. The sampling was conducted by lowering a conductivity, temperature and depth (CTD) profiler throughout the water column to the depth of 10 to 20 meters. The second sampling that took place in the same region on May 12, 2014, with 8 stations profiled.

Near shore suspended-sediment concentration (SSC) was measured using an optical backscatter sensor (OBS) attached to the CTD. Surface salinity and pressure were measured using the CTD, and surface water samples were collected at the same time as the cast, to use in calibrating the OBS.

3.2 River Gauge and Marine Data

River turbidity data were obtained from the USGS river gauge on the Diversion near Port Angeles (USGS station 12046260; waterdata.usgs.gov). Water levels during the cruise were obtained and used to compare SSC with the tidal cycle on both April 11-13 and May 12 (NOAA Station 944090; tidesandcurrents.noaa.gov).

3.3 Data Analysis

Water samples from the plume were drawn through pre-weighted filters, and dried overnight at 50° C. These filters were re-weighed to determine the SSC from the samples, following a method similar to that of Davies, (2013). After weighing, the concentration was compared to the OBS voltage data from the CTD at a depth of 0.5 meters, the linear relationship between measured suspended-sediment concentration and OBS voltage is used to calibrate the instrument as described by Ogston et.al (2000).

4. Results

4.1 Salinity

Surface salinity in the Elwha Delta and Strait of Juan de Fuca varies not only from day-to-day but also by location. High salinity was observed in stations that showed no presence of the plume, while low salinity was present on the stations that have a plume. In Figure 2, the green points on the map show stations outside of the plume, while the brown points showed the presence of plume. During April 11- 13 Station M10, E2, and H2 showed surface salinity that range from 0 to 25 PSU (Fig. 3). M10 was located near the river mouth; E2 and H2 were located on the east side of the river mouth. All these stations showed increasing salinity at 15 m depth.

During the May 12 sampling, the salinity at the same stations stayed constant with the previous sampling dates with the addition of a station that is near the tripod location. Station tripod 1, tripod 2, F4, and M10 showed lower salinity values that range from 0-25

PSU while the rest of the station showed salinity values of 30-32 PSU from the surface to bottom, at 15-25 m depth (Fig. 4).

4.2 Suspended-Sediment Concentration

Calibrated OBS data from CTD demonstrates that the surface plume is present in certain stations April 11 to 13. Stations that show a surface plume were M10, M30, F2, F4, H2 and F15 (Fig. 5), while bottom plumes were observed on station F4, F2, H2, and A1. Bottom plumes in these stations were observed at 10 to 20 m depth. Station E10, E2, E5, M6 did not show the presence of a plume (Fig. 6).

During the May 12 sampling, surface plumes were generally higher and none of the stations showed the presence of bottom plumes. Stations showing a surface plume were Tripod 1, A01, Tripod 2, F4, M11, M10, M30, F2, and E8 (Fig. 7) and the stations that showed absence of surface plumes were E10, H2, A1, and M13 (Fig. 8). The deepest surface plume observed was Tripod 1 where it showed a surface plume up to 5 m and the rest of the stations showed surface plume up to 2 m depth.

4.3 River Discharge and Turbidity

Turbidity was relatively high on April 11 sampling with fluctuating values from April 11 to 13. On April 11-13 the high turbidity was 90 Nephelometric Turbidity Units (NTU) while the lowest was 45 NTU (Fig. 9). On May 12, the turbidity was 90 NTU, similar to April 11-13 sampling date, the value continued to get lower to 80 NTU and peaked the next day to 130 NTU.

From winter to spring, the river turbidity was 800 NTU at March 1 relative to the big flood event. River turbidity at that time was 1400 NTU, while the lowest turbidity was 0 NTU relative to wintertime in January (Fig. 10). Our sampling occurred during relatively low values of turbidity relative to winter discharge.

4.4 Strait of Juan de Fuca Tides

During April 11-13 sampling, the lowest tides during the day was 0.8 meters relative to Mean Lower Low Water (MLLW) and the highest tide was 1.8 meters relative to MLLW (Fig. 11). During this sampling time, the tides fit into a mixed semidiurnal cycle and during each sampling day the category of the tides falls into ebb and flood.

On May 12 sampling, the highest tide showed a value of 1.59 m relative to MLLW, while the lowest value is 0.14 relative to MLLW. All these tides fit into a mixed semidiurnal tide cycle and during sampling it was categorized as ebb and flood tide (Fig. 12).

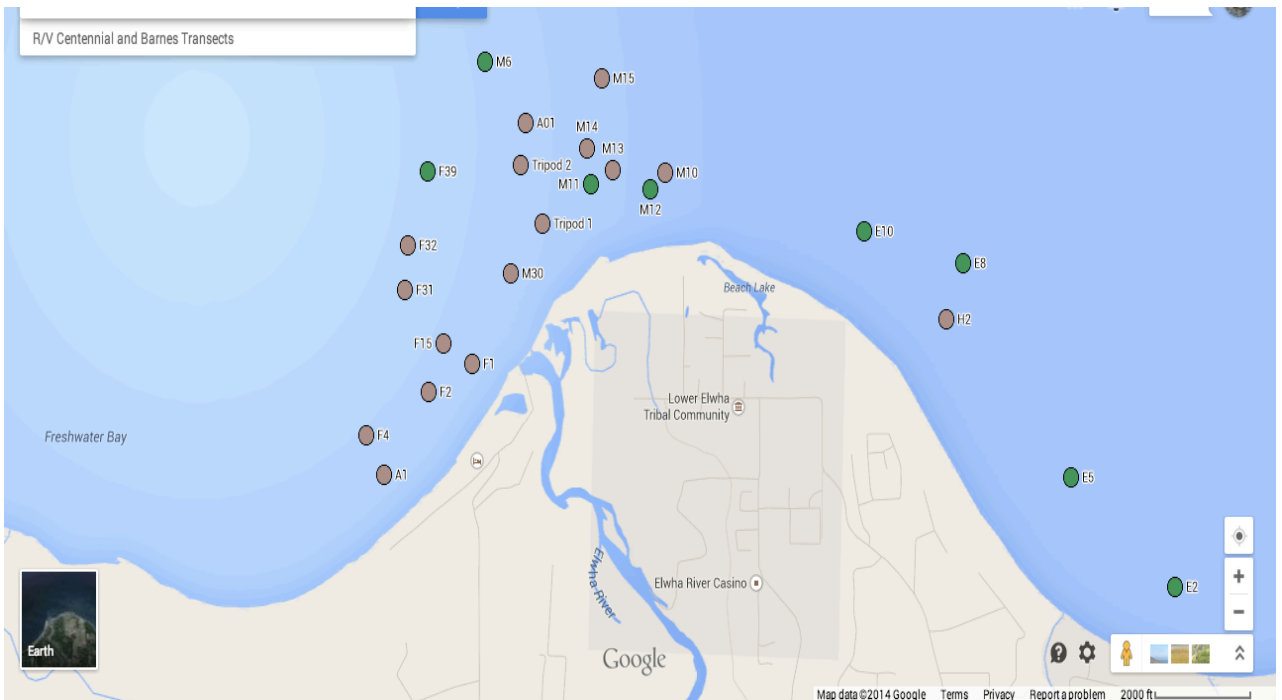


Figure 2. Transect map showing positions of the river plume. Note that the west part is where Freshwater Bay is located and the east side is Ediz Hook (Not shown on map)

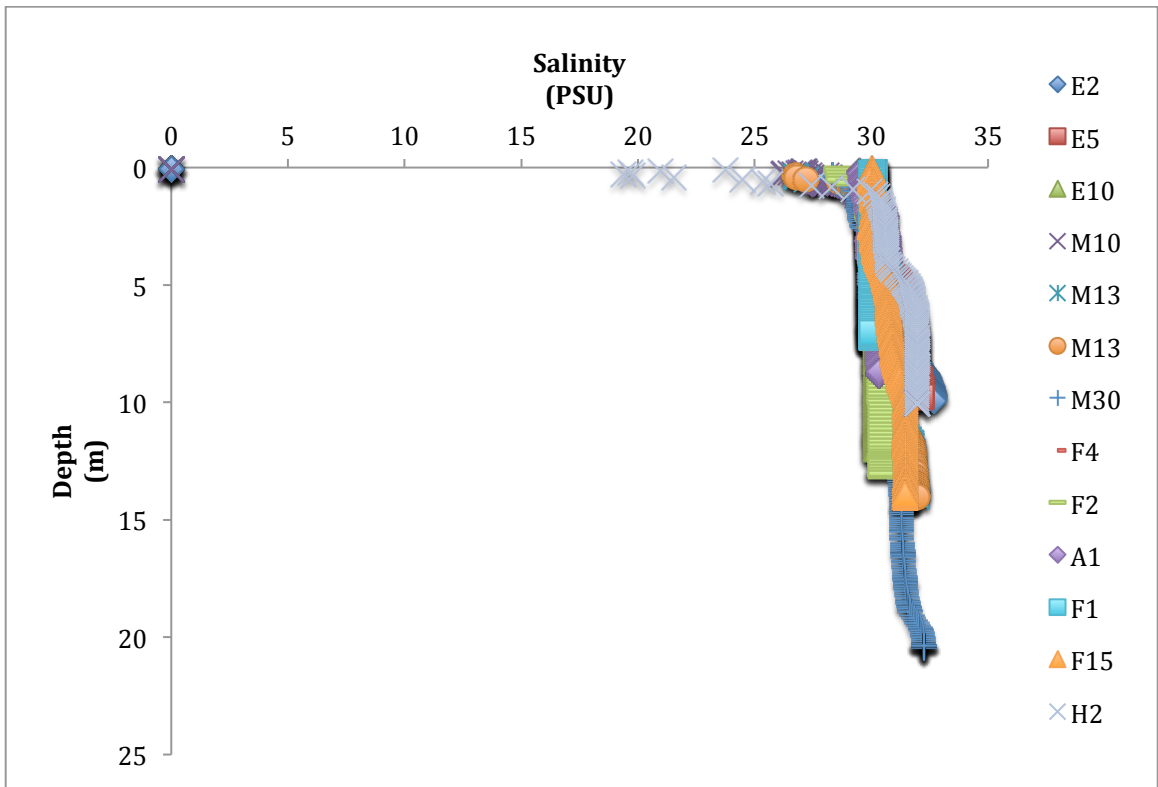


Figure 3. Salinity versus depth from April 11-13 2014 sampling

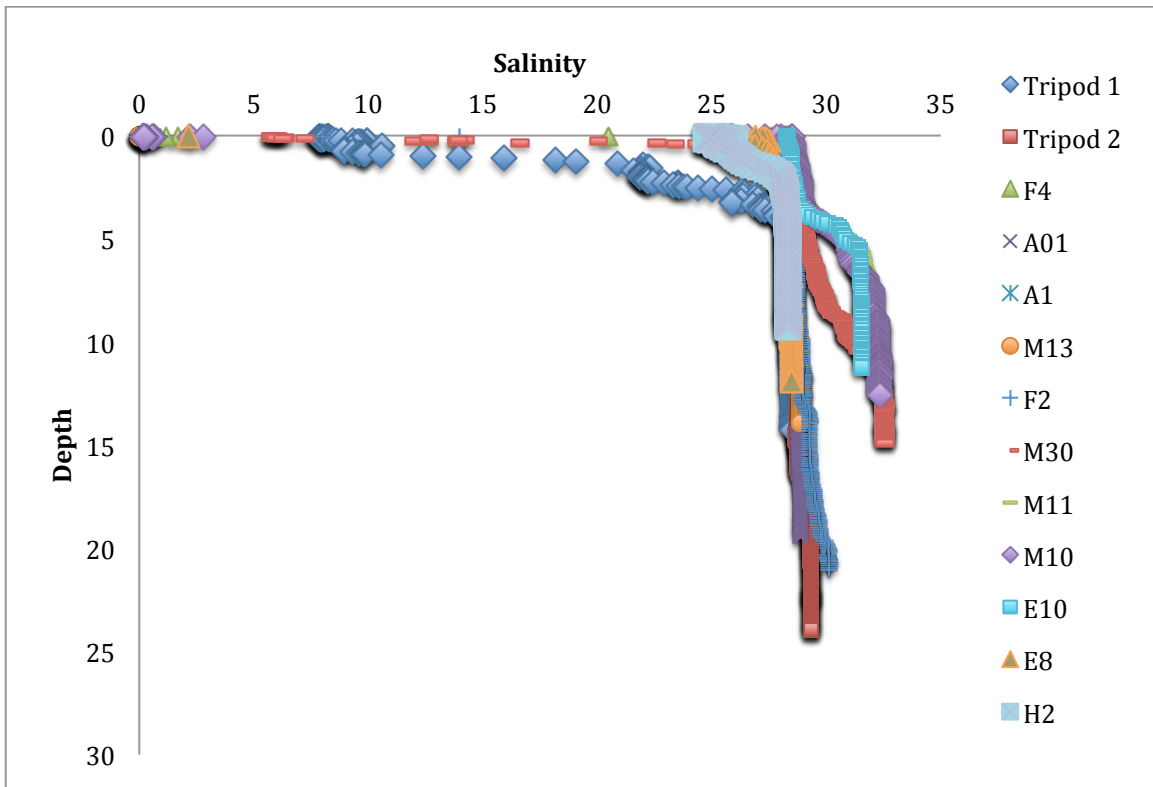


Figure 4. Salinity versus depth on May 12 2014 sampling

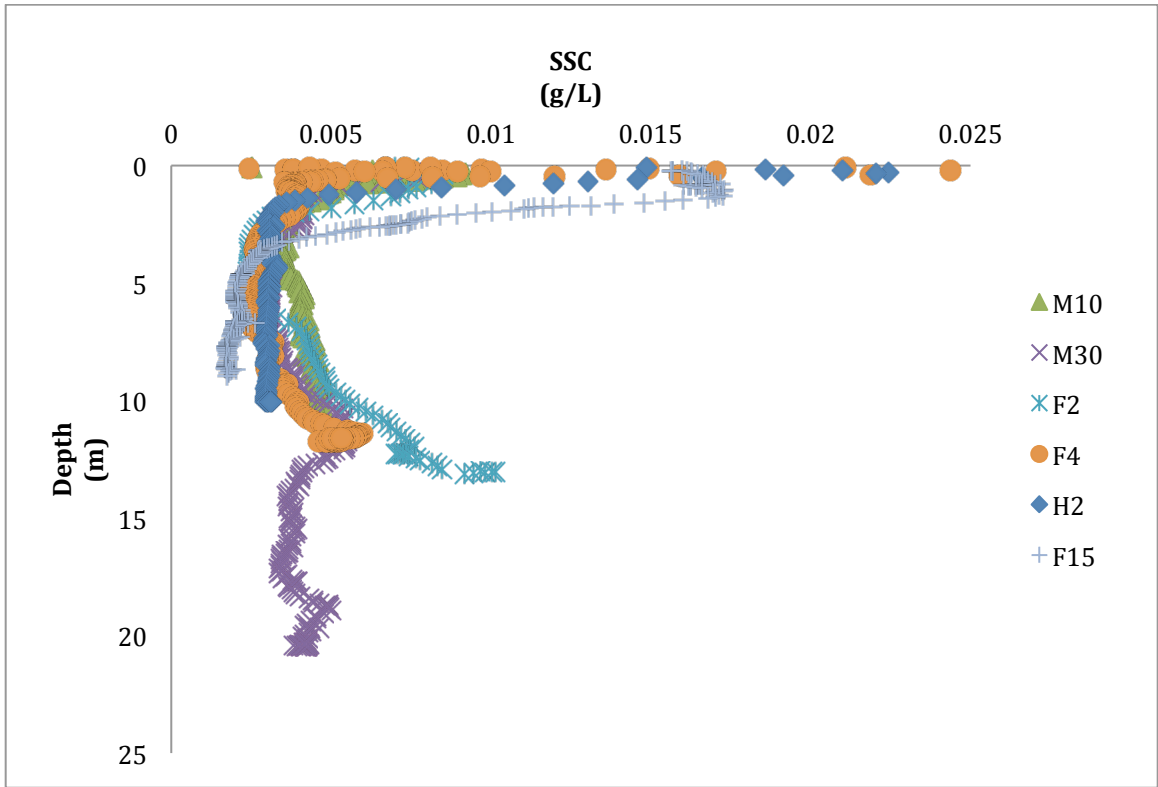


Figure 5. Surface plume observation during April 11-13

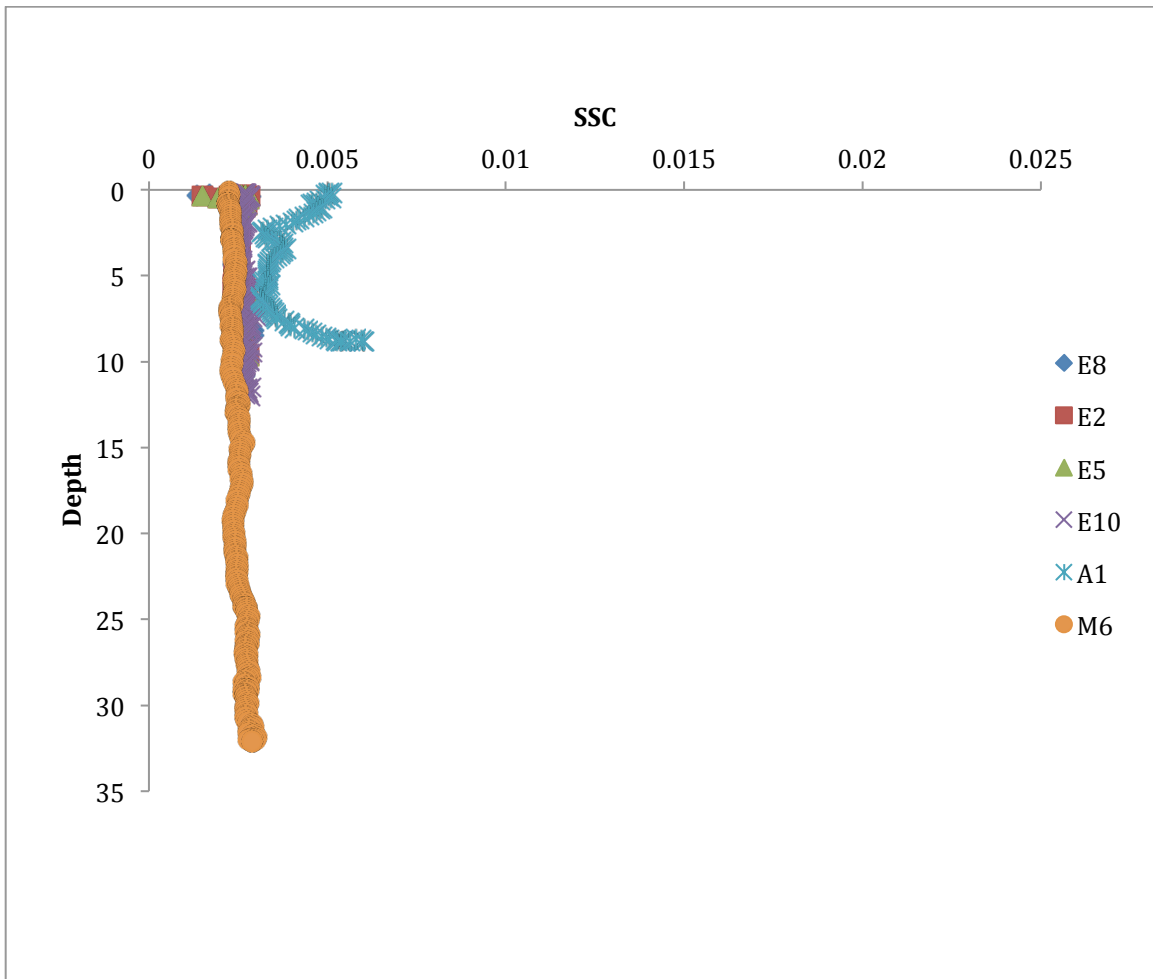


Figure 6. Stations with the absence of surface plume during April 11-13 sampling. Note that A1 showed no signs of a surface plume and showed a presence of a bottom plume instead

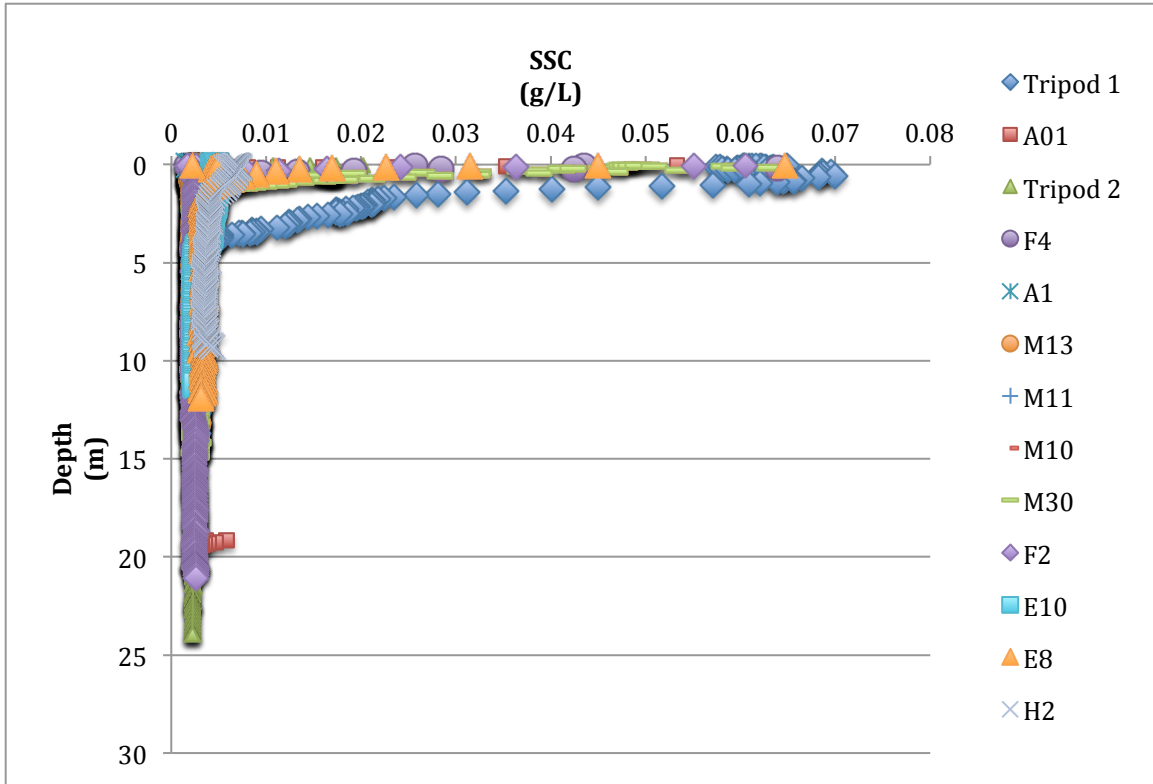


Figure 7. Stations with the presence of plume, during May 12 2014 cruise.

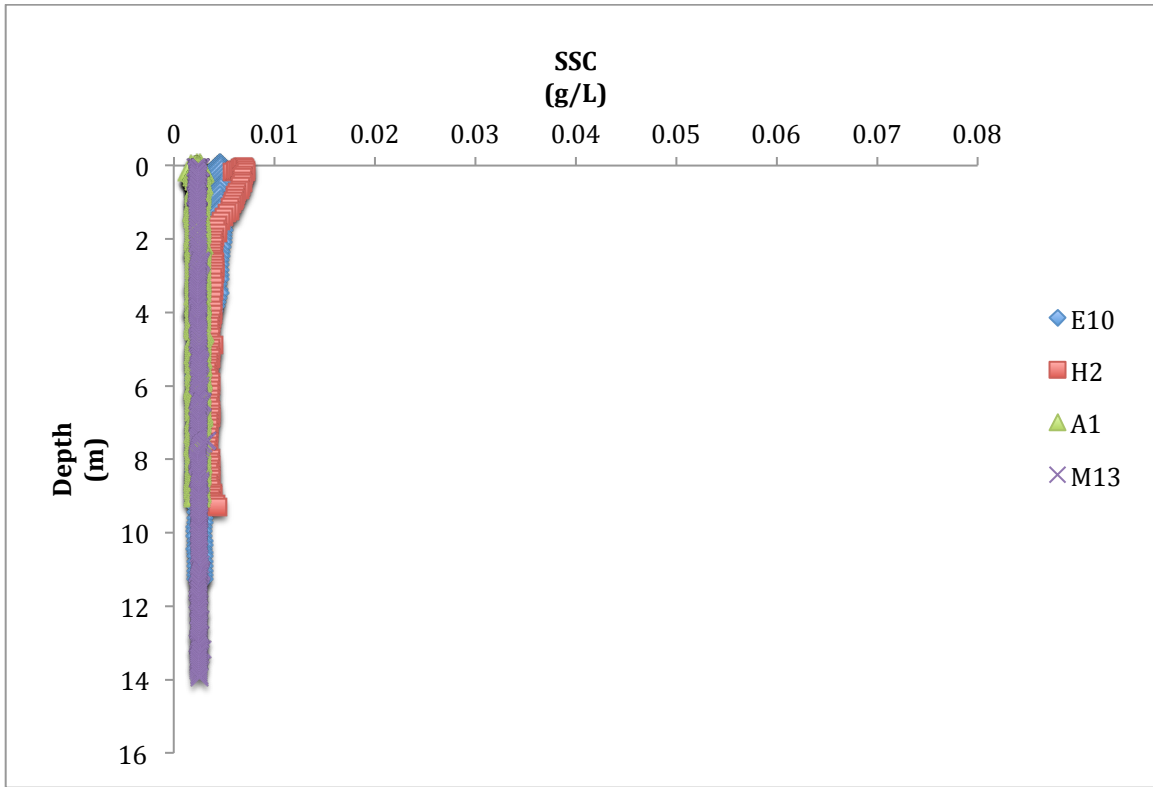


Figure 8. Station with the absence of surface plumes during May 12

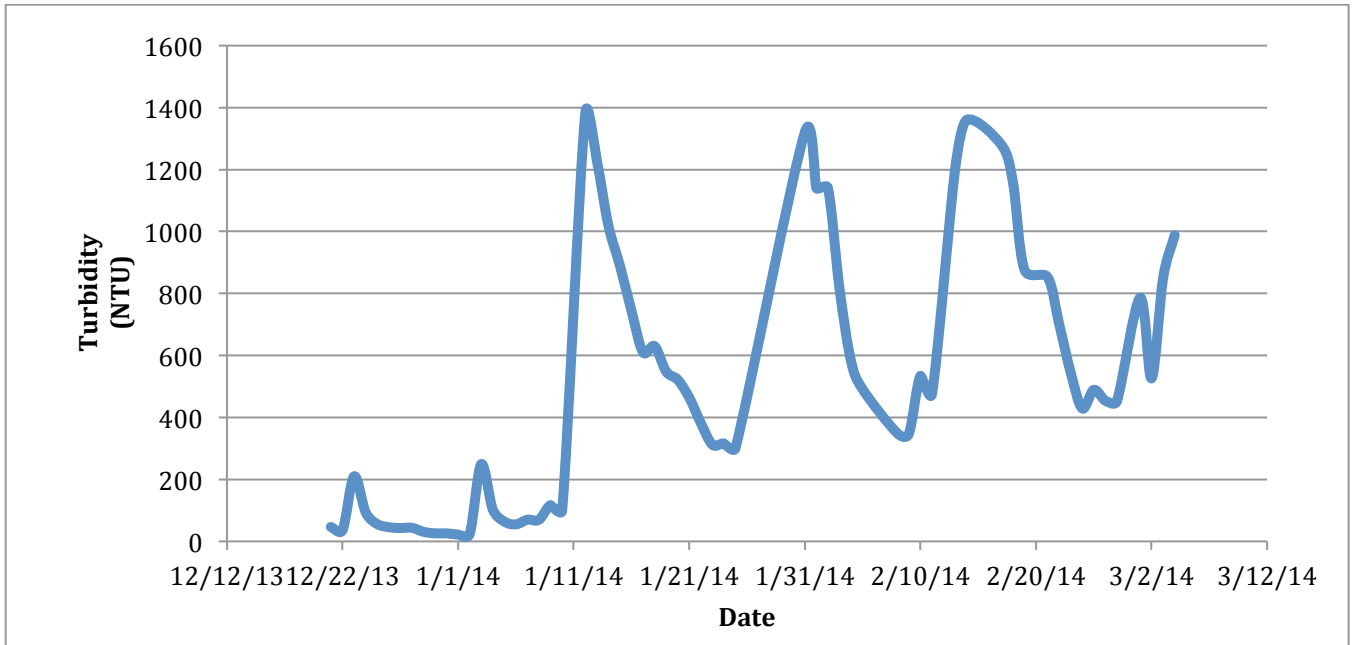


Figure 9. Turbidity time series from December to March before sampling

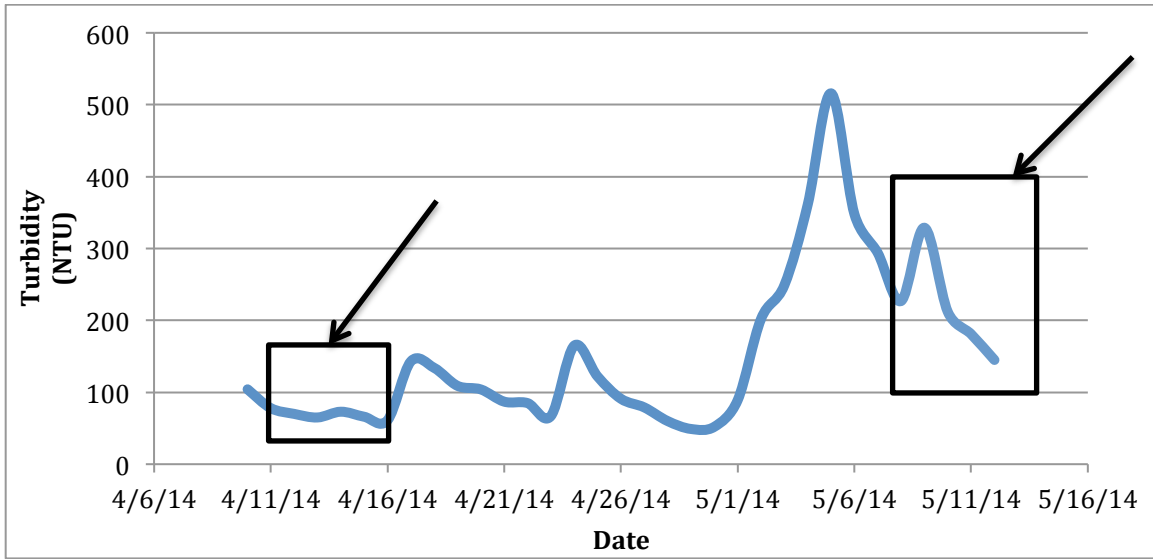


Figure 10. Turbidity from April to May. Note that the arrow shows the sampling dates from the Elwha River USGS gaging station 12046260

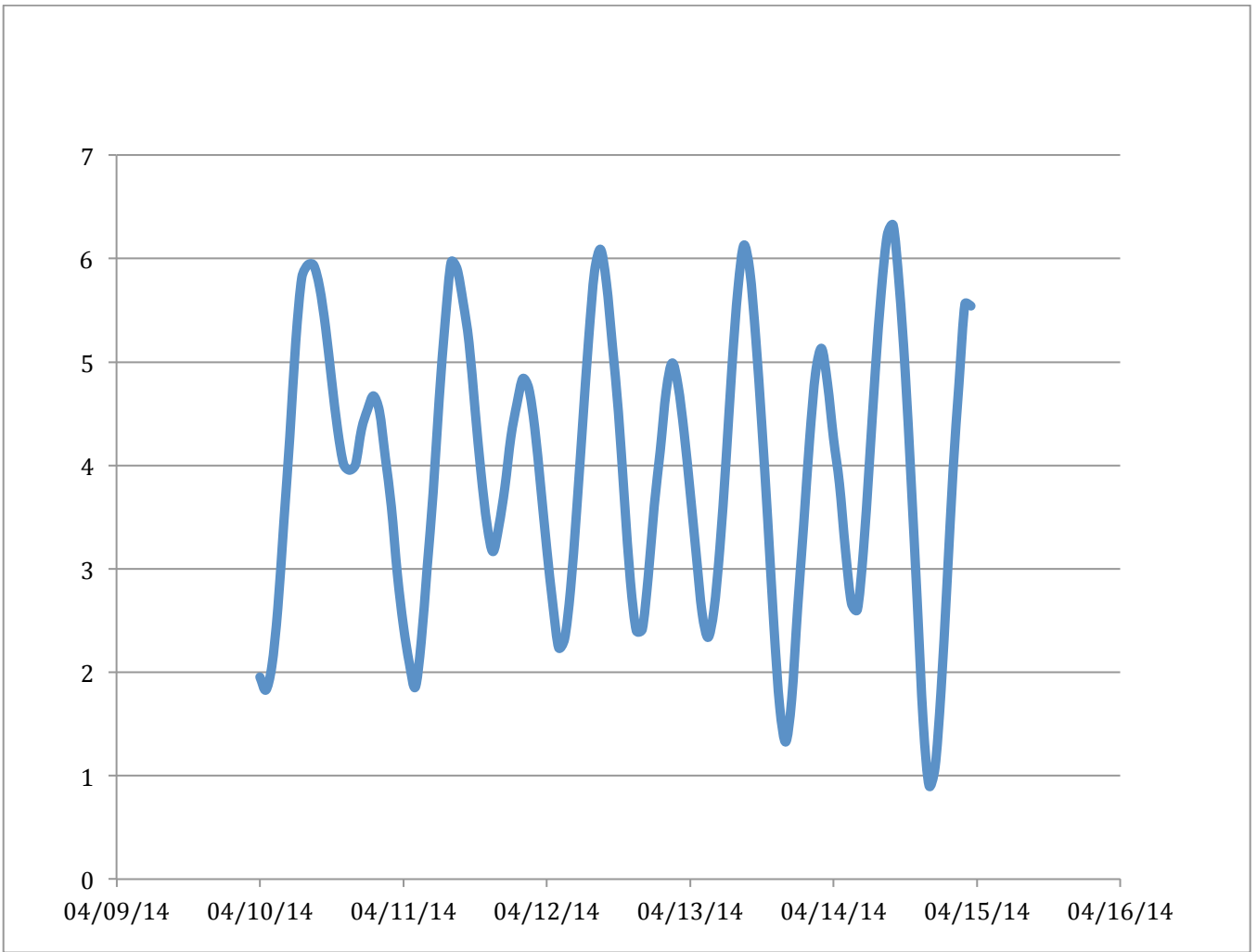


Figure 11. Tide during April sampling

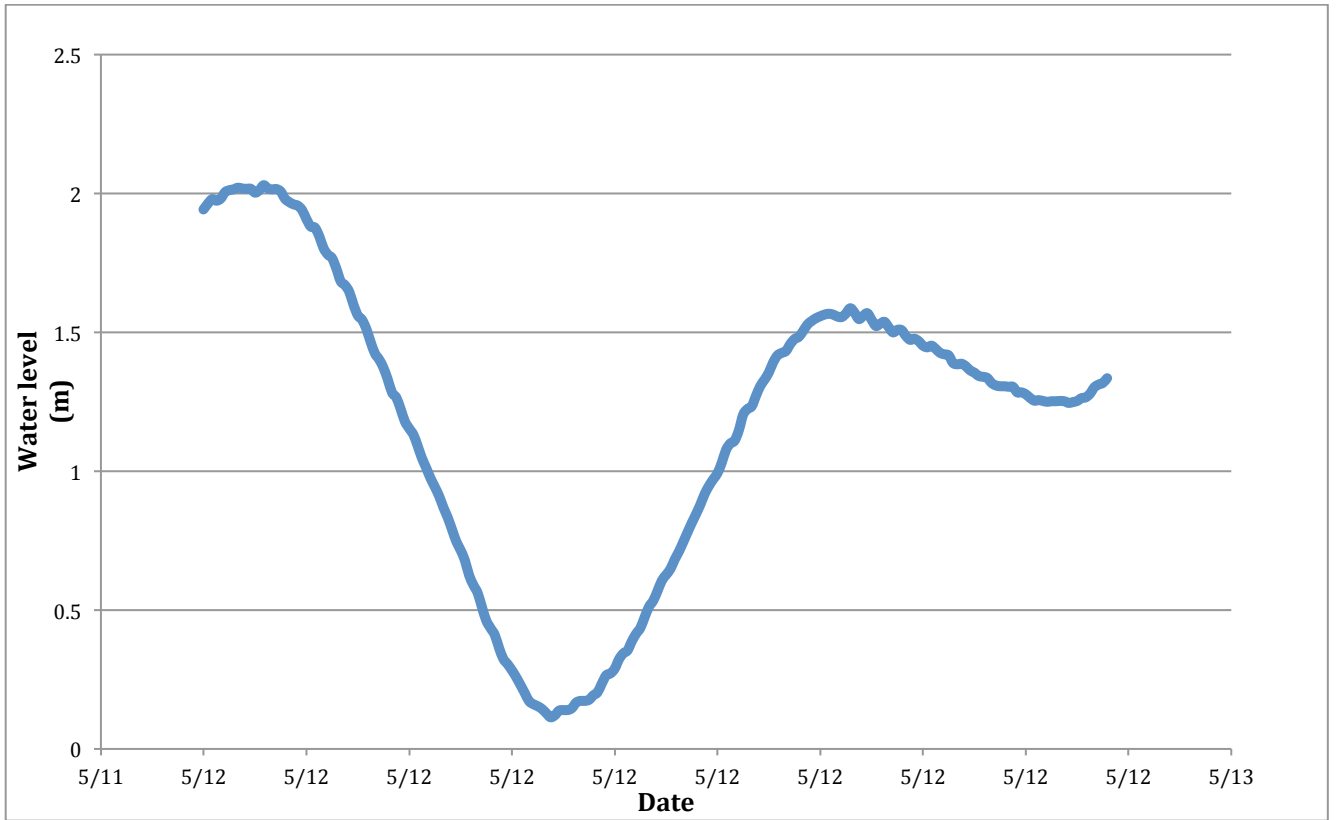


Figure 12. May 12 2014 Tides

5. Discussion

5.1. Effects of tides vs. river plumes and salinity

Warrick et. al (2011) hypothesized that Elwha River forms a buoyant plume that originated on the western side of the delta. River plumes varied in space and time during April and May sampling. River plume is defined by high suspended-sediment concentration and low salinity. Stations that were located on the west side of the delta during the April sampling tended to show more surface plumes, while the station located on the east side of the delta showed bottom plume in 10 m depth. Stations that did not show a plume such as E8, E6, E2, E5, E10, M6, and A1 have a minimum salinity of 29-32 PSU. Most of the stations were collected during ebb tides and once the tide started to flood in, the plume advected to the east (Fig. 13), resulting in a lower salinity value of 25-30 PSU.

During the May 12 cruise, the majority of stations were located off the Elwha River where the plume flowed directly into the strait, although most of the suspended-sediment that was observed, was located on the west side of the delta which is the Freshwater Bay (Fig. 14). The majority of the stations showed surface salinity from 0-25 PSU. During that time, the tidal phase was a flood tide. Stations that originally had a plume in the April sampling showed a dispersal of plume illustrating the tidal cycle impact on the location of the plume.

Warrick (2011) created a model of behavior of Elwha River plume during flood and ebb tides. They observed that the tides were initially flood tide in the west but it started to be advected to the east. Also based on that model, 50% of the time the plume was on the east while only 10% of the time the plume was on the west. Based on this

model, majority of the plume was in the west during both April and May sampling but it is speculated that will eventually advect to the east.

The effect of tides on the location of the river plume in the strait varies, and its movement in the water is affected by the changing tide and it also indicate a strong mixing in the strait in comparison to Warrick (2011).

5.2 Salinity vs SSC

In order to predict whether or not the plume is present, salinity versus SSC on both dates of sampling were made. On the April sampling, Salinity versus SSC showed a correlation of high SSC and low salinity. However, it was observed some values of high SSC and high salinity and this may be caused by the old plume getting re-suspended and presence of bottom plumes (Figure 15). On May, the same correlation was found and some values of high salinity and high suspended sediment concentration were also found, which means that there was a little bit of bottom plume when compared to the vertical profile of SSC (Figure 16).

This implies that the plume from the dam removal had started to shift. On the stations where no plume was observed but has a low salinity, it shows that some of the freshwater from the Elwha River was in the Strait and it caused stratification. During the April sampling, based on observation there was plenty of waves from the shoreline. Therefore it explains the presence of a bottom plume on April, while in May there were no waves observed at all. This implication was that the river plume was getting re-suspended and the source of the river plume was from Elwha River. However, sometimes in the April sampling we see low salinity water from the river, but with no

suspended-sediment. What might have happened was either it was low sediment suspended in the river or the sediment settled out of the low salinity water. Because the dam removal is going on, there must be sediment in the river. Therefore, in the case when low salinity and high SSC was observed, the sediment must be settling out of the surface waters. It is also speculated that winter months and flood events from prior to sampling affects the values of SSC in the river plume, and the reason that SSC was observed but still remains in the same area during sampling is due to the weather and external conditions.

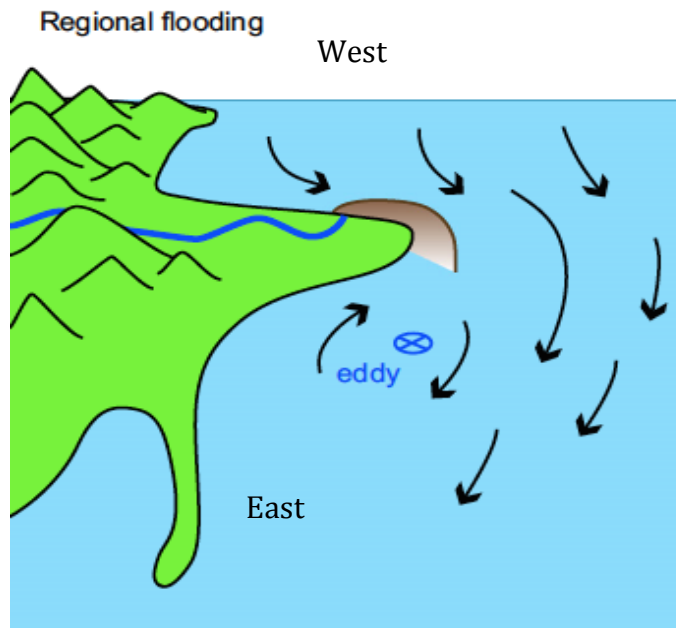


Figure 13. Flood tides on the Strait (Warrick, 2011)

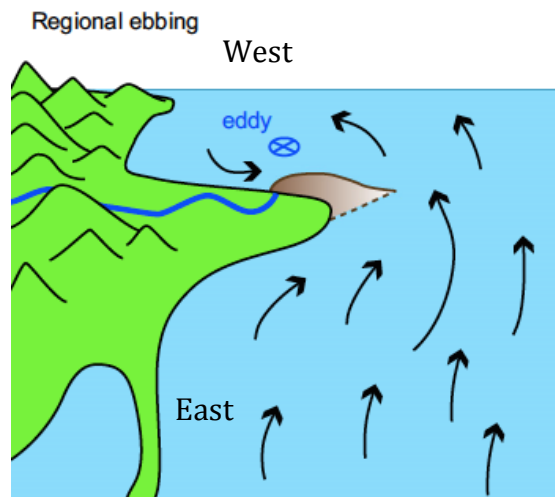
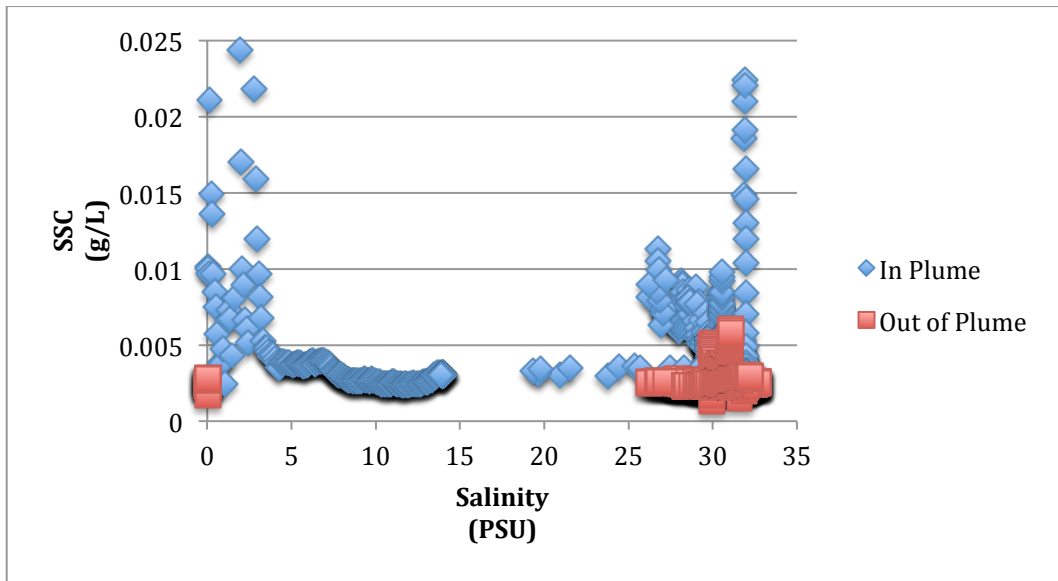


Figure 14. Ebbing tide models in the Strait (Warrick, 2011)



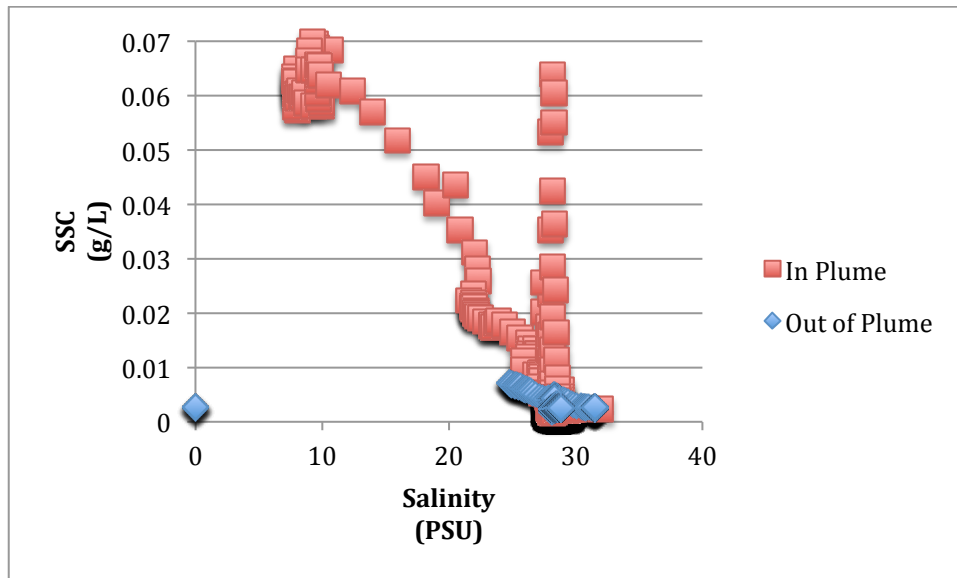


Figure 16. Minimum salinity versus maximum SSC for May sampling

6. Conclusion

In this work, CTD data were used to observe salinity and suspended sediment concentrations, and compared them to see where the plume location. A previous study has indicated that river plumes are moved by tides. Our research demonstrates that:

1. Turbid river plumes are present during flood tides on both April and May sampling. A bottom plume was also observed on the April sampling in stations that were located in the East side of the delta and the Strait.
2. Low salinity indicates the presence of a turbid river plume. However, it is not always the case and in places where salinity was low but no suspended sediment were present in the plume, it might be a stratification process, that maintains low surface salinities and a settling process that removes the suspended sediment.

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