Preliminary impacts of the Elwha Dam removal project to primary productivity

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Abstract

Dam removal on the Elwha River has increased sediment concentrations in the buoyant river plume emptying into the Strait of Juan de Fuca. Such increased turbidity can decrease light available for primary production in the water column and may negatively impact primary production, which could have bottom-up effects on the entire food chain. To investigate the effects of turbidity, sediment profiles, light profiles, and chlorophyll-a profiles from the delta were analyzed for both in-plume and out-of-plume stations. Differences in sediment concentration and light attenuation occurred between stations within and without of the plume, and trends suggest that mixing in the water column may enhance primary production within the plume.

1. Introduction

Light availability and processes affecting it play an important role in primary production in an estuary. The Elwha River dam removal has resulted in a high concentration sediment plume dispersing from the river mouth. This sediment may result in turbid marine waters (Warrick & Stevens, 2011), which can have consequences for primary productivity. On the Amazon River delta, processes increasing sediment concentration in the water column appear to have a strong impact on light attenuation, which reduces primary productivity (Smith & Demaster, 1996). As primary production may have strong bottom-up effects on a food chain to be felt at the level of secondary consumers such as juvenile fish, understanding the impact of dam removal on phytoplankton could service this and other restoration undertakings. This study evaluates the impact of sediment concentration on light attenuation, and correlates this impact to levels of chlorophyll-a found within and outside of the freshwater plume on the Elwha Delta.

2. Background Section

2.1. Regional setting

The Elwha River on the Olympic Peninsula flows from the Olympic Mountains into the Strait of Juan de Fuca, forming a delta (Fig. 1). The Elwha and the Glines Canyon dams, constructed on the Elwha River in 1913 and 1926 respectively, had a combined sediment trap efficiency of about 0.93, according to the difference in above-dam and below-dam water sediment concentrations from 2006-2007 (Curran et al, 2009). This limited sediment deposition to the Strait to only a few thousand cubic meters per year, resulting in a coarser delta substrate and altering ecological processes (Warrick et al., 2008). Moreover, the trapped sediment resulted in the gradual creation of sediment-filled lakes behind the dams (Lakes Aldwell and Mills), which collectively retained about 34 million m^3 of sediment.

In the spring of 2012, the Elwha Dam was fully deconstructed, and as of May 2013 all but 10 m of the Glines Canyon Dam had been removed. Dam deconstruction has released a combined 6.8 million m^3 of sediment from the former lakes, increasing downstream turbidity and sediment deposition to the marine environment (Schwartz, 2013). The plume is dynamic, moving east with the flood tide and retreating west during ebb tide, and is subject to vigorous mixing along the plume’s front and basal edges (Warrick & Stevens, 2011). Therefore, plume turbidity, settling rates of sediment, and regions of decreased light penetration may vary with weather conditions and exhibit a dynamic impact on primary productivity in the plume.

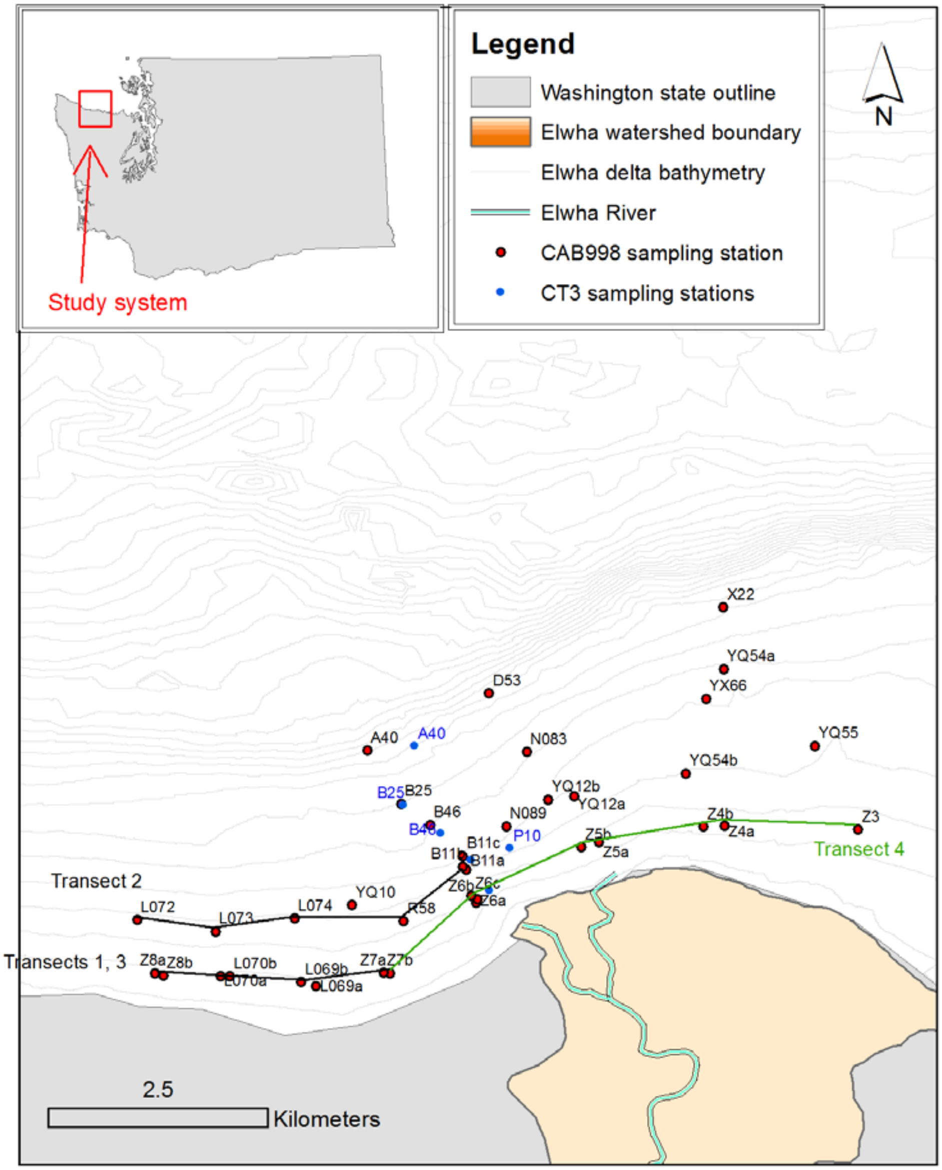

Figure 1. Map of the Ewha River Delta where data collection took place. Orange points were collected on the 13-15 April, 2013, and include PAR and OBS profiles. Four transects (13 stations) were analyzed. Blue points were collected on the 28 April, 2013, and include PAR and Fluorometer profiles.

2.2 Topical Background

In the Strait of Juan de Fuca, the phototrophic zone is nutrient rich and often extends deep into the vertical water column (up to 20 meters). However, primary production by phytoplankton (photosynthesizing diatoms, dinoflagellates, and micro-algae) is low due to lack of mixing in the vertical water column (Masson et al., 2009). In the nearby Strait of Georgia where the Fraser River exits into the marine environment, mixing of the vertical water column appears to boost phytoplankton productivity. Similarly, one would expect the Elwha River discharge to increase primary productivity relative to the Strait of Juan de Fuca.

Prior to dam removal, chlorophyll-a, a proxy for primary production, was examined at eight sites along the Elwha River delta, with ranges falling between 0.74 and 1.7 mg m^{-3} (Chen, 2008). The highest concentration of sediment at the river mouth was measured at 0.03 g L^{-1} (Emily Eidam, personal communication). Since the dam removal, however, the Elwha River plume has contained a greater concentration of suspended sediment (Warrick et al, 2011), which may increase turbidity and light attenuation in the water column, potentially impacting primary productivity. Previous studies on the effects of increased sediment load to a small delta following dam removal in Wisconsin found decreased species richness of phytoplankton initially, but overall little impact to the phytoplankton productivity (Thomson et al, 2005).

3. Methods

3.1 Data collection and water sampling

Data collection occurred from the 13-14 Apr, 2013 on the *R/V Clifford A. Barnes* (cruise CAB998), and again on the 28 Apr, 2013 onboard the *R/V Centennial* (cruise CT3). Sampling occurred at various stations on the Elwha delta (Fig. 1), both within and outside of the freshwater plume. Fluorometer and additional PAR profiles were collected from 4 stations during cruise CT3.

The freshwater plume is visible from a boat on the water's surface. It appears murky brown and cloudy due to suspended sediment discharged from the river, and there is a distinct boundary between the clear waters from the Strait of Juan de Fuca and the sediment-laden waters of the Elwha River. At all stations, the water's surface was visually inspected and was recorded as being inside of the freshwater plume where cloudy.

PAR and OBS water column profiles were collected from 26 stations during cruise CAB998 and data from 4 alongshore transects (13 stations total) was analyzed. Turbidity was measured throughout the water column by an optical backscatter sensor (OBS) attached to a CTD (conductivity, temperature, depth), which was lowered into the water column until it touched bottom, then retrieved. PAR profiles were obtained with a LiCor Light Meter. Ambient light was measured approximately 0.5 m above the water's surface, and within the water column at 1 m, 2 m, 5 m, and where depth allowed, 10 m depths. Water samples were collected in conjunction with OBS profiles. A Niskin water sampler was used to retrieve water from within one meter of the water's surface. Samples were stored in plastic sample bottles in a fridge or cooler until processing.

PAR and Fluorometer profiles were collected from six stations during cruise CT3. A WetLabs EcoStar fluorometer attached to a Seabird CTD was lowered through the water column until it touched bottom, then retrieved. Method of PAR profile collection remained unchanged.

3.2 Data processing

PAR readings, obtained in units of W m^{-2}, were transformed into the light attenuation coefficient profiles for each station using the Beer-Lambert equation,

$$I_z = I_o * e^{(Kd*z)}$$

Where I_z is W m^{-2} at depth z, I_o is ambient light at the water's surface, and K_d is the light attenuation coefficient (Dennison et al, 1993). K_d was calculated for each depth of 1 m, 2 m, 5 m, and where possible, 10 m depths from the ambient sunlight.

OBS readings were transformed into sediment concentration profiles after being calibrated with sediment concentrations from the water samples. Niskin water samples were filtered gravimetrically using dried and pre-weighed Millipore 0.42 µm filters. Finished filters were dried overnight at ~60°, dessicated for two hours, and then weighed for final sediment dry weight. This procedure provided sediment concentrations in g L^{-1} in the top 0.5 m of the water surface. Corresponding OBS readings in volts were plotted against sediment concentrations to obtain the equation,

$$y = 0.4661x + 0.0033$$

Where y is sediment concentration in g L^{-1} and x is volts. This equation was applied to OBS profiles and plotted against depth below water surface (in meters) to obtain sediment concentration profiles.

Fluorometer readings were recorded by the instrument in chlorophyll-a concentrations of mg m^{-3}. These readings were plotted against depth below water surface to obtain chl-a concentration profiles for each station. Six stations were initially sampled, but inadequate instrument calibration time at two of the stations resulted in inaccurate chl-a readings. Thus, these two stations were omitted from data analysis.

4. Results

4.1 USGS hydrographic data

All water column profiles for this study were collected in the month of April, 2013. Data on the 13-15 April were collected around MLLW, with tide ebbing about 0.3m and flooding about 0.6m during data collection (WA 9444090, tidesandcurrents.noaa.gov), (Fig. 2). River discharge remained at about 57 m^3 s^{-1} for all three days. Turbidity in FBUs was measured between 400-550 FBUs from 13 Apr to about noon 14 Apr, after which turbidity measures dropped to between 250 and 400 FBUs (USGS 12045500, waterdata.usgs.gov).

On 28 April, 2013, data was collected during low tide, which was -0.6m below the average MLLW. Discharge from McDonald Bridge was about 40 m^3 s^{-1} but dropped steadily to 34 m^3 s^{-1} by the end of the collection period. Turbidity was between 200 and 300 FBUs.

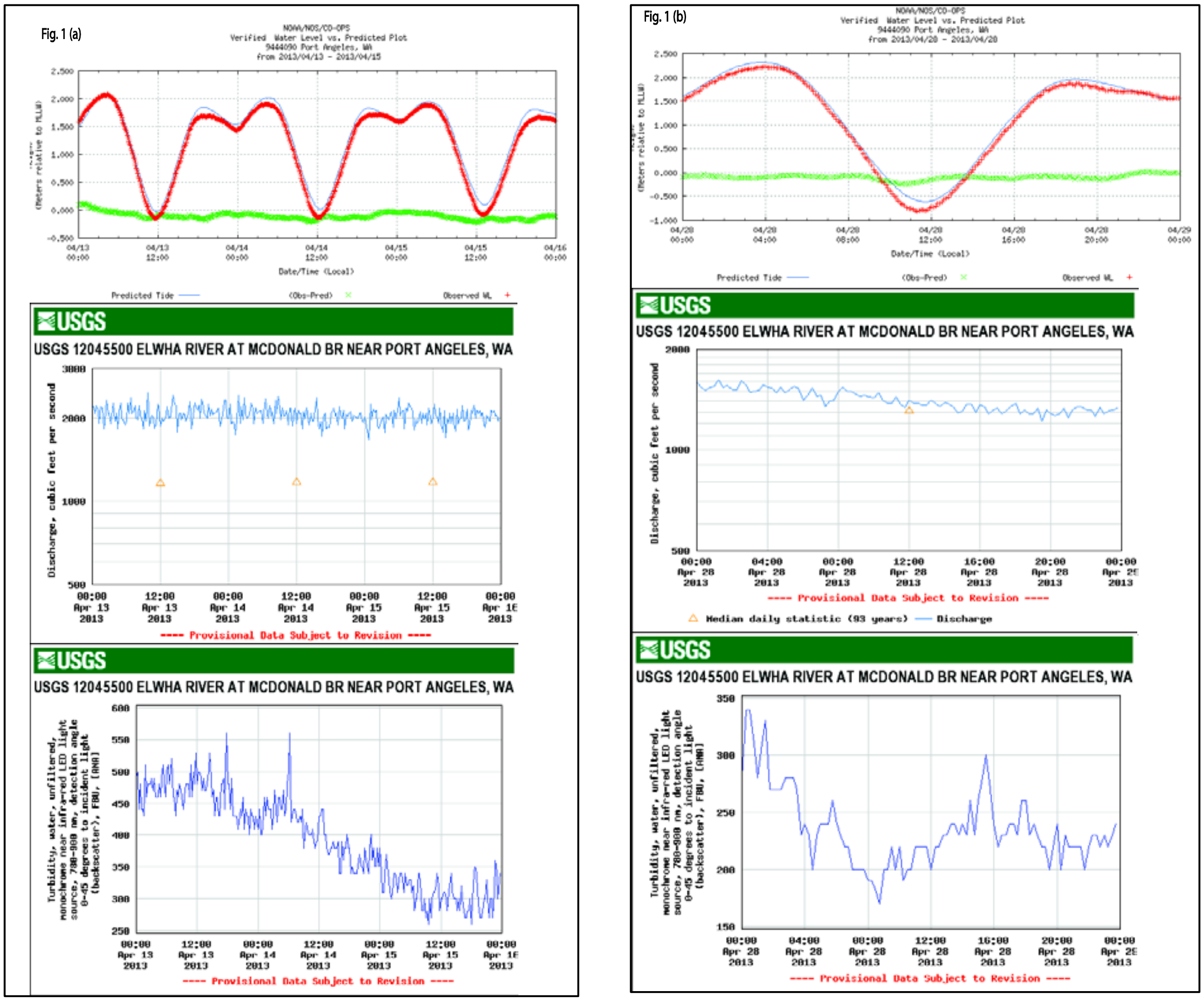

Figure 2. Tidal range (WA 9444090, noaa.tidesandcurrents.gov), river discharge and turbidity (USGS 12045500, usgs.waterdata.gov) from the Elwha River, for the 13-15 Apr, 2013 (a), and for 28 Apr, 2013 (b).

4.2 Satellite data

Satellite data of chlorophyll-a production in the Strait of Juan de Fuca was obtained from Giovanni Ocean Color Radiometry 8-Day Data for dates 22-20 Apr, 2008, and 22-30 Apr, 2013 (Fig. 3), (disc.sci.gsfc.nasa.gov/giovanni/). For 2008, when chlorophyll-a concentrations were measured in a previous study, satellite data confirms that the highest levels near the Elwha River mouth were between 2.5 and 10 mg m^{-3}. In 2013, satellite data shows an average concentration of 10-30 mg m^{-3} chlorophyll-a.

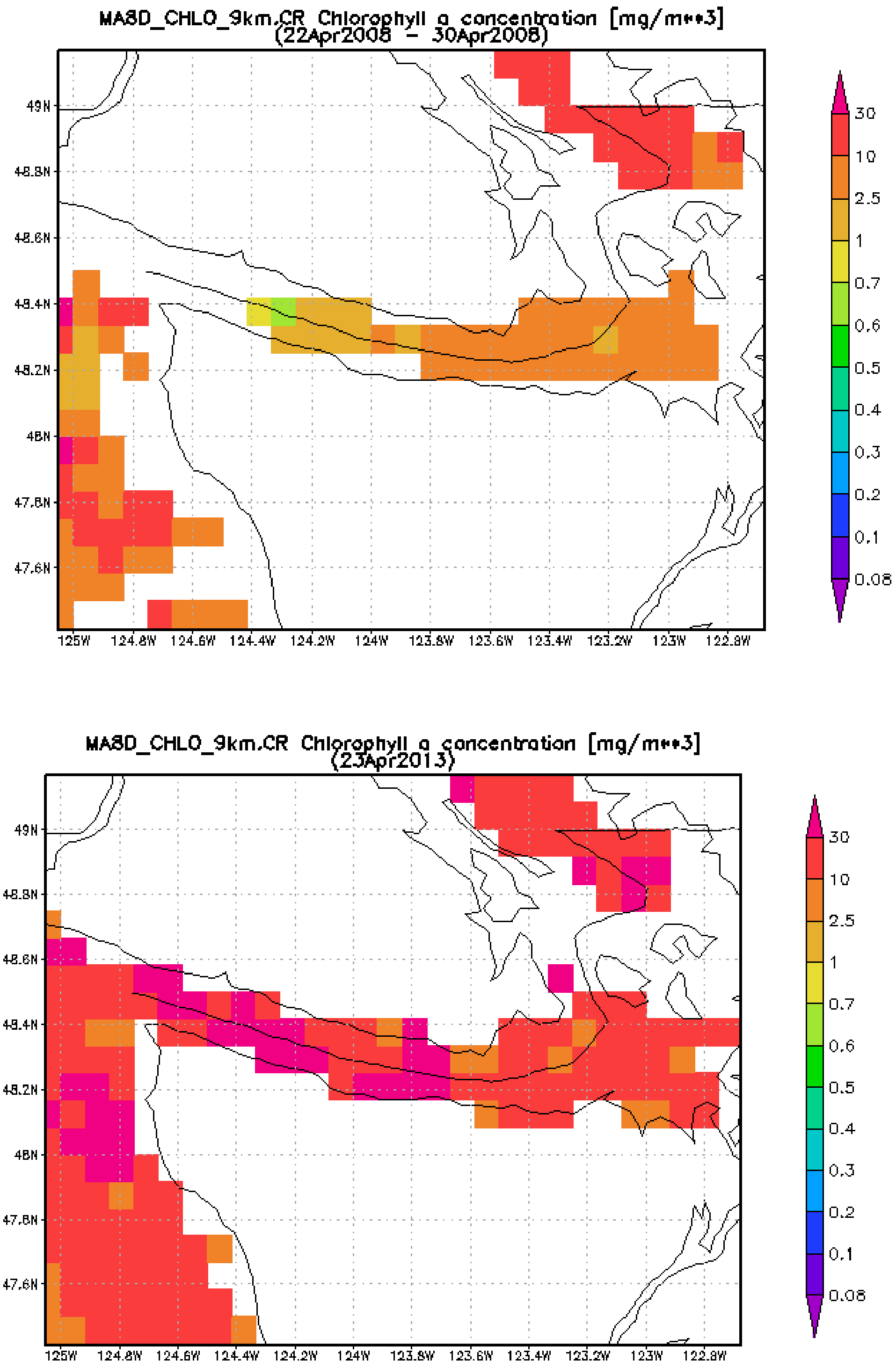

Figure 3. Satellite images from Giovanni showing 8-day averaged chlorophyll-a concentrations in the Strait of Juan de Fuca, 2008 & 2013. The Elwha Delta is found at about 48.15N, 123.5W.

4.3 Water column profiles

4.3.1 Sediment profiles

Sediment concentration profiles (SSC, in g L^{-1}) were graphed for alongshore Transects 1-4, with transects 1 and 2 being collected on 13 Apr, 2013 and transects 3 and 4 being collected on 14 Apr, 2013 (Figs. 4-7). Values ranged from 0.01 to 0.3 g L^{-1}.

Sediment concentrations were compared for stations located within and outside of the freshwater plume. Within, concentrations were elevated in the top 2-4 m of the water column for some stations (B11a & R58a in Transect 2, and Z6b in Transect 4), but this trend was not consistent across all stations inside the plume. Many stations that appeared to be inside the plume during data collection showed concentrations of sediment similar to stations outside of the plume (i.e. Z7b & L069b in Transect 3, and Z5a & Z4a in Transect 4), around 0.05 g L^{-1}. Surprisingly, stations Z8a and L074a (Transects 1 and 2, respectively) both contained a higher concentration of sediment in the top 4 m of the water column despite being recorded as outside of the freshwater plume.

4.3.2 K_d profiles

The light attenuation coefficient K_d was calculated for each depth from PAR readings (in units of W m^{-2}) obtained at Transects 1-4 on the submarine Elwha Delta. These coefficient values were graphed in conjunction with sediment concentration profiles for visual comparison (Figs. 4-7). On the graph, the K_d coefficient is represented by red circles at the corresponding depth. Lower K_d values (in m^{-1}) indicate greater light penetration, while higher values represent less light penetration and therefore, greater light attenuation. At 1 m depth, values ranged from 1.5 to 10.2 m^{-1} for all stations.

Plotted against depth, K_d values showed overall trends in light attenuation. Sunlight decreased more or less exponentially throughout the water column. Light attenuated rapidly between from atmospheric sunlight to 1 m depth, and from a 1 to 2 m depth in the water column, but decreased more slowly with greater depths. Stations Z8a and Z3a (Transects 1 & 4, respectively) were exceptions to this trend. Inside the freshwater plume, light generally attenuated more drastically than outside of the plume. Values inside the plume ranged from 2.5 to 10.2 m^{-1}, while outside the plume ranges fell from 1.5 to 4.4 m^{-1}.

The relationship between light attenuation and SSC was further investigated by a linear regression. K_d coefficients for light attenuation to 1 m depth was plotted against corresponding sediment concentrations, and a linear regression provided an R^2 value of 0.44 (Fig. 8).

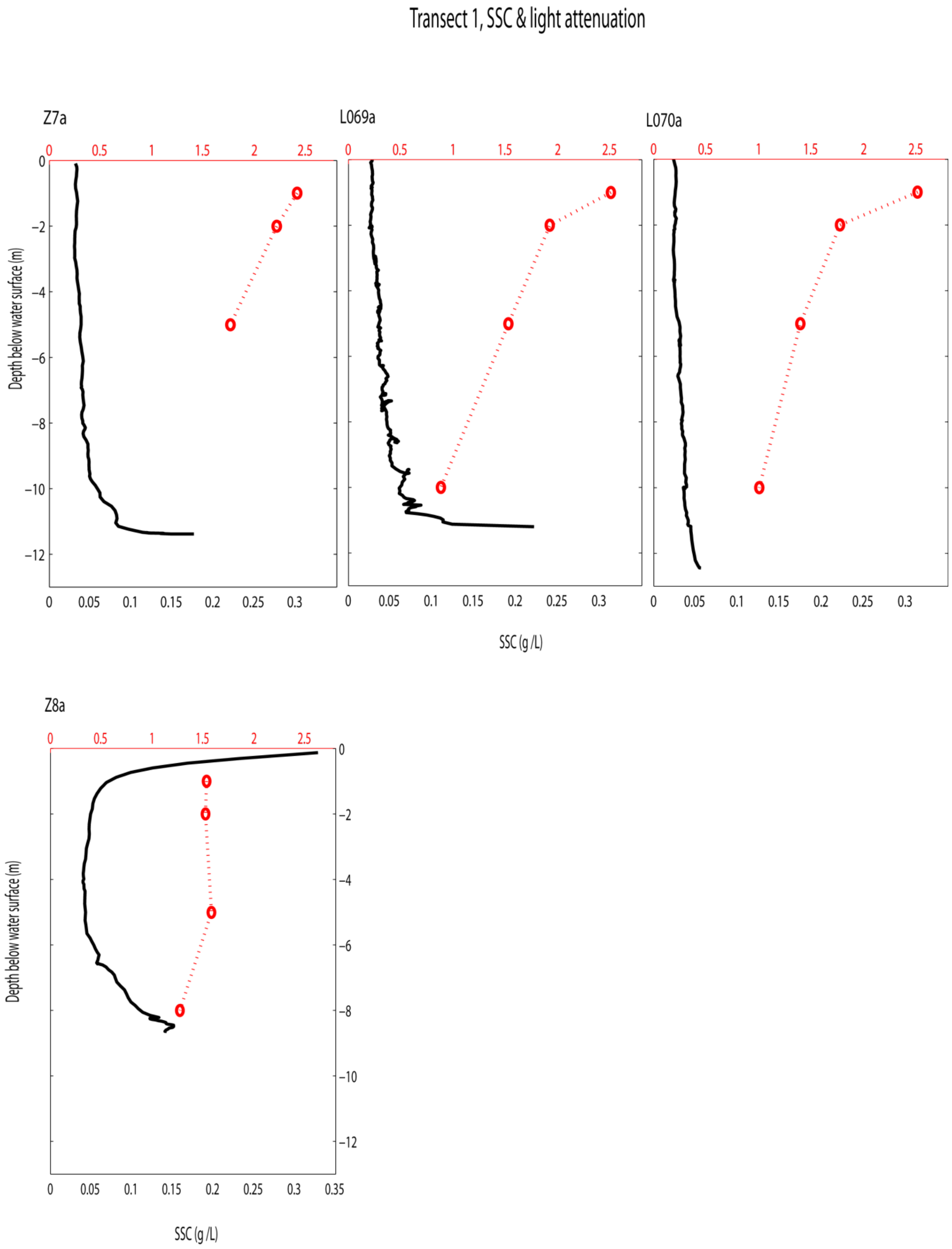

Figure 4. Suspended sediment concentration profiles (SSC, bottom x-axis in black) and light attenuation profiles (K_d, top x-axis in red) for Transect 1. All stations were located outside the freshwater plume. K_d values (m^{-1}) are on the upper x-axis.

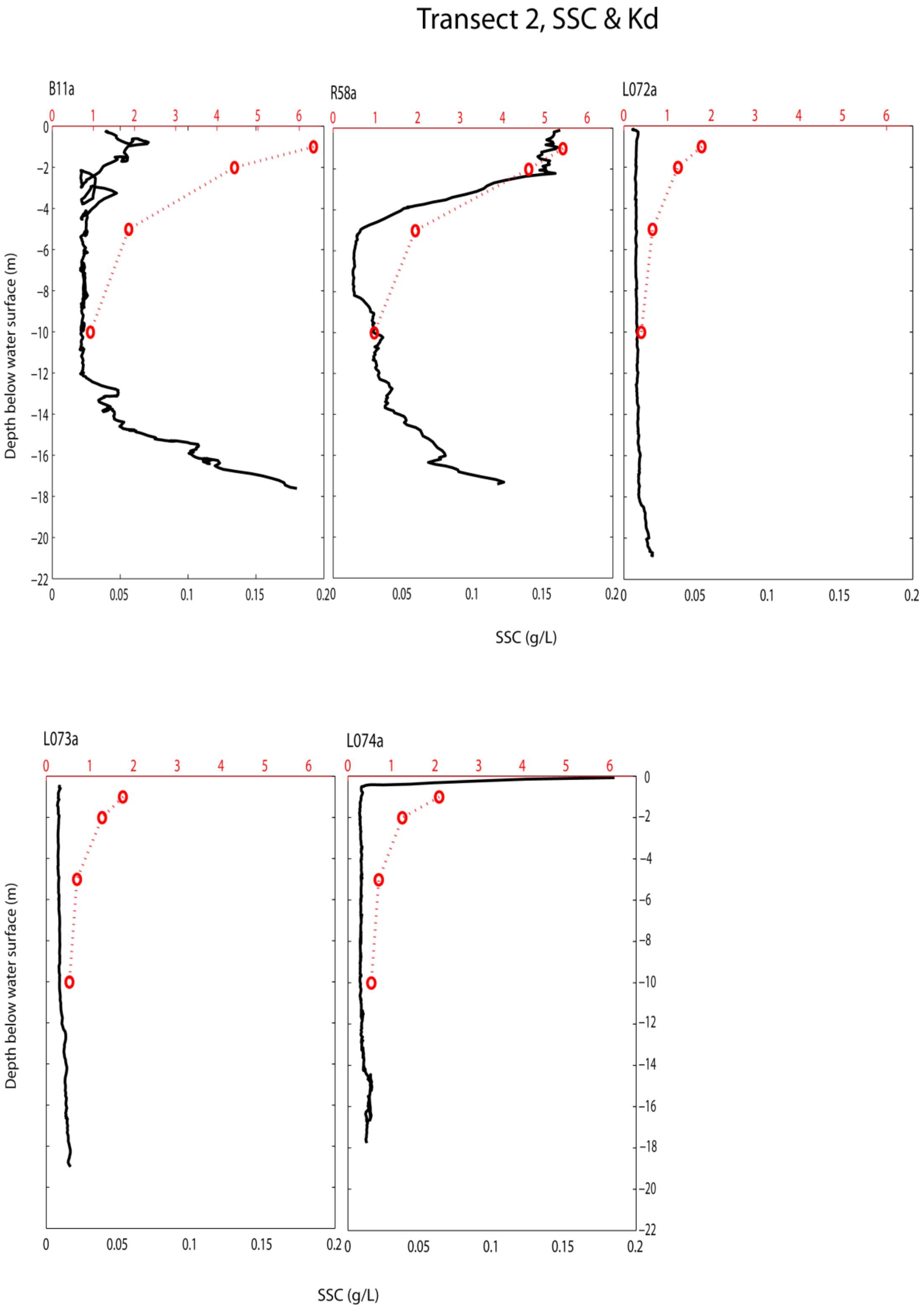

Figure 5. Suspended sediment concentration profiles (SSC, bottom x-axis in black) and light attenuation profiles (K_d, top x-axis in red) for Transect 2. Stations B11a and R58a were located within the plume. K_d values (m^{-1}) are on the upper x-axis.

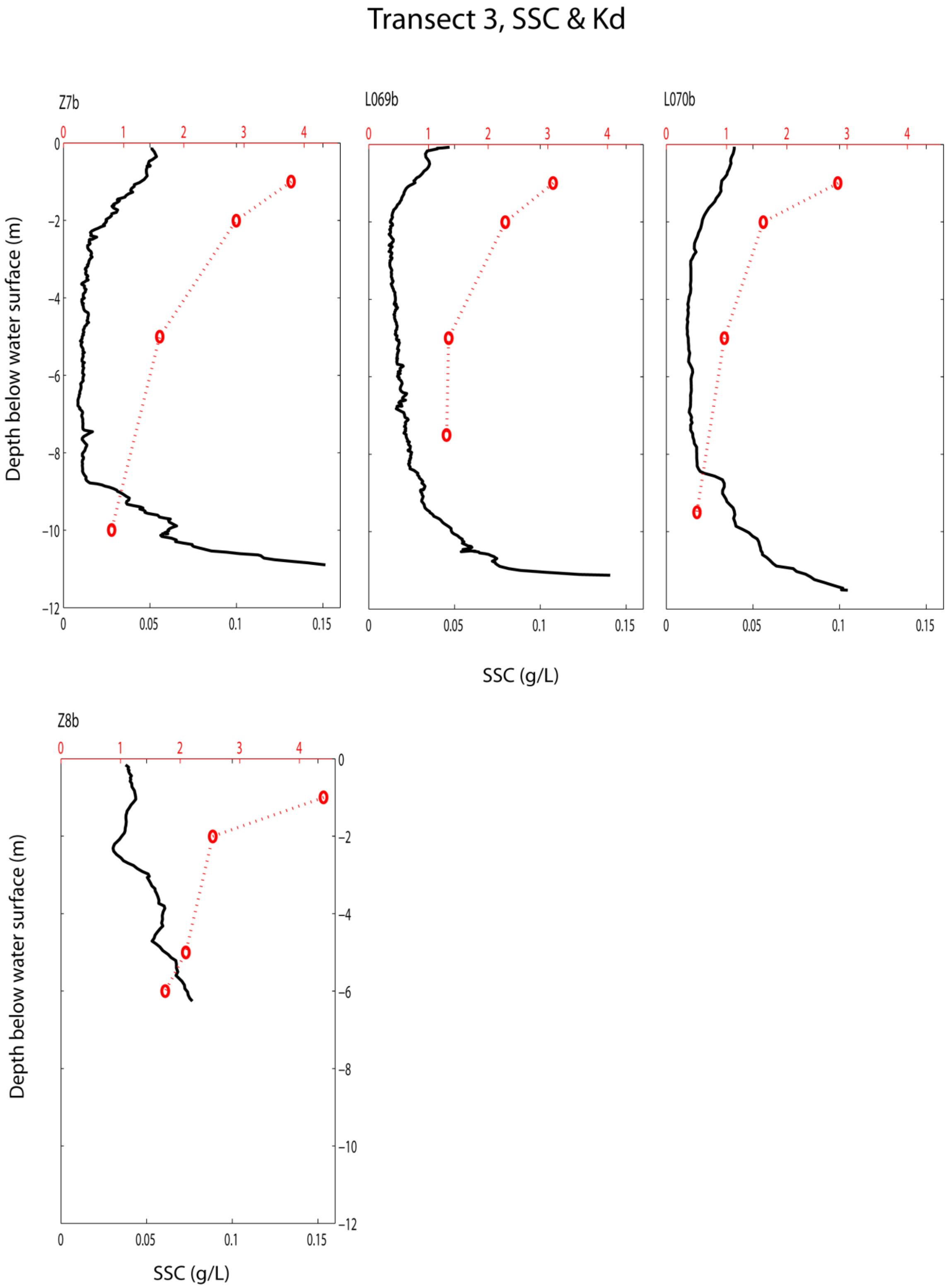

Figure 6. Suspended sediment concentration profiles (SSC, bottom x-axis in black) and light attenuation profiles (K_d, top x-axis in red) for Transect 3. Stations Z7b and L069b were located within the plume. K_d values (m^{-1}) are on the upper x-axis.

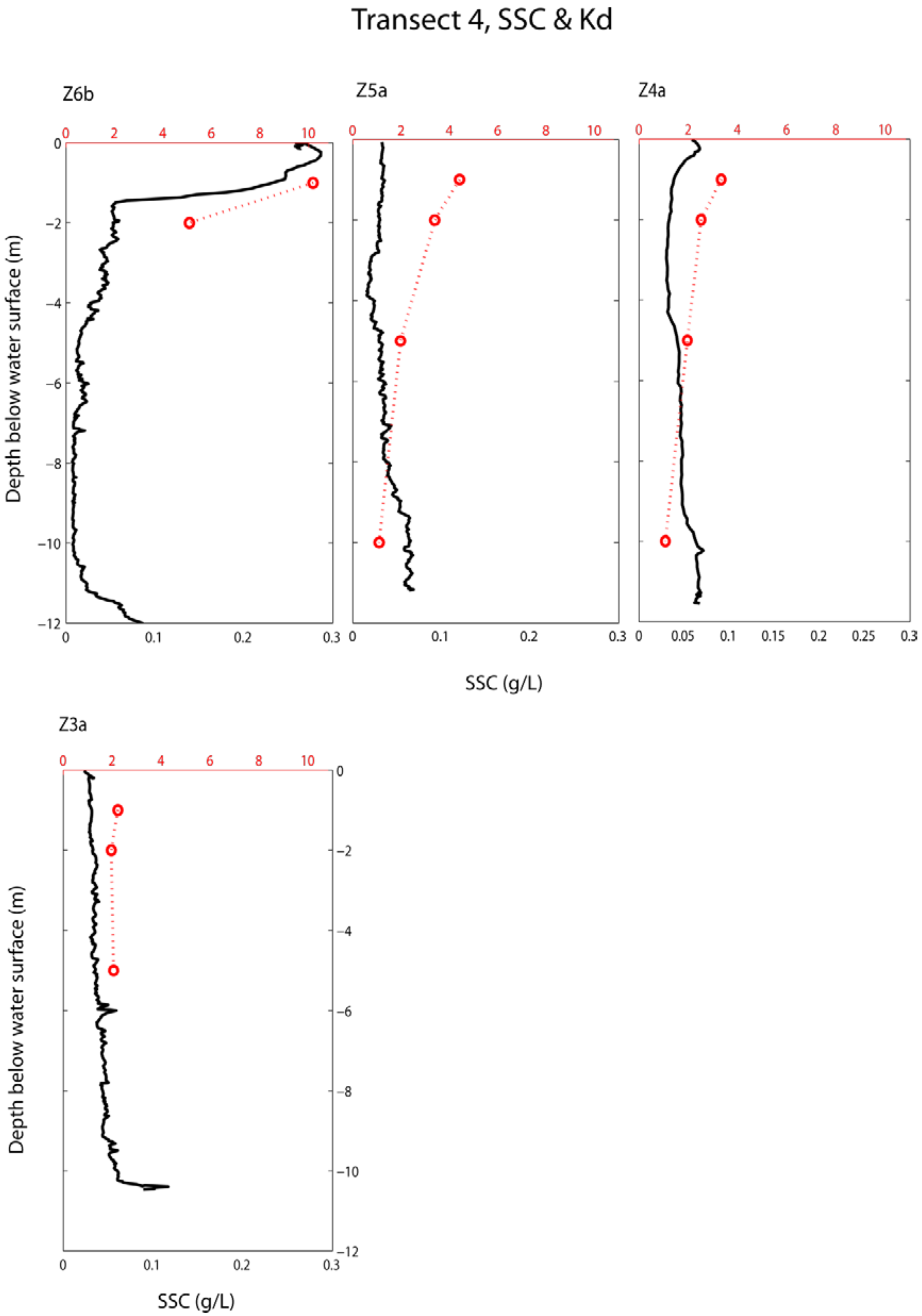

Figure 7. Suspended sediment concentration profiles (SSC, bottom x-axis in black) and light attenuation profiles (K_d, top x-axis in red) for Transect 4. All stations were located within the plume. K_d values (m^{-1}) are on the upper x-axis.

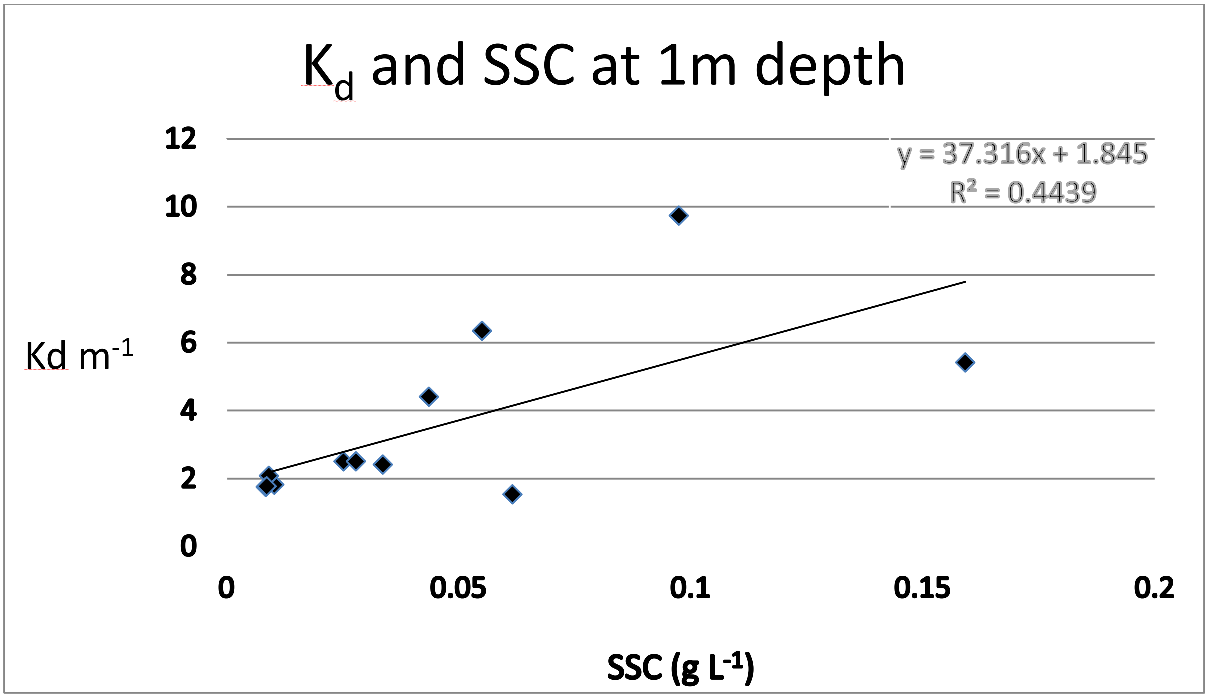

Figure 8. A linear regression of the light attenuation coefficient to 1 m below water's surface and suspended sediment concentration for the corresponding depth. An R^2 value of 0.44 indicates that variation in sediment concentration explains about 44% of variation in light attenuation.

4.3.3 Chlorophyll-a profiles

To assess photosynthetic activity on the delta, fluorometer profiles (in chl-a concentrations of mg m^{-3}) can provide a proxy for photosynthesis, although limited interpretations may be concluded from this dataset alone.

Fluorometer profiles were graphed to reveal high concentrations of photosynthesis throughout the water column at all stations and at most depths. Only once was the fluorometer deployed within the plume, but all four deployments displayed levels of photosynthesis that are high for the Strait of Juan de Fuca, with readings that ranged between 2.5 and 9 mg m^{-3}. The three deployments occurring outside of the plume displayed chlorophyll-a concentrations that increased with depth until 10-14 m, and then appeared to decline (see Fig. 9). The one deployment inside the plume displayed chl-a concentrations in the top 1 m that were higher than any other readings at that depth, but then decreased rapidly to 2.5 mg m^{-3} by 2 m below the water's surface.

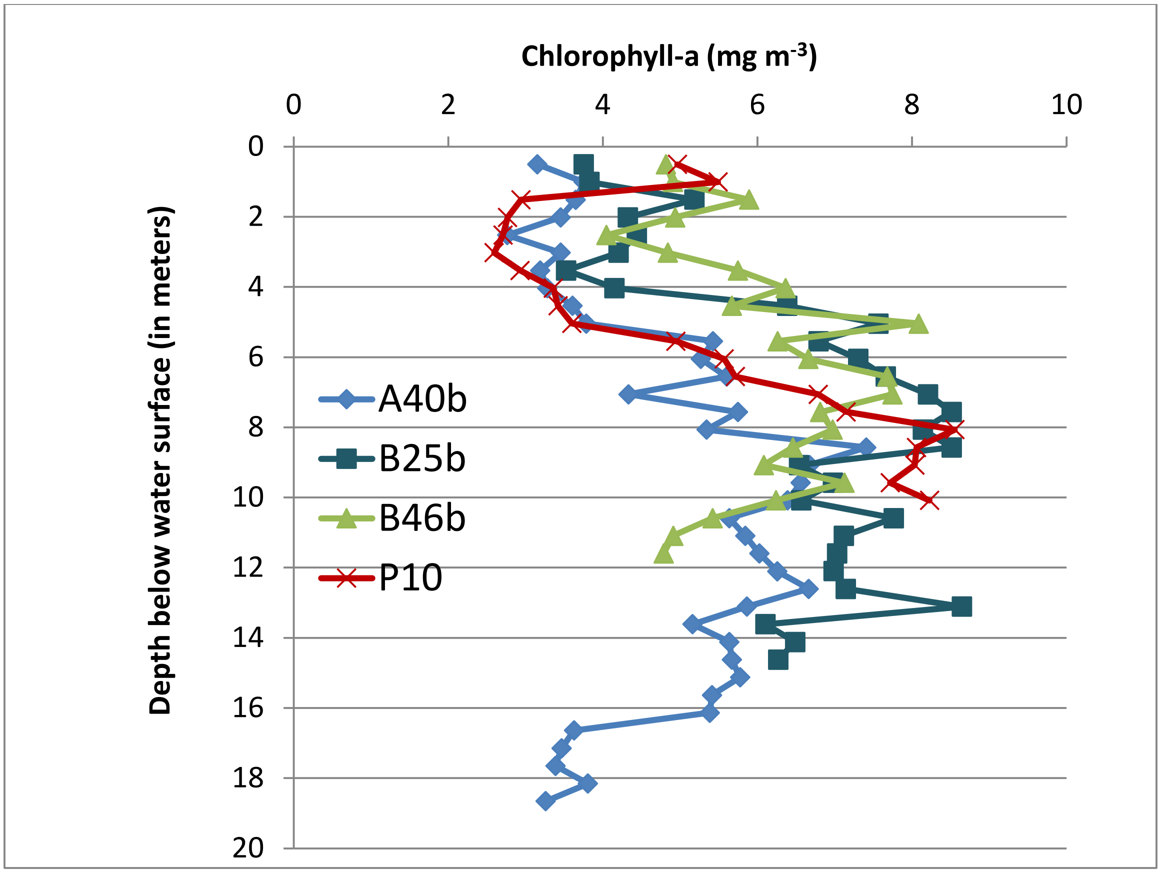

Figure 9. Chlorophyll-a concentrations for all four fluorometer stations. Stations A40b, B25b, and B46b (blue and green-colored profiles) were measured outside of the freshwater plume. Station P10 (red) was measured within the plume.

5. Discussion

5.1 Sediment in the plume

Dam removal has increased the amount of sediment being discharged into the Elwha Delta and suspended in the freshwater plume. In contrast to concentrations collected in 2008, maximum suspended sediment concentrations in the freshwater plume have increased 100-fold since dam removal.

Visually, the appearance of a freshwater plume is not always indicative of greater concentrations of sediment. Although it was surprising to find such variation in sediment concentration within the plume, a hypothesis can be formulated. Particles filter out of the plume at differing rates, depending on mixing in the water column and particle size. Where the plume was more recently discharged from the Elwha River, larger particles have yet to filter out of the plume and turbidity is higher. Where the plume is older, larger particles have filtered out of the plume and only smaller, less-dense particles such as silt and clay remain. Therefore, while they reflect light and cause the appearance of a sediment-laden plume, the actual concentration of sediment is lower than expected (i.e. 0.05 to 0.1 g L^{-1} throughout the entire water column). The collection of profiles along transects spatially supports this hypothesis. Stations B11a, R58a, and Z6b were located in close vicinity to the main mouth of the river, where the new plume would be originating. Other stations that appear to be inside the plume were further from the river mouth and exhibit more homogenous levels of sediment throughout the entire water column.

High values of sediment concentration found outside of the plume (i.e. stations Z8a and L074a) were most likely the result of poor instrument calibration prior to deployment on the delta, or the result of poor data processing in the lab. Although it is unlikely that this data represents true sediment concentration in the top meter of the water column, further analysis with more datapoints should be collected and analyzed for greater confidence.

The sediment concentration profiles also recorded the bottom boundary layer in the lower 2 m of the water column, where sediment concentration is higher as particles leave suspension and settle on the bottom of the delta floor. Although this was not a focus of our study, it is interesting to note that the OBS can record these increased sediment concentrations just above the delta floor.

5.2 Light attenuation

Light attenuation is increased by scattering and absorption of light in the water column. Suspended sediment, organic material such as phytoplankton, and dissolved solids can all play a part in attenuating light (Gallegos & Moore, 2000).

On the Elwha Delta, suspended sediment appears to increase light attenuation in the water column. Where greater concentrations of sediment occur, K_d coefficient values were correspondingly greater (Fig. 3). A linear regression of some of these values supported this hypothesis, and suggests that suspended sediment concentration is responsible for almost half of light attenuation in the water column at 1 m depth (Fig. 8).

While exciting, this dataset reveals that more research could quantify the other variables impacting light attenuation on the delta. Due to the limited time of data collection, many factors influencing light attenuation could not be analyzed for long-term trends. For example, primary productivity may be having a significant impact on light attenuation, so that during seasonal blooms or other large variations in primary productivity, the amount of light available to the benthic communities is considerably reduced. Alternatively, high river discharge events may increase the amount of suspended sediment to the delta, such that sediment concentrations become responsible for almost all of the light attenuation in the water column. Until these variables are studied in conjunction with light attenuation, conclusive results cannot be extrapolated.

5.3 Chlorophyll-a

Averaged chlorophyll-a data from 22-30 Apr, 2008, and from 22-30 Apr, 2013, obtained from Giovanni Satellite data indicated that regional concentrations were similar to those measured on the Elwha Delta in both years. This suggests that measurements of chl-a were taken during a phytoplankton bloom in the spring of 2013, while previous data was collected during a time of typical phytoplankton activity.

Chl-a concentrations measured on the 28 Apr, 2013 were much higher than standing stock rates in the Strait of Juan de Fuca, but corresponded to rates found in the discharge of the nearby Fraser River. Station P10, measured inside of the plume, showed remarkably high levels of primary production in the top 1 m of the water column, but decreased drastically by meter 2. This is most probably a result of mixing in the water column, churning phytoplankton-rich salt water together with phytoplankton-poor freshwater, but such a hypothesis requires vigorous testing.

In order to truly assess primary productivity in the field, chl-a profiles should be collected both within and outside of the plume during or following differing tidal conditions and discharge events, and should be collected seasonally for at least a year. Additionally, rates of photosynthesis and respiration should be quantified in order to establish a baseline level of primary production on the delta. Finally, during both seasonal blooms and baseline levels of standing stock, respective phytoplankton species compositions should be assessed to determine any correlation between these primary producers and related ecological factors, such as juvenile salmon success.

6. Conclusion

Dam removal on the Elwha River has increased the amount of sediment delivered to the Elwha Delta. This has resulted in higher concentrations of sediment throughout the delta water column, and much of this sediment may remain in the freshwater plume for some time, though visual observations of the plume do not necessarily reflect actual sediment concentrations. Where there is increased sediment concentration, light attenuation is higher, and variation in sediment composition may account for as much as 50% of the variation in light attenuation under certain hydrological conditions. At the time of the study, chlorophyll-a concentrations were higher than both those found in 2008 and the average rates of chl-a in the Strait of Juan de Fuca, but based on satellite data, this may be the result of a spring bloom. Impacts of dam removal on primary productivity cannot be assessed from such short-term data, but this study provides a basis for further investigation into possible biological consequences for dam removal and ecosystem restoration.

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I will miss all of the Sed Heads group and the wonderful kitchen staff who pampered me whenever possible. Last but not least, I will miss all knoll events and the refreshments provided.

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