

**Impacts of Suspended Sediment on Light Attenuation and Primary Productivity
near the Elwha Delta**

Marine Sedimentary Processes Apprenticeship

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Abstract

The Elwha River on Washington State's Olympic Peninsula was home to two dams for almost a century. Dam removal began in 2011, releasing sediment into the Elwha River, forming a pronounced river plume. It is important to evaluate the response of the river ecosystem to such a drastic change. We examined light attenuation associated with the plume, using photosynthetically-active radiation measurements along with suspended sediment concentrations. Results suggest that there is not enough light penetrating depths of 5 m for successful primary production of some species. Suspended sediment in the water column prohibits light penetration > 10% water depth. As a result, the habitat of *Z. marina*, a local sea-grass species requiring a minimum of 18.6% light penetration, is likely affected. Based on suspended sediment concentrations in the water and the available light, it is hypothesized that *Z. marina* needs to grow at shallower depths away from the river plume in order to receive sufficient light in the Elwha delta.

1. Introduction

In 2011, the largest intentional dam removal in United States history began on the Elwha River, located in Port Angeles, Washington. Prior to removal, the dams had been fully functioning for almost a century. As a result of the dams, an estimated 25.6 m³ of sediment accumulated in the two reservoirs. Release of this sediment has resulted in high suspended sediment concentrations (SSC) near the river mouth. Excess sediment entering the marine environment, and the formation of this surface plume, could affect benthic primary productivity. This project is the largest intentional dam removal in United States history, making it an excellent reference point for future studies. According to a study

conducted by the Northwest Science Association assessing the creation of conceptual models based off of the Elwha removal project, the dam removals presents an unique opportunity to study the biologic consequences of this behavior while simultaneously observing habitat changes. Dam removal also provides management strategies for future projects (Woodward et al., 2008). Understanding the impacts on benthic species could lead to better supervision of restoration processes for the Elwha and future dam removal projects.

1.1. Topical Background

The influx of new sediment generated a substantial surface plume over much of the subaqueous portion of the delta, although the plume can fluctuate vertically, permeating below the surface of the water column. Plumes in the Elwha are dynamic, affecting multiple areas over a short time scale. Fluctuations occur on many time scales. On a seasonal basis, increased rainfall and annual snowmelt lead to increased plumes in the summer and winter months, respectively, and tidal processes shift the plume on a daily scale. The areas affected most by reduced light penetration differ on a regular basis, and areas impacted most from reduced primary productivity depend on the location of the plume. Understanding how these changes impact energy transfer through the trophic levels is highly important for assessing ecosystem response to dam removal. In a study focused on analyzing the effects of water quality and suspended sediment on growth and the success of submerged aquatic vegetation (SAV) in Chesapeake Bay, light attenuation was sufficient to inhibit restoration of SAVs (Gallegos, 2001). The current study evaluates the effects of suspended sediment in the river plume on light attenuation, and how this may affect the primary productivity of benthic species in the Elwha delta.

2. Background

2.1. Regional Setting

The Elwha River is located in Washington State, originating in the Olympic Mountains. It is a small mountainous river emptying into the Strait of Juan de Fuca, just west of Port Angeles. A series of modifications make this an interesting watershed to study. Natural processes include intense wave and tidal action, lateral sediment transport along the coast, and suspended sediment in the water column (Gelfenbaum et. al, 2009). However, like many rivers in the U.S. a series of dams were installed to generate hydropower. The first dam was built in 1913, and the second in 1927. Over the course of almost an entire century, the dams have changed the discharge of river, virtually stopping steady flow of sediment from upstream and altering ecosystems in this region. In total, the dams trapped almost 25.6 m³ of sediment (NPS, 2014).

Dam removal began in early 2011, releasing trapped sediment from upstream. Research suggests that ~ 50% of the flow will eventually reach pre-dam conditions of ~ 42 m/s, and will transport the sediment from the former reservoirs back into the marine environment. The new influx of sediment formed a pronounced surface river plume. Plume formation increased the turbidity on the delta, and sufficiently reduced light penetration throughout the water column.

3. Methods

3.1. Study site and sampling goals

Nine sites on the Elwha delta were chosen to examine the effects of suspended sediment in the river plume on light attenuation. These sites were chosen in order to gain representative

The suspended sediment observed in this study ranged from the east side of the delta to the river mouth and west into Freshwater Bay (Fig. 2). These areas of sampling will allow for observation of the plume dynamic, and assessing the daily trends that change with tides, weather, and seasonal patterns. A change in plume location and suspended sediment concentration will affect the amount of light attenuation. These changes will be compared to minimal light requirements for *Z. marina*, a sea grass species local to Puget Sound.

3.2. Sampling and sample analysis

Surface water samples, Conductivity, Temperature, and Depth (CTD) casts, and light attenuation measurements using a photosynthetically-active radiation (PAR) sensor were collected during the two day research cruise 11-13 April, 2014, aboard the *R/V Clifford A. Barnes*. Depth profiles of light saturation were collected with PAR, and measurements were taken at 1, 2, 3, 4, and 5-m water depths. A baseline reading of light intensity above water was measured as a constant. Salinity values provided by the CTD casts compared throughout the depth profile. Additionally, suspended sediment concentrations (SSC) were determined using measured samples and data from the CTD at all stations. SSC profiles were examined to identify where in the water column had the highest concentrations of suspended sediment. In an attempt to focus on attenuation due to SSC in the plume, the attenuation coefficient (K_d) was calculated to compare to other

studies and factor out other variables that may attenuate light such as marine organisms, particulate, and dissolved organic matter, using a method described in Dennison et al. (1993). K_d was compared to depth to evaluate where the most attenuation is occurring. K_d was then used to determine the percentage of light penetrating to 5-m depth for all stations. Minimal light requirements for *Z. marina*, a local sea grass species, were described in Dennison et al. (1993) and compared to the percentage of light penetration recorded at sites in the Elwha.

4. Results

4.1. Light Profiles

A control value of light data collected with the PAR sensor was recorded immediately above the water surface, which ranged from 350 $\mu\text{mol}/\text{m}^2\text{s}$ to > 3000 $\mu\text{mol}/\text{m}^2\text{s}$ (Fig. 3). Samples at 1 m water depth of clear water (no plume), were taken at stations M11 and M30 (Fig. 3), and had values ranging from 200 to 800 $\mu\text{mol}/\text{m}^2\text{s}$ (Fig. 3). At station M10 and F5, where the water appeared extremely turbid, PAR values ranged from 335 to 460 $\mu\text{mol}/\text{m}^2\text{s}$ disregarding shadowed stations. Light availability became scarcer as depth increased to 5 m. Stations out of the plume were recorded at 70-150 $\mu\text{mol}/\text{m}^2\text{s}$, whereas areas inside of the plume display values from 5 to 40 $\mu\text{mol}/\text{m}^2\text{s}$ at 5 m water depth.

4.2. Percent of Light Penetration

Percentage of light penetration was compared to depth (Fig. 4). All stations show a higher percent of light penetration at shallower depths (1 m), which decrease gradually with increased depth. Values at out-of-plume stations (M11, M30) range from 6-26% at 1

m water depth and decrease to values of 2-4% at 5 m. Stations F5 and M10 taken inside of the plume have values reaching 11-14% at 1 m water depth. Observed light penetration decreases slightly across the depth profile, with penetration percentages of 0.06-1.3% at 5 m (Fig. 4). One station reached the minimal light requirement for *Z. marina*, station A1 located west of the river mouth displayed 40% light penetration at 5 m water depth.

4.3. Suspended Sediment Concentrations

Suspended sediment concentrations were measured to investigate on light attenuation due to sediment in the water column. Typically surface plumes have higher concentrations of suspended sediment (Fig. 5); however, on average the profiles display only a slight decrease in SSC throughout the depths sampled. Stations inside of the plume exhibit higher SSC values relative to those outside of the plume, at all depths. Station F5 has a relatively low SSC at 1 m, and drastically increases with depth to 5 m. Stations M11 and M30 have an almost linear relationship of SSC throughout the depth profile, exhibiting little change from 1-5 m. Station F2 (A) taken inside of the plume has a very high near-surface SSC at 1 m (0.29 g/L) and gradually increases down to the 3 m mark, where it displays an extremely sharp decrease in SSC from 3-5 m. This is an interesting comparison to station F5, although both are inside of the plume. F2 (A) and F2 (B) are the same location, with data recorded 12 hrs apart, but their suspended sediment concentration profiles differ significantly. F2 (B) closely resembles other stations taken outside of the plume, with a higher surface concentration that gradually decreases with depth. F2 (A) behaves more like stations inside of the plume, with higher concentration values at all depths (Fig. 5).

4.4. K_d light attenuation values

An attenuation coefficient was paired alongside the depth profile to evaluate light absorption throughout the water column (Fig. 6). Minimal attenuation coefficient rates were 0.035 in clear water (without sediment). Station M10 located inside of the plume has a high attenuation coefficient value at 1 m water depth but decreases steadily as depth decreases. This trend somewhat resembles an exponential decay curve. The majority of the stations recorded (both in and out of the plume) follow this trend, starting with high values and decreasing over the depth profile. Stations inside of the plume on average have higher attenuation coefficients over the depth profile than those outside of the plume comparatively. Station F5 is the only exception, with a high attenuation coefficient at 1 m, and decreasing slightly until 2 m, increasing again until 3 m and displaying a slow decrease for the remainder of the depth profile.

5. Discussion

5.1. Relationship between PAR readings and depth

PAR data collected within the Elwha river plume suggest that there is sufficient light attenuation at depths of 5 m to hinder successful primary production by some benthic species (Fig. 3). Presence of the plume influences light penetration, allowing for a higher percentage of light penetration in clearer water than in more turbid areas inside of the plume. PAR values decrease with depth in areas where the plume is present, and turbid water prevents much light penetration through the water column. More light reaches depths of 1 m than 5 m, however, there is a drastic decrease in light penetration as depth increases when the plume is present. In a specific comparison between in plume

and out of plume stations (M10 and M11), the control measurement had PAR values that ranged from 3550 $\mu\text{m}^2/\text{s}$ (clear water) to 2917 $\mu\text{m}^2/\text{s}$ (in plume). PAR values change significantly when making a comparison between plume and clear water. More attenuation occurs as depth increases inside of the plume than in clear water. We see, therefore, a direct correlation between higher suspended sediment concentrations and light attenuation. Knowing that sediment discharge has increased by as much as 13% since dam removal, we expect there to be major impacts on local habitats (Woodward et al, 2008).

A change in habitat has implications for the primary productivity of many species near the Strait of Juan de Fuca, and the health of the ecosystems in the future. Light penetration is relatively low at 5 m in clear ocean water lacking suspended sediment, meaning that an influx of suspended sediment could have a large impact on productivity levels of benthic biota, effecting the rest of the ecosystem. This data is correlated to other literature. Fairhead and Cheshire (2004) focused a study on the primary productivity levels for *Ecklonia Radiata*, a kelp species which grows in adverse conditions with little light availability.

5.2. Correlation between K_d and minimal light requirements from past research

Previous studies have examined minimal light requirements for several species found in the Puget Sound region, based on the maximum depth of the survey area and K_d (Dennison et al., 1993). In this study, light at 5 m was calculated for all stations, and compared to minimal light requirements for *Z. marina*, a seagrass species found in Puget Sound. This revealed that with a single exception, not enough light was reaching the

seabed to ensure *Z. marina* survival. Station A1 located west of the river mouth near Freshwater Bay showed 40% of light remaining, well above the 18.6% required for survival. This was an anomaly, as the majority of stations showed less than 5% light remaining at 5-m water depth. These conclusions are similar to those found in other studies observing light attenuation of submerged aquatic vegetation (SAV). In Chesapeake Bay, light requirements for SAV's were analyzed to determine if successful mitigation could be used to restore population biomass (Gallegos, 2001). In this study, the suitability of the environment was determined by assessing water quality standards while measuring the average amount of attenuation at 1, 3, 5, and 12 m water depth. Similar to the current study, the results concluded that not enough light was reaching the seabed in order for restoration of diminished SAV species in Chesapeake Bay (Gallegos, 2001). This has implications for future research. Multiple studies have determined that SAVs need copious amounts of light to survive, in areas where light is accessible at depths greater than 5 m.

5.3. Relationship between suspended sediment concentrations and K_d

SSC was evaluated alongside the K_d derived from the data to determine how much light was being attenuated due to sediment in the water column. Figure 5 shows SSC from each station against the attenuation coefficient. Stations F5 and F2 (A) are both located inside of the plume, and appear to be outliers in the data due to their high SSC values. Figure 3 shows SSC as a function of depth, which further demonstrates this relationship. The majority of stations follow a similar trend, maintaining low suspended sediment concentration along with the attenuation coefficient. It's expected that stations

inside the plume (F5, F2 (A)) have a much greater SSC content than those located outside the plume.

F5 further stands out, as there is evidence of a bottom nepheloid layer. The formation of a bottom plume suggests sediment resuspension of particles in the water due to tidal or wave action. F2 (A), meanwhile, displays a variable SSC profile (Fig. 5). F2 (A) is found near the mouth of the river where the plume is typically most concentrated. However, F2 (B) which is in the same location does not show the same trend. Data were collected at this station on two separate days, and based on their respective profiles, it is evident that the plume shifted location between times of data collection. An increase in SSC relative to the K_d has many implications for these two areas. A higher K_d means that less light reaching through the water column to depths of 5 m to increase productivity. Plume fluctuations in location and concentration are frequent, meaning that primary producers are not always affected. These fluctuations are mostly driven by seasonal patterns, resulting in a higher variability in the winter and summer months due to peaked river discharge caused by increased rain fall, and annual snowpack melt (Gelfenbaum, 2009). Tidal and wave action also contribute to plume fluctuations in location and concentration. The plume moves position with the daily flood and ebb tides, and sediment is resuspended and distributed to different layers of the water column due to tidal cycles and intense wave action. This has implications on light attenuation in these regions. If the plume extends vertically past the surface layer, there is increased attenuation at deeper depths. Increased light attenuation due to seasonal, daily, and weather fluctuations impacting both incoming light and the plume will lead to an indirect effect on primary productivity of benthic organisms in the Elwha.

6. Conclusion

The purpose of this study was to analyze light attenuation due to suspended sediment in the Elwha River plume and its possible effects on primary productivity levels in this ecosystem. Data shows that light attenuation is higher in areas where the plume is present, relative to areas without the plume. PAR data collected at all sites around the Elwha demonstrated that less light reaches depths of 5 m than depths of 1-2 m. The plume was also discovered to be dynamic during the course of this study, and most likely on seasonal and tidal time scales as well.

Comparing SSC and light attenuation, higher attenuation was observed in regions where the SSC is greater (in plume). Two stations (F5 and F2 (A)) show intensity values which were different relative to the other sites. F5 shows the presence of a bottom plume not seen at any other site, likely due to the resuspension of seabed material by wave and tidal action. F2 (A) exhibits high SSC at all depths, and a correspondingly high K_d value. This site was near the river mouth where the plume was likely to be most concentrated. It also differs from F2 (B) even though the two profiles are from the same station. This was due to the plume shifting location between data collection periods.

Previous studies determined the minimum light requirement for survival of a local Puget Sound sea grass species, *Z. marina* (Dennison et al., 1993). Using the attenuation coefficient equation from Dennison et al. 1993, the K_d value at 5 m depth at every station was used to determine the fraction of light reaching that depth. A comparison was then made to the minimal light requirement, concluding that only one station (A1) was fit for survival of *Z. marina*. Areas where the plume was present exhibited little to no light

penetration at 5 m, with many of these stations showing less than 5%. Currently, there is not enough light reaching the seabed for *Z. marina* in most of this coastal ecosystem to thrive. Dam removal and the associated river plume has likely had a direct impact on primary productivity for species in the Elwha delta. This evidence also suggests that there may be consequences for primary producers in future dam removals as well, due to the influx of suspended sediment.



Figure 1. Gelfenbaum, 2004. The Olympic Peninsula in Washington State, depicting the Elwha River.



Fig 2. A Google Earth image depicting the transect used for PAR, CTD, and water sample

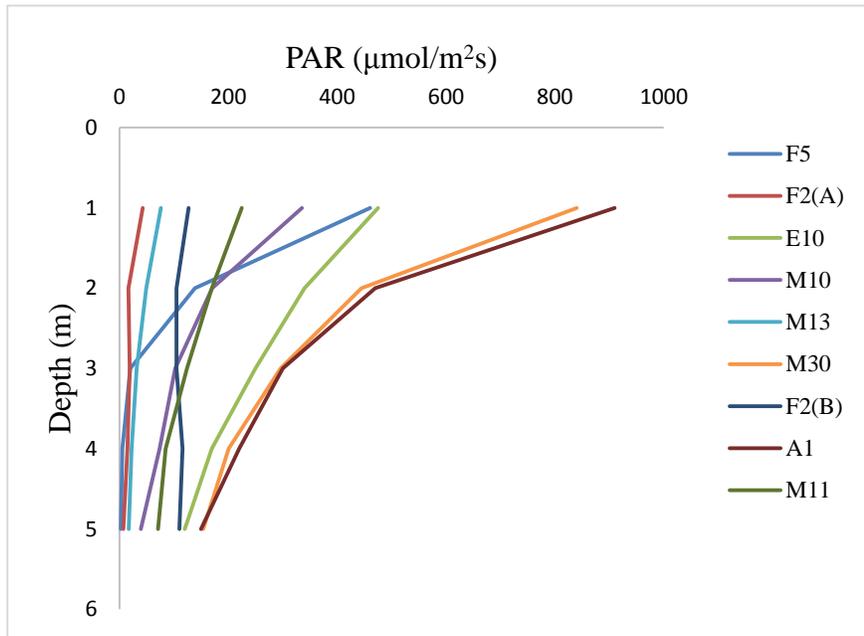


Figure 3. PAR v. depth for the stations sampled in this study. Profiles F2(B), F2(A), and M13 were collected in the shadow of the boat.

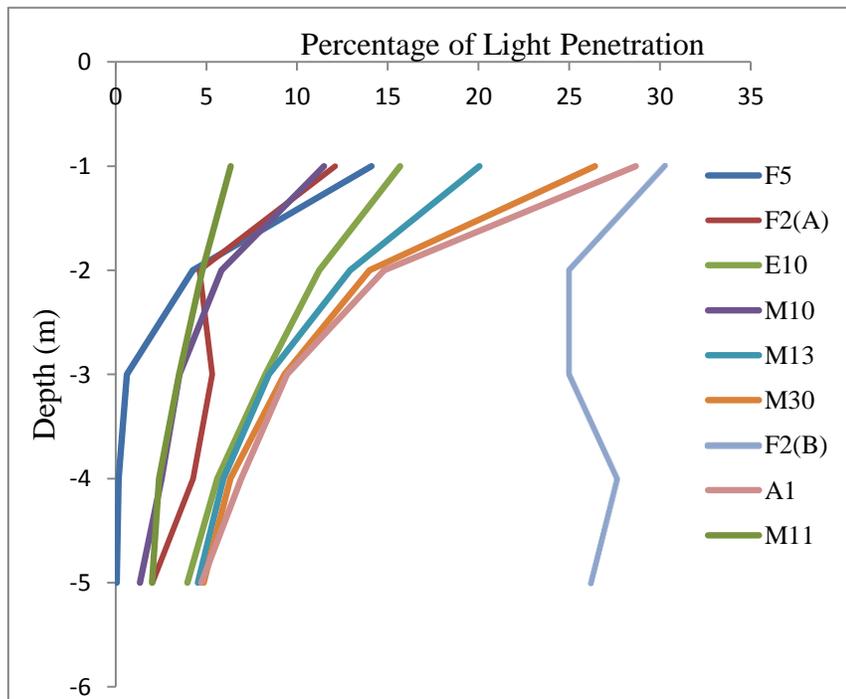


Figure 4. PAR penetration percentage v. depth for all stations. Station F2(B) exhibits high PAR penetration throughout the depth profile.

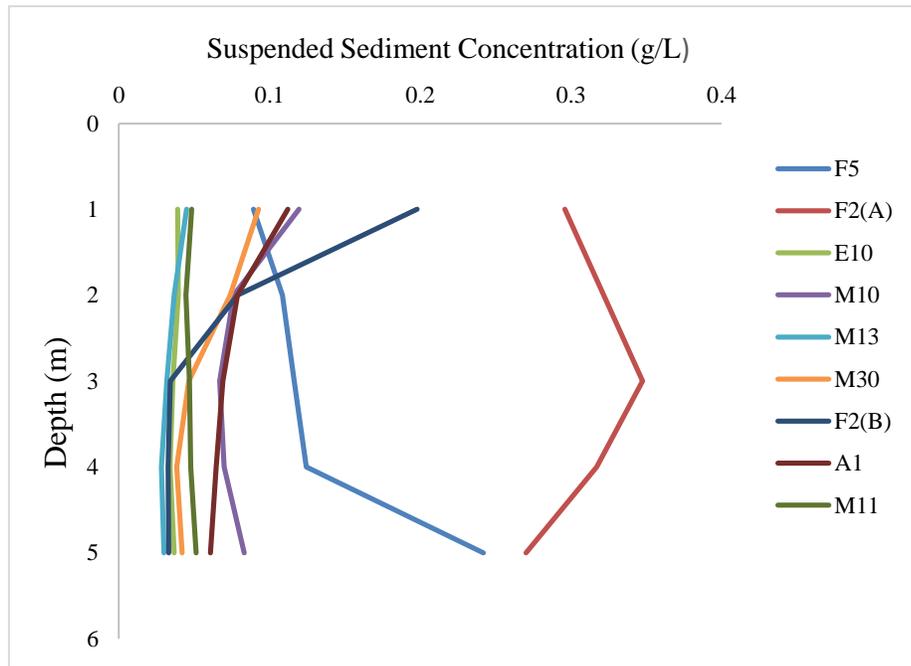


Figure 5. Suspended sediment concentration v. depth. F2(A) displays a bottom plume while F2(B) has a high SSC. This demonstrates the plume

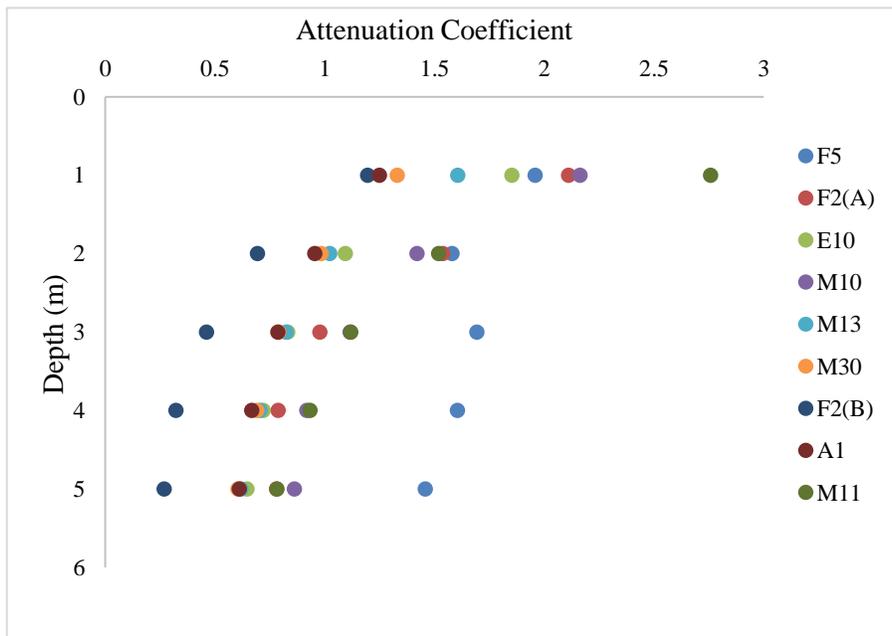


Figure 5. Attenuation coefficient v. depth. Station F5 (in medium blue), is the only station that does not exhibit the exponential decay trend.

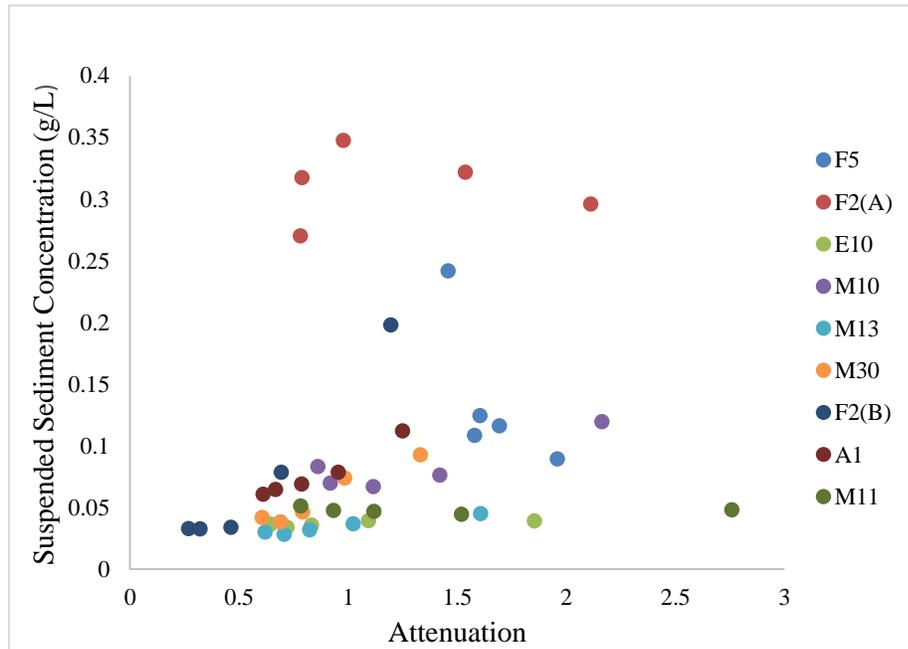


Figure 6. Suspended sediment concentration v. attenuation coefficient. Station F2(A) and F5 do not follow the same trend, exhibiting large spikes.

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