

**Elwha dam removals effect on the carbon cycle: tracking particulate organic carbon
in the nearshore**

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Abstract

Dam removal is an emerging technique for ecosystem management. Reservoirs behind the dams are known to be both carbon sinks and sources. The Elwha dam removals in Washington State are the largest dam removals in U.S. history. In this study the fate of the carbon stored in the reservoirs upon its abrupt release is evaluated. Sediment samples from the estuary, delta and water column were tested for their particulate organic carbon content through loss-on-ignition testing. Grain sizes of sediment samples were analyzed and volume estimates of carbon deposits were calculated. The results indicated that particulate organic carbon was preferentially deposited in two locations. The large woody debris typically settled on the subaerial delta, while the carbon sorbed to silt and clay settled in the estuary and subaqueous delta. The sudden release of the reservoirs resulted in a condition where river meandering through the former reservoir beds is minimal. As a result, approximately half of the carbon likely sorbed to the sediment in the reservoirs remains. The rapid sediment accumulation resulted in a higher-than-average carbon burial rate of the roughly 165,000 +/- 124,000 tonnes of carbon deposited on the delta. This suggests dam removal can not only restore an ecosystem and may also be able to help mitigate climate change.

1. Introduction

The Elwha River dam removal is the largest intentional dam removal project in U.S. history (NPS, 2014). Two dams of these sizes have not been purposely removed before, and with 83% of the river protected within the National Olympic Park (Duda et al., 2008), this presents an excellent research opportunity to document the ecosystem's

response. The Elwha river dam removal may also reflect the changing of perspectives on hydropower. The dam removal was unprecedented because it valued ecosystem protection over electricity production, although the electricity produced from the dams by the time of relicensing was minimal (Gowan et al., 2006). In 1979, the manager of both the Glines Canyon and the Elwha dam applied for relicensing by the Federal Energy Regulatory Commission (Winter and Crain, 2008). While investigations were being done to determine the most effective fish ladder, the Elwha Tribe was the first to call for removal of the dam, in 1986 (Gowan et al., 2006). For the state and federal agencies, the call for dam removal sounded too radical, especially without any thorough investigation of the costs and ecological impacts (Gowan et al., 2006). Extensive technical analysis was then conducted to explore the dam removal possibility and in 1992, to much surprise, Congress passed the Elwha Act calling for “full restoration of the ecosystem” (Elwha Act, Public Law 102-495). The act however did not specify how the ecosystem restoration should occur, and much debate for almost twenty years resulted over the ambiguity (Gowan et al., 2006). The final decision to restore the river through removal of the dams is a tacit acknowledgement that dams are a disturbance to ecosystems. Opportunities to study the recovery of a river post dam have been infrequent, because this is an emerging ecosystem management technique (Doyle et al., 2003). In order to fully understand the impacts of hydropower on an ecosystem, we need to study the way it recovers from the impacts of dam removal.

Currently there is a debate on whether hydropower has a positive or negative impact on climate change. Part of the International Hydropower Association’s mission is to expand hydropower’s role as a climate change solution (hydropower.org). The

Intergovernmental Panel on Climate Change (IPCC) acknowledges hydropower's ability to reduce substantial carbon emissions but has not come to the consensus on whether the emissions from the reservoirs negates the emissions saved from the renewable energy created (Kumar et al., 2011). The International Rivers Network review found that although reservoirs sequester 2.5 % of anthropogenic carbon globally, reservoirs emissions have been estimated to be 60% higher than their sequestration (Parekh, 2004). Dam reservoirs interrupt the carbon cycle by collecting and storing organic matter for decades. As this organic matter begins to decompose anaerobically, both CH₄ and CO₂ emissions are released (Rudd et al., 1993; Fearnside, 2000; Louis et al., 2000). Dam removal releases this stored carbon abruptly, and little is known about how dam removal affects the global carbon cycle. Roughly 45% of global carbon burial occurs on deltaic sediments (Hedges and Keil, 1995). With a rushed release of sediment, it is unknown if carbon burial will occur at the natural rates, and how that will affect climate change going forward. Before that can be answered, the location of carbon released after dam removal must be determined, which is the focus of this study.

Freshwater systems are often ignored in global carbon budgets. Recent studies show that freshwater systems play a significant role in the carbon cycle. American rivers alone offgas approximately 97 +/- 32 Tg of carbon (Butman, Raymond, 2011). Lakes and reservoirs hold the equivalent of 17% of the atmospheric budget despite only making up 0.6% of global water surface (Einsele et al., 2001). Rivers play an important part in the global cycle by transporting organic matter into the ocean, and small mountainous rivers have been found to transport a disproportionately high amount of carbon into the ocean (Goni et al., 2013). The majority of the organic matter that is transported to the ocean

from the river is either respired or remineralized on the delta (Hedges et al., 1997). Carbon in rivers can be found in mainly three different forms: dissolved inorganic carbon, dissolved organic carbon and particulate organic carbon. In this study we will measure the particulate organic carbon (POC), which accounts for a substantial portion of the carbon budget in both rivers and marine cycles (Einsele et al., 2001). This study will use loss-on-ignition analysis, which burns off all organic matter from a sample, with the assumption the mass lost was all carbon (Heiri, 2001). An estimate of the carbon content in the reservoirs was calculated between July and September 2013 (Wing, 2014). Work by Curran et al. (2014), found that 50% of sediment had been released as of September 2013, thus this study estimates the carbon content from Wing (2014) represents half of the carbon originally stored in the reservoirs. Wing's estimate will be used to compare to the amount of carbon this study will estimate was deposited nearshore, following dam removals. This study will attempt to locate where the majority of the particulate organic carbon is stored after a dam is removed. By studying where carbon is stored after a reservoir is released, it will give us further insight into the freshwater carbon cycles and the carbon exchange between the river and ocean, which could help refine global carbon budgets. It may also help explain how dams alter the carbon cycle.

2. Background

The Elwha River is a 72-km-long, small mountainous river draining Washington State's Olympic Peninsula. The Elwha runs from the Olympic Mountains to the Strait of Juan de Fuca, which connects Puget Sound to the Pacific Ocean (Fig 1). Puget Sound and the Strait are biologically diverse, glacially carved basins (Duda et. al, 2011). Glaciers

define much of the geology surrounding the coastal portion of the Elwha, which explains the poorly sorted and wide range of sediments found in the river (Warrick et. al, 2009). The rocks found in the Elwha are primarily comprised of sandstone, shale and basalt (Tabor,1988).



Figure 1. Location of the Elwha River. The river drains the Olympic Mountains into the Strait of Juan de Fuca and out to Pacific Ocean. Accessed from <http://soundwaves.usgs.gov/2005/02/ElwhaRiverMapLG.jpg>

The Elwha River basin's moderate temperature is the result of being shielded from arctic winds by the Cascade Mountains and being next to the ocean which stabilizes the temperature (NPS, 2011). The Elwha basin is also on the edge of the rain shadow created by Mt. Olympus, which creates a steep precipitation gradient (Duda et. al, 2008). Elwha precipitation ranges from ~550 cm in the upper basin to ~100 cm near the mouth of the river (Kloehn et. al, 2008).

There were two dams on the Elwha river: the Glines Canyon Dam and the Elwha Dam. The Glines Canyon Dam was 64 m high, constructed from 1910-13, and on river kilometer 7.9, the Elwha dam was 32 m high, constructed in 1925-27, and on river

kilometer 21.6 (Duda et. al, 2011). The water trapped behind the dams created large reservoirs, which later collected sediment and large woody debris (Duda et. al, 2008). Lake Aldwell was estimated to have 4.6 +/- 1.5 million m³ of sediment trapped in it, while Lake Mills was estimated to have 21 +/- 3.1 million m³ of sediment trapped in it (NPS,2014). The dams have interrupted sediment transport, causing the riverbeds to coarsen, the beaches and delta to erode, and biological communities to change (Shaffer et. al, 2008). Deconstruction of dams began in 2011, and as of April 2014, all of Elwha dam had been removed and most of what was visible from above the river was removed from Glines Canyon dam; by October 2014 the dam removal will be finished (NPS, 2014). It is estimated that in two to five years most of the sediment will have been released and the river will return to normal turbidity levels (Randle et. al, 1996).

3. Methods

3.1. Sample Collection

Samples were collected from April 11-13, 2014, in areas identified as regions where sediment might accumulate in the coastal and nearshore environments (Fig 2.). These included the estuary, beach, sub-aerial and sub-aqueous delta, the river mouth, and inside and outside of the plume. Efforts were made to take samples that spatially represent the different sediment compositions and characteristics of each environment. At each of the nineteen sites on shore, ~500-g sediment samples were collected using a shovel to a depth of ~15 cm. Thirteen seabed samples were collected to spatially represent regions along and across the shore using a Shipek grab sampler onboard the R/V Clifford A. Barnes. Five ~15-L surface-water samples were collected in the river

mouth, inside and outside the visible surface plume. River discharge data was collected from the USGS site 12046260 at Elwha river diversion near Port Angeles (waterdata.usgs.gov).

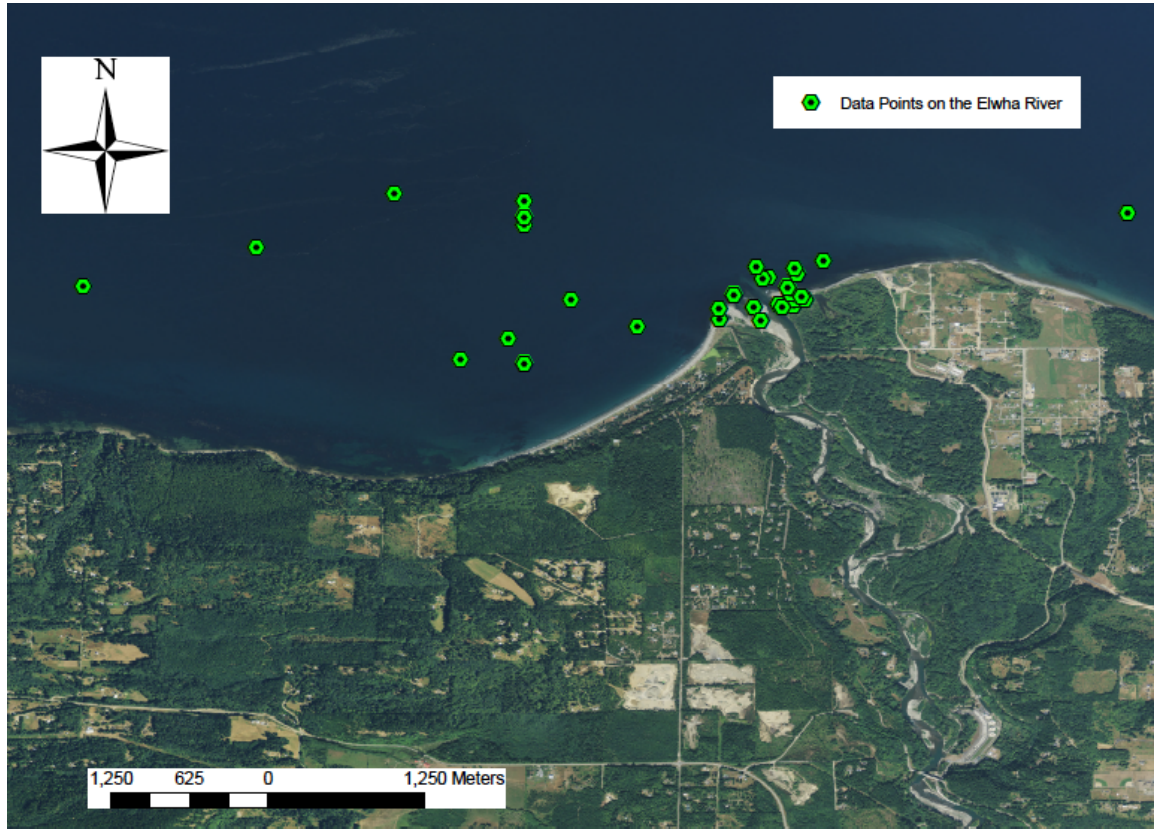


Figure 2. Location of sample sites on the Elwha River. Each dot represents where a sample was taken, with a total of 38 samples collected, nineteen of them onshore, thirteen offshore, and five water samples. Efforts were made to take samples that spatially represent all sediment compositions and characteristics of each environment. Aerial photo credit to U.S. Department of Agriculture

3.2. Surface Suspended-Sediment Concentration Procedure

Surface water samples were used to determine the suspended-sediment concentration (SSC) in the surface plume. A known sample volume was drawn through 0.7 μm , pre-weighed, glass fiber filters (GFF). Approximately ten filters were used for

each 15-L sample. Filters were then dried at 50°C and re-weighed to determine SSC. GFFs were used so they could later be combusted.

3.3. Loss-on-Ignition Analysis

To determine the amount of particulate organic carbon (POC) in each sample, loss-on-ignition analysis was performed, using a method adapted from Townsend, (2012) and Heiri et al., (2001). For the sediment samples, a 30-g homogenized sample was placed in a tin and heated at 50°C for 12 hours or until dry, placed in the dessicator until room temperature to prevent water absorption, and weighed.

Once dry, GFFs were also put in the dessicator for one hour and then weighed. Each sample's filters were placed together in a single tin. All samples were then combusted in a muffle furnace at 500°C for six hours (including the one hour of preheat). The oven was then turned down to 50°C and allowed to cool for 2 hours. The samples were then put in the dessicator for an hour to continue cooling to room temperature, and re-weighed. The weight lost during combustion is assumed to represent the POC content.

3.4. Grain-Size Analysis

In order to compare the carbon content of sediment across a range of particle sizes it is necessary to understand their relative distribution. Grain-size distributions were determined using a method derived from UW Sediment Laboratory manual (UW, 1998). First, a homogenized subsample of ~25-45 g was taken and weighed. Pebbles larger than -4 ϕ were removed, dried and individually measured and weighed. The sample was then wet sieved using a dispersant solution (NaPO₄) and deionized water, through a 4- ϕ sieve.

Sediment smaller than 4 ϕ was separated into sizes of 4 ϕ to to 8 ϕ using pipette analysis as described by the UW Sediment Laboratory manual (UW, 1998). Sediment larger than 4 ϕ was dried, weighed and placed in the Rotaptm for ten minutes. Samples were separated at intervals from -4 to 4 ϕ , which were individually weighed. Grain-size statistics were compiled and computed using Folk and Ward statistics, in the computer program Gradistat (Blott, 2010). Once carbon content was calculated from the loss-on-ignition method and standardized for grain size, the total amount of carbon on the nearshore and coastal areas was estimated. Surface area was calculated by the following $SA = ((D_{50}/2)^2) * 4 * \pi$.

3.5. Analysis of Total Particulate Organic Carbon Calculation of the Nearshore and Coastal areas

Using ArcGIS, sample locations were plotted with different colors on aerial photos. Each point's color represented a certain range of POC%, ranging from low to high carbon percentage. Averages of the samples in the estuary and nearshore complex were calculated, these were multiplied by the estimate in tonnes of sediment deposition from the reservoirs in these two locations (Curran et al., 2014) to create an estimate for carbon in the estuary and nearshore complex. These estimates were combined to approximate the total carbon in the delta, which in this study delta refers to the estuary, subaerial and subaqueous deltas.

4. Results

4.1. River Discharge

Samples were collected in April during low flow conditions, with average turbidity of ~ 69 FNU during the three days. Given the range of turbidity for the month of April, between 55-202 FNU, turbidity was low during the time sampled. On May 12, sampling was also conducted at low flow. Turbidity was at an average of ~75 FNU, which was relatively low for the range of 55-215 FNU that occurred during the month of May.

4.2. Surface Suspended-Sediment Concentration and Surface POC

The suspended-sediment concentration measured on April 11-13, 2014 inside the active plume was .045 g/L , inside the remnant plume it was .064 g/L and in the river mouth it was .182 g/L. The suspended-sediment concentration taken on May 12, 2014 near the river mouth was .177 g/L and outside the plume it was 0.0025 g/L. On either dates, the highest concentrations of SSC were found near the river mouth (Fig. 3). The concentration of surface POC during the April cruise, in the river mouth was .035 g/L, in the active plume was .015 g/L ,and in the remnant plume POC concentration was .018 g/L (Fig. 4). During sampling on May 12, concentration of POC near the river mouth was .0067 g/L and outside of the plume it was .0013 g/L (Fig. 4).

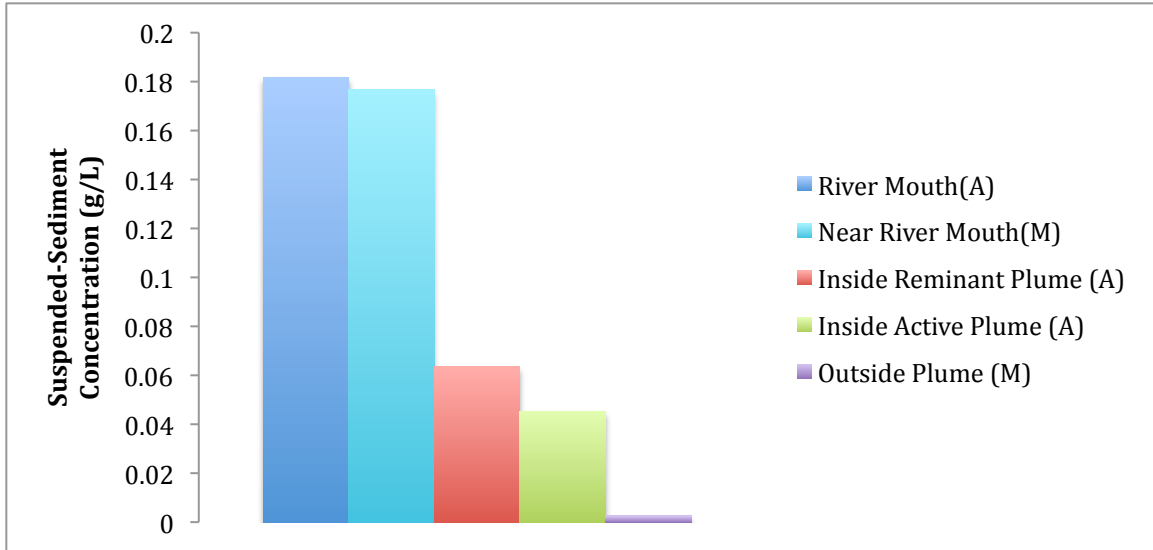


Figure 3. Surface suspended-sediment concentrations from water samples. (A) represents the samples collected during the April cruise, (M) represents the samples collected during the May cruise. Samples collected closest to the river mouth had the highest sediment concentrations.

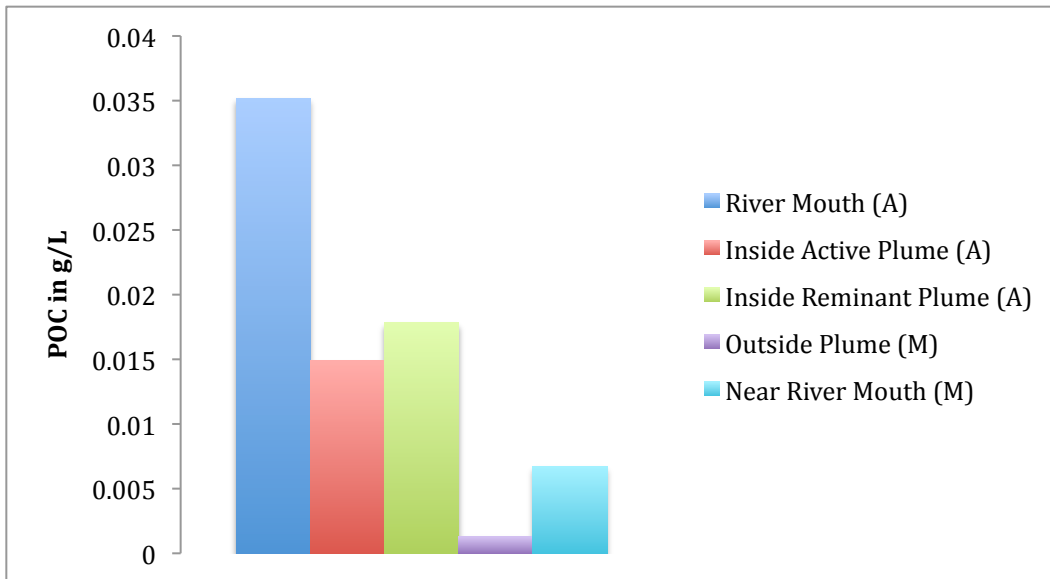


Figure 4. POC in suspended sediments. (A) represents the samples collected during the April cruise, (M) represents the samples collected during the May cruise. Trends were only found between samples in the same month, finding that near the river mouth had the highest percent of POC.

4.3. Grain Size

Grain size of samples collected was found to vary greatly between locations. The average D_{50} for onshore samples was 1.70 mm, which compared to offshore samples had a D_{50} of 0.17 mm (Table 1). Larger grain sizes were found onshore. D_{50} onshore ranged from 0.0035 to 27 mm, D_{50} offshore ranged from 0.0031 to 0.58 (Table 1). The average onshore mud percentage was 47%, compared to the average offshore mud percentage, which was 54% (Table 1). Grain-size analysis was not done on the suspended-sediment samples due to the sample size being too small. The percentage of mud in suspended sediment was assumed to be 100% due to its suspension near the surface for extended periods. Coarser sediment was found on the riverbed and subaerial delta (Fig. 5). Fine sediment was found in the estuary and subaqueous delta (Fig. 5).

Table 1. Results of the grain-size analysis and carbon calculations. The percentage of mud was calculated relative to the total sample mass. The percentage of mud in suspended-sediment concentration (SSC) was assumed to be 100%. Larger grain sizes were found onshore.

Grain Size Analysis			
	Median D_{50} in mm	Average D_{50} in mm	Range D_{50} in mm
Onshore	0.06	1.70	0.0035-27
Offshore	0.09	0.17	0.0031-.58
	Median Mud %	Average Mud %	Range Mud %
Onshore	58	47	0.2-100
Offshore	55	54	12.6-92
SSC	100	100	100-100

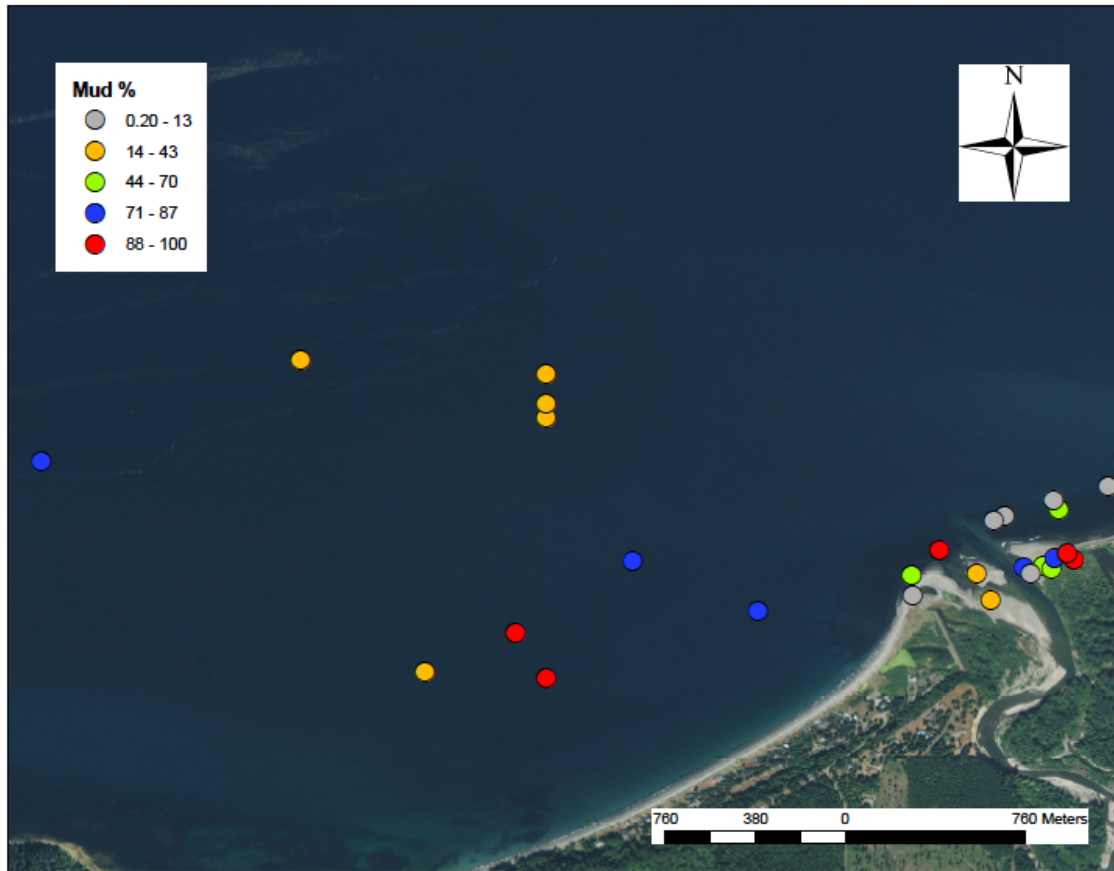


Figure 5. Percentage of mud deposited in the nearshore. The majority of mud was found in the estuary, the river mouth and the subaqueous delta.

4.4. Particulate Organic Carbon Concentration

Particulate organic carbon, calculated as a percent of each samples total mass, displayed greater variability onshore. In the onshore sites, the average percentage of POC was 3.6%, with a range from 0.76 to 14% (Table 2). In the offshore sites, the average percentage of POC was 3.5% with a range from 1.05 to 7.08% (Table 2). In the suspended-sediment concentration sites, the average percentage of POC was 21% with a range from 3.7 to 50% (Table 2). Fine sediment has more surface area, so to normalize for grain size between samples, POC was also calculated as a percent of the mud fraction

in the sample. Normalized for mud, average onshore percentage of POC was 78% with a range from 1.3 to 410% and offshore percentage of POC was 8.2% with a range from 1.2 to 20.4% (Table 3). Percentages over 100% indicated more carbon in the sample than mud. Grain-size analysis was not performed on the suspended sediment, so their carbon percentages could not be normalized to grain size. POC% was found to increase with mud percentage (Fig. 6).

Table 2. Percentage of POC concentrations, relative to the sample’s mass. Larger variation of carbon content was found onshore. Suspended-sediment concentrations (SSC) had on average the largest amount of carbon.

Carbon %		
	Range	Average
Offshore	1.05-7.08%	3.5%
Onshore	0.76-14%	3.6%
SSC	3.7-50%	21%

Table 3. POC concentrations normalized to mud percentages. The concentrations of carbon calculated as a percent of mud fraction in each sample. Percentages over 100% indicated more carbon in the sample than mud.

% POC normalized to mud		
	Range	Average
Onshore	1.3-410	78%
Offshore	1.2-20.4	8.2%

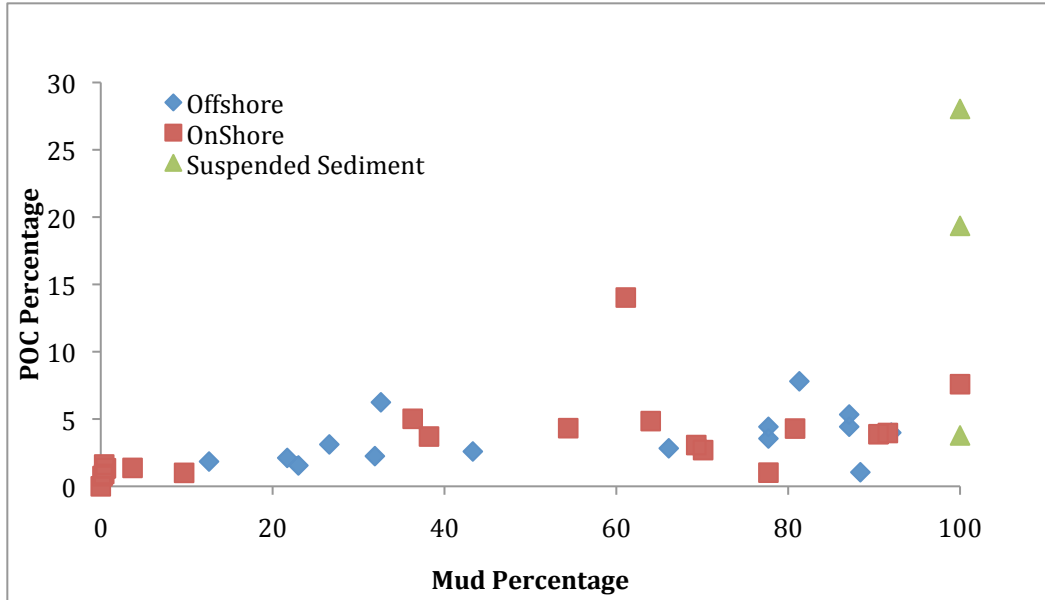


Figure 6. Mud percentage versus POC percentage. POC was calculated as a percentage of the sample’s mass. POC concentrations rose with mud percentages. Not all samples shown, POC percentage axis limited to 30%. Suspended sediments were assumed to be 100% mud.

4.5. Location of Particulate Organic Carbon

Each sediment sample’s percentage of POC was mapped using ArcGIS (Figs. 7-10). The highest concentrations of POC were found in the samples furthest offshore (Fig. 8), between the subaqueous delta and Freshwater Bay, and near the estuary (Fig. 7). When normalized to the percent mud, the highest concentrations of POC were found on the delta (Fig. 9), while the area between the sub aqueous delta and Freshwater Bay (Fig. 10), and the area near the estuary (Fig. 9) had the lowest concentrations of POC.

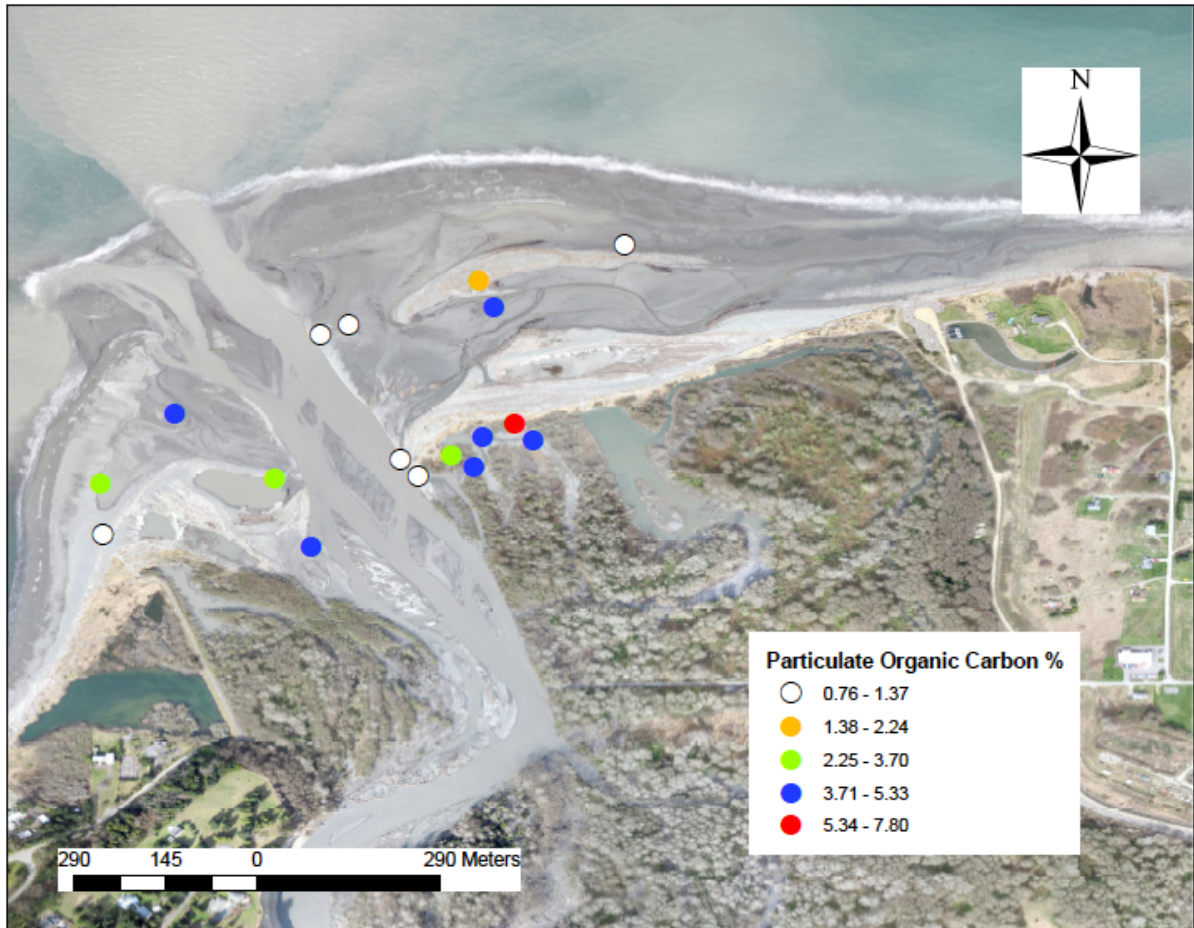


Figure 7. Particulate organic carbon percentage relative to sample's mass. Highest concentrations were found in the muddy deposits of the estuary, lower concentrations were found in the sand deposited on the sub aerial delta. Aerial photo credit to Andy Richie, National Park Service

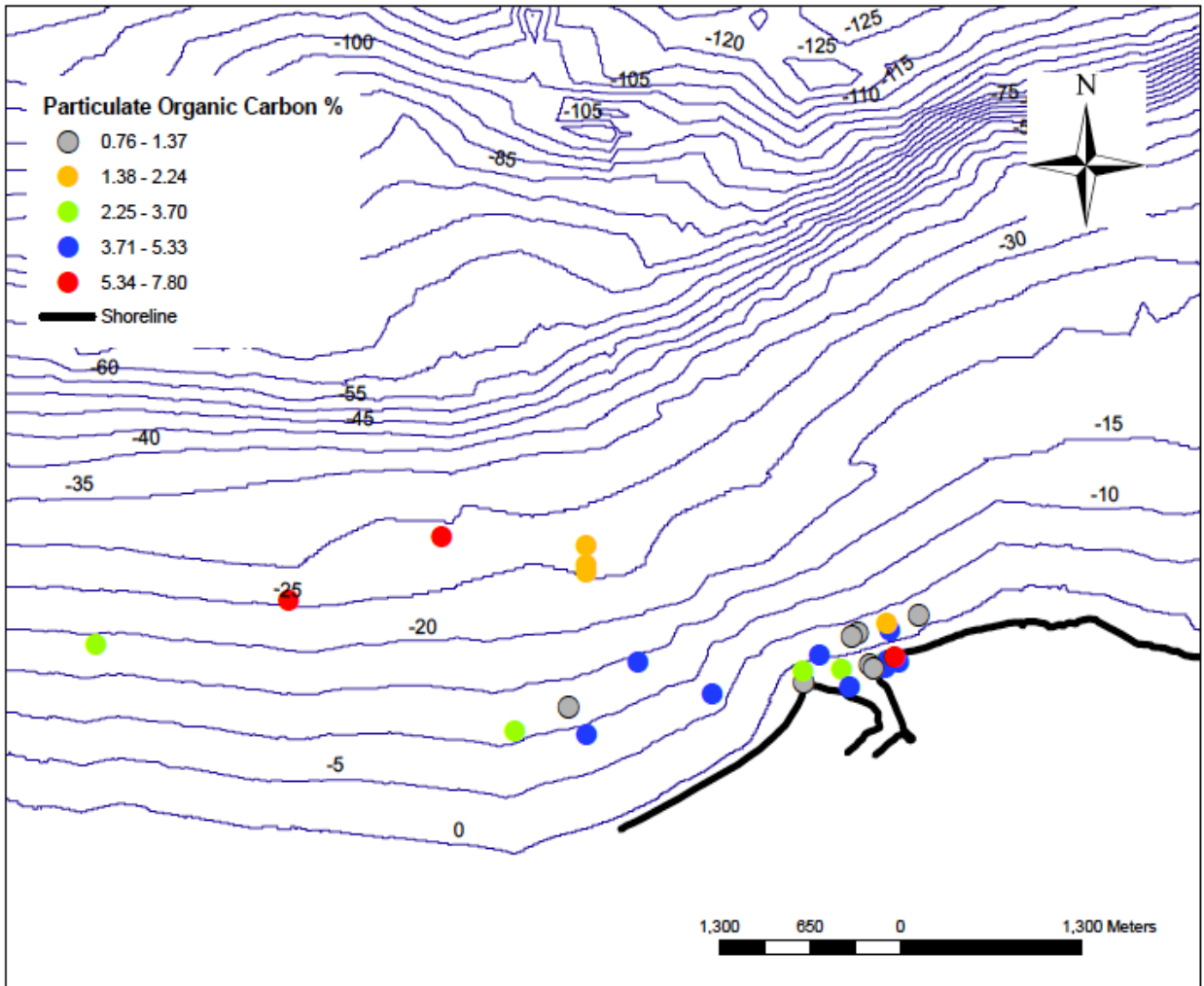


Figure 8. Particulate organic carbon percentage relative to sample’s mass. Samples tended to increase with carbon as the distance increased offshore. Highest concentrations of carbon were found in the deepest locations.

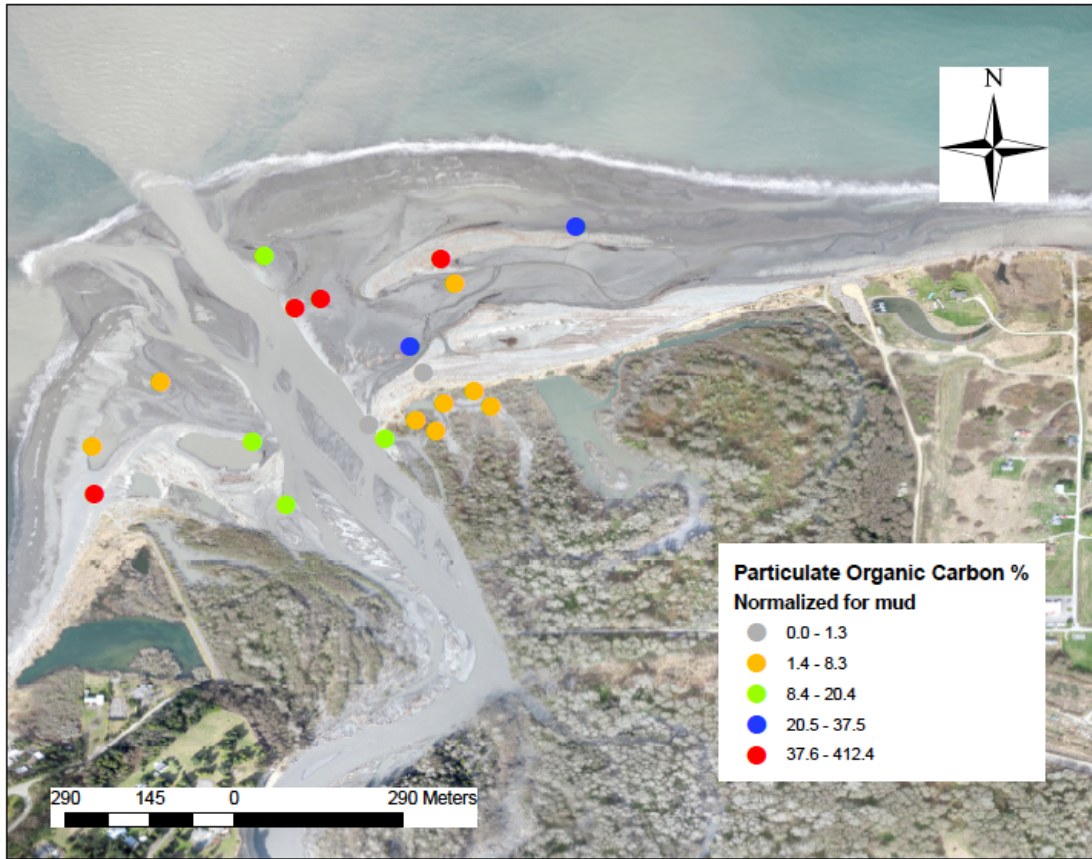


Figure 9. Particulate organic carbon normalized for mud percentage. The concentration of carbon calculated as a percent of mud fraction in each sample. The highest concentrations were on the sandy deposits of the subaerial delta. The lowest concentrations were on the muddy deposits of the estuary and sandy deposits of the subaerial delta. Aerial photo credit to Andy Richie.

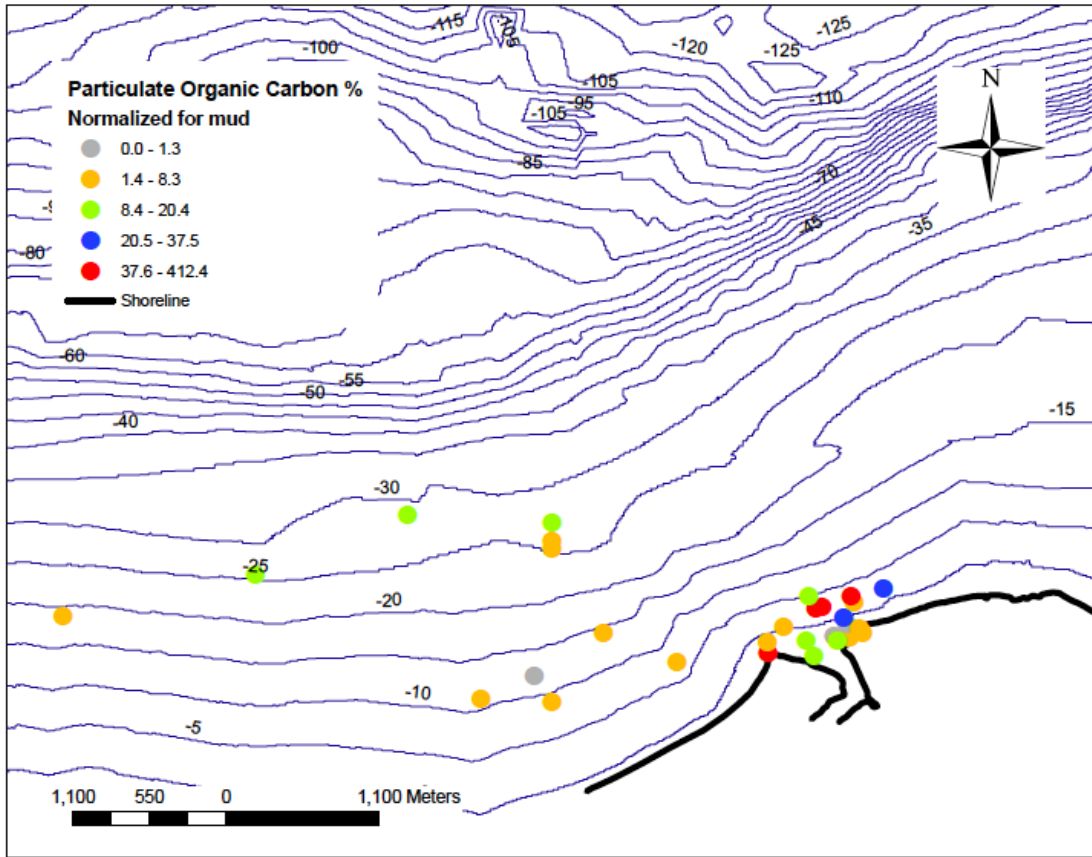


Figure 10. Particulate organic carbon normalized for mud percentage. The concentration of carbon was calculated as a percent of mud fraction in each sample. The lowest concentrations were found offshore.

5. Discussion

5.1. Surface Suspended-Sediment Concentration and Surface POC

In general, coarser-grained sediment falls immediately out of the plume near river mouths, while finer-grained sediment stays in suspension longer, causing the highest turbidity near the mouth of a river. Given that carbon sorbs to sediment particles, and finer-grained sediment has a higher surface area per volume than coarser-grained sediment, higher concentrations of carbon were expected further out from the river (Keil et al., 1997). Interestingly, the highest carbon concentration was observed in the river

mouth in May (Fig. 4). In April, the sample near the river mouth had the lowest observed carbon concentration of all the samples, excluding the sample collected outside the plume (Fig. 4). This variation may be due to marine carbon sources, such as diatoms, which are found on the water surface. Diatoms were found to increase the organic carbon content in marine sediments by up to thirty times from what would be expected from the organic carbon/surface area (OC/SA) relationship (Keil et al., 1994). Another factor may be a grain size difference between samples that was not analyzed due to the small amount of sediment collected on the filters. Looking at the April and May cruises separately the trend shows that percent of carbon by mass increases with the amount of sediment.

5.2. Relationship between grain size and carbon in particulate matter

Two types of carbon were examined for their POC content: small carbon particles, and large organic matter. The results showed a relationship between particulate organic carbon and grain size, where the percent of carbon increases linearly with the mud percentage (Fig 11). Mud has more surface area for POC to sorb to, relative to larger coarse material, an OC/SA relationship that has been well noted (e.g. Mayer, 1994). Given the scatter of the data, other variables must be responsible for the POC concentrations (Fig. 12). Carbon in the form of large woody debris does not contain a relationship with grain size, and may explain some of the variability observed in Fig. 12. Other literature suggests that oxygen content influences carbon content, with low oxygen areas having particles with more carbon coatings (Hedges and Keil, 1995). This may explain some of the observed variability, however oxygen concentrations were not measured on the seabed.

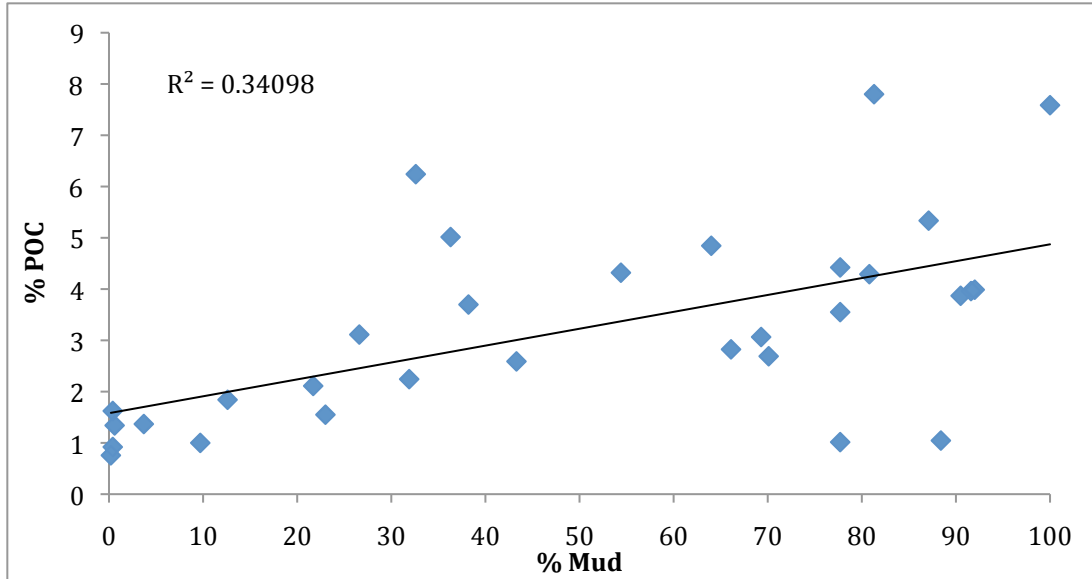


Figure 11. Mud percentage versus particulate organic carbon percentage. POC concentration increases with mud percentage. Given the scatter of the data, other variables are also responsible for carbon in the samples.

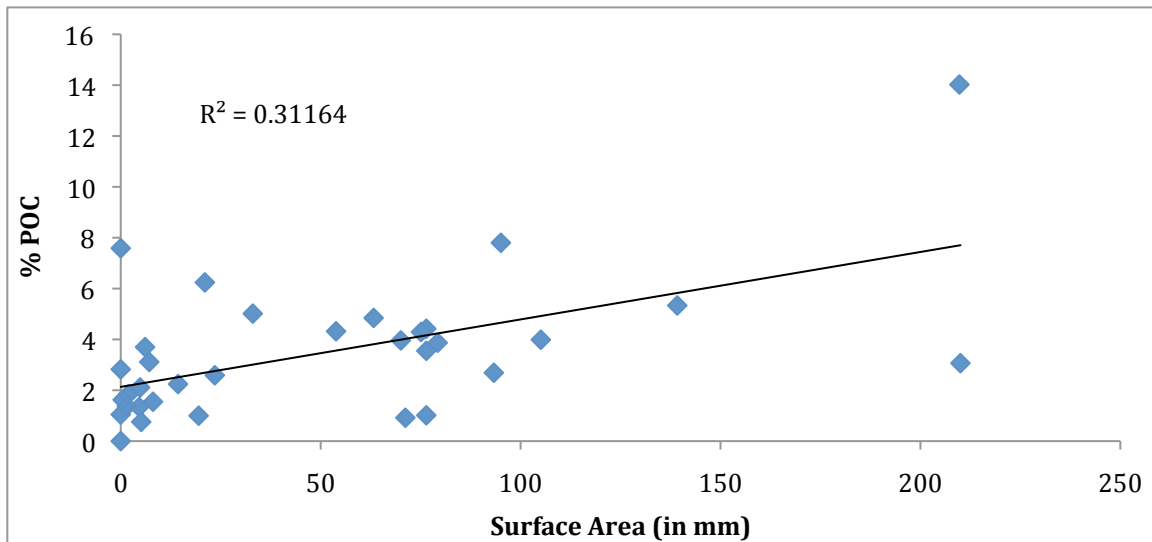


Figure 12. POC percentage by mass versus surface area. POC concentrations increase with surface area.

5.3. POC Depositions Locations

Based on the positive relationship between POC and mud, areas with a high mud percentage are therefore expected to have high carbon content. This trend is evident in

Fig. 7 & 8, where it is observed that the highest concentrations of carbon are furthest offshore, and the second highest concentrations are found in the muddy estuary deposits. Examining the grain-size distribution of the sample allows us to infer the POC percentage, with coarser-grained samples on average having lower POC percentage. The relationship between grain size and POC is strong enough to conceal other relationships that explain POC's variability. For example, when normalized for mud percent, the sinks of carbon are in opposite locations, and offshore and the estuary demonstrates the lowest concentrations of carbon (Fig. 9 & 10). This shows that while these areas may have more POC in percentage, this may be a reflection of increased surface area, rather than higher POC concentrations. The highest concentrations of carbon were found on the subaerial delta. These concentrations were observed in the organic mats, which are commonly found underneath the sand and from the large woody debris, both of which are sourced from material released from the former reservoir (Fig. 9). The large organic debris and organic mats are nearly 100% carbon and thus a significant sink of carbon. It is possible that due to their size, these particles are found near the river mouth and move with larger grain sizes, which causes them to stay on the delta. This study found the two varieties of organic carbon matter deposit in two different locations. The large surface debris settles on the subaerial delta, while the small particles of organic matter sorb to silt and clay, and are carried into the estuary and out to the ocean. This pattern of different organic matter types settling in different locations has been observed in other studies (Keil et al., 1994).

5.4. POC Estimate of the Elwha River Delta and its effect on the global scale

Using the percentages of carbon observed in each region and the estimate of total sediment released to date as calculated by Curran et al. (2014), this study made a rough estimate of carbon currently stored in the delta. Curran et al. (2014), estimates 200,000 tonnes of sediment have accumulated in the estuary. Based on this study's average carbon percent of 3.7% +/- 2.3% in the estuary, this suggests that a total of 7300 +/- 4600 tonnes of carbon deposited on the estuary (Table 4). The nearshore estimate of sediment accumulation was 4,400,000 tonnes (Curran et al., 2014), the average percentage of carbon was 3.7% +/-2.8%., making the estimate for the total in the nearshore delta 158,000 tonnes (Table 4). Combining these estimates gives an estimate for POC at 165,000 tonnes deposited +/- 124,000 tonnes (Table 4). Wing (2014) estimates the carbon stored in Lake Aldwell and Lake Mills, to be a total of 228,040 tonnes. His study used CHN (carbon, hydrogen, nitrogen) analysis to calculate total organic carbon. While our study used LOI analysis to calculate POC, which is less accurate, the results are comparable. Wing (2014) also found a range of carbon percentage of 0.7-1.7%, while this study's estimates of carbon percentage in the coastal area ranged from 1 to 14%; this suggests that the higher carbon percentage deposited nearshore. My estimates of POC percentage contains a large amount of uncertainty due to the following factors: samples were collected from the surface not taking into account the differences of POC via depth, a bias of selecting samples that are dense in carbon content, and estimates were based off of a sample size of 37. Furthermore, in this study carbon percentage was averaged over

the entire area rather than estimating for each area of similar composition, resulting in a higher estimate for the carbon on the delta.

Table 4. Location of deposition of carbon in tonnes. **Calculation based off estimate that half of the sediment in the reservoirs have been released, thus at least half of the carbon is released. *Calculated by Wing (2014).

Location of POC	Tonnes of Carbon
Reservoir Before**	~456,000
Reservoir After*	~228,000
Estuary	7300 +/- 4600
Nearshore	158,000 +/- 119.000
Total Carbon on Delta	165,000 +/- 123,000

Approximately 50% of the sediment in the reservoirs has been eroded (Curran et al., 2014). Given that carbon sorbs to sediment, this study estimates that over half of the carbon has been released from the reservoirs and into the environment. Multiplying Wing's (2014) estimate by two, this study's estimates of the initial amount of carbon in the reservoirs was ~456,000 tons of POC. The abrupt releases from the dam removals caused the river to swiftly erode through reservoir sediment, down to pre-dam riverbed conditions, creating deeply entrenched valleys out of the reservoir's sediment to either side. As a result, much of this sediment will stay in the reservoir, leaving as much as half of the carbon buried in this sink. Carbon burial is based on organic material, carbonate content and the rate of sediment accumulation (Einsele et al., 2001). The dam removal's sudden release of sediments will increase the sediment accumulation rates, increasing the amount of carbon buried. This implies that the dam removal resulted in a net increase of carbon stored in sinks in both the reservoirs and the delta, with most stored in the reservoir. Removal of the reservoirs prevented further CO₂ and CH₄ offgassing from

anaerobic decomposition (Louis et al., 2000), suggesting dam removal can help mitigate climate change.

5.5. Suggestions for Future Research

Further research needs to be done to fully understand how hydropower affects the carbon cycle, and whether dam removal on large rivers will also result in carbon storage. Suggestions for future studies include sampling using cores to take into account depth, a larger sample size and preselected randomized sample locations to prevent bias. Research to expand on this study would include measuring dissolved carbon and rates of carbon flux after dam removal.

6. Conclusion

As the perspectives on hydropower continue to shift, dam removal is becoming more common. Dams alter the carbon cycle and disrupt both the sediment and nutrient transport. This study found that the Elwha dam removals resulted in carbon being deposited in two locations. The large woody debris settled on the subaerial delta, while the small particles of carbon sorbed to silt settled in the muddy deposits of the estuary and offshore on the subaqueous delta. The sudden release of the river as the dams were removed trapped approximately half of the carbon sorbed to the sediment that stayed in the reservoirs. Roughly 165,000 +/- 124,000 tonnes of carbon were deposited on the delta. Due to the rapid sediment accumulation, carbon was buried at a higher than average rate on the delta, creating another carbon sink. So overall the dam removals removed the emission source for the reservoirs and created new areas of carbon storage, suggesting dam removal could play a role in climate change mitigation.

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