

**Using  $^7\text{Be}$  and textural characteristics to trace the source of sediment in the Elwha  
Delta**

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Marine Sedimentary Processes Research Apprenticeship, spring 2012

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*Keywords:* Elwha delta, beryllium-7, grain texture, sediment transport, sediment source

## **Abstract**

The removal of the two dams on the Elwha River provides a large-scale backdrop for sediment transport research. The demolition will stimulate sediment-laden flows downstream, directly impacting the Elwha delta and the marine environment. This study uses two different tracers to track sediment movement along the Elwha River and in the Strait of Juan de Fuca: beryllium-7 ( $^7\text{Be}$ ) and grain texture and mineralogy. The objective of this study is to draw conclusions about the source of sediment reaching the mouth of the river. Using these tracing methods, we found that (1)  $^7\text{Be}$  functions as a useful tool when researching sediment transport during dam removals, (2) the grains examined at the mouth of the Elwha River are a mixture of both sediment from upriver and from the glacially deposited bluffs along the shoreline, and (3) there is evidence of sediment from the former reservoirs making its way to the delta. The source of sediment reaching the delta is most likely a mixture of normal depositional processes due to fluctuating river discharge and reworking of the river bed sediments due to dam removal as the former reservoirs, Lake Mills and Lake Aldwell, erode into their pre-dammed form.

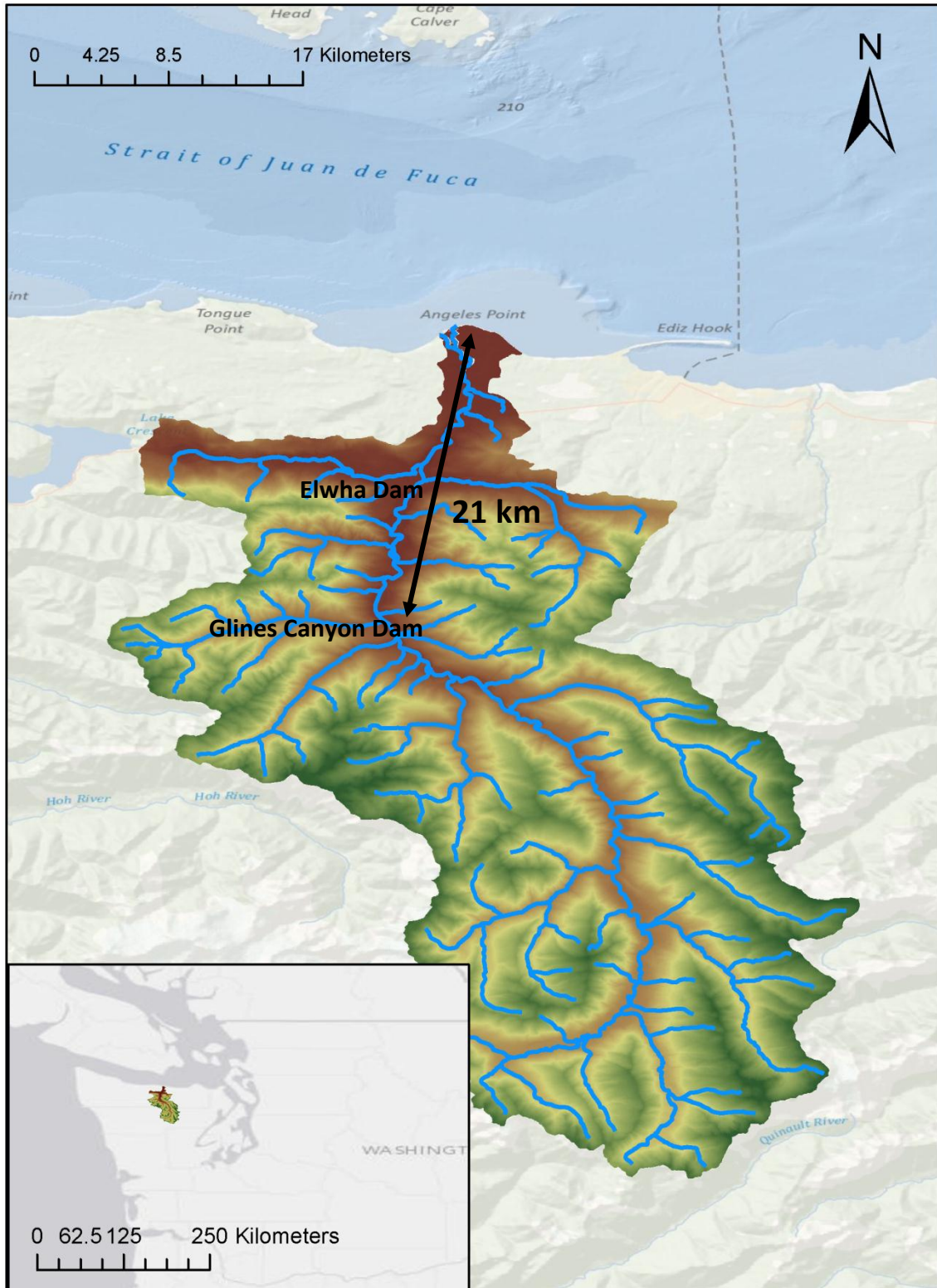
## **1. Introduction**

Scientists analyze the existence, absence, and abundance of radioisotopes to understand past events, explain current processes, and make future predictions. Beryllium-7 ( $^7\text{Be}$ ), a cosmogenic radioisotope produced in the atmosphere, can be used for such research.  $^7\text{Be}$  has a consistent fallout rate and can be detectable on surface soils and fine-grained sediments. This radioisotope is useful when considering specific, episodic events because of its short half life ( $t_{1/2} = 53.3$  days). With these features in

mind, scientists have been able to use  $^7\text{Be}$  as an effective tracer of sediment mobilization (Blake et al., 2002).

A second useful tracer of sediment transport is the comparison of grain mineralogy and texture. By tracking the composition, roundness, and the resemblance to a sphere (sphericity) of individual grains, trends can be observed throughout a certain sampling area. Unlike  $^7\text{Be}$ , this tracing tool will display a more long-term sediment transport trend within a certain sampling area.

These two tracers are useful tools when analyzing flood sedimentation on river systems, and may be valuable in a system that recently experienced a dam removal. For the past century, the Elwha River, which flows from the Olympic Mountains to the Strait of Juan de Fuca, was home to two dams: the Glines Canyon and the Elwha (Fig. 1). Both structures are now in the process of complete removal, and the effect of sediment transport on the entire fluvial system (from mountains to estuary) is a major topic of uncertainty. The case of the Elwha River is unique because of the short distance from the dams to the river mouth (~21 km from the Glines Canyon dam to the ocean), which means we can observe the impact of the demolition rather rapidly as sediment is transported downstream and into the marine environment. Because of the close proximity of the dams to the Strait of Juan de Fuca,  $^7\text{Be}$  analysis is potentially an effective technique to identify short-term sediment transport in the first stages of the removal. The use of these two tracers will lead to a better understanding about the source of sediment reaching the Elwha delta.



**Figure 1.** Elwha watershed highlighted within the Olympic Peninsula, Washington. Basemap courtesy of Western Washington University (<http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb/>).

## **2. Background**

### *2.1. Regional Setting*

The Elwha watershed is located on the Olympic Peninsula in northern Washington (Fig. 1). The Elwha River runs northward from the Olympic Mountains to the Strait of Juan de Fuca near Port Angeles, with a total length of ~71 km (Fig. 1). Much of the river is surrounded by old growth forest and ~83% of the river lies inside the Olympic National Park (Wunderlich et al., 1994). With the construction of the two dams, the major supply of sediment from upriver to the Elwha delta has been stifled and a gradual accumulation of trapped sediment in the two reservoirs has occurred (Lake Aldwell and Lake Mills) (Duda et al., 2011). This inability for sediment to move downstream has caused erosion of the shoreline on the eastern side of the Elwha River mouth (Warrick et al., 2009).

The river experiences varying weather as it travels from the mountainous upper reaches to sea level. There are, however, two dominant peaks of precipitation and, subsequently, river discharge throughout the year. One occurs during late spring and summer due to snowmelt, and the other during autumn and early winter due to heavy rainfall. Throughout a given year, the Elwha River has varying flow with a high mean flow of 340 m<sup>3</sup>/s (during the two peaks), and a low mean flow of 8.5 m<sup>3</sup>/s during late summer and early fall (Pohl, 2004).

### *2.2. Topical Background*

The use of <sup>7</sup>Be in marine geology is relatively new. Olsen et al. (1986) studied the fundamental properties of the isotope and its possible functions in research. They concluded that the critical variable for detecting <sup>7</sup>Be concentration is the length of time it

has been adsorbed to particles. This allowed scientists to use  $^7\text{Be}$  as an indicator of short-term, episodic events, in contrast to the long-term isotope tracers such as  $^{210}\text{Pb}$  and  $^{234}\text{Th}$  (Sommerfield et al., 1998). Studies using  $^7\text{Be}$  have investigated various aspects of sediment transport. In Blake et al. (2002),  $^7\text{Be}$  was observed to be an effective tracer of soil erosion, deposition on floodplains, and atmospheric impacts on the oceanic environment. However, it is uncertain whether  $^7\text{Be}$  functions as an effective tracer of sediment transport following dam demolition because the surface sediment being analyzed has been exposed to the atmosphere for a short length of time.

### **3. Methods**

#### *3.1. Field sampling*

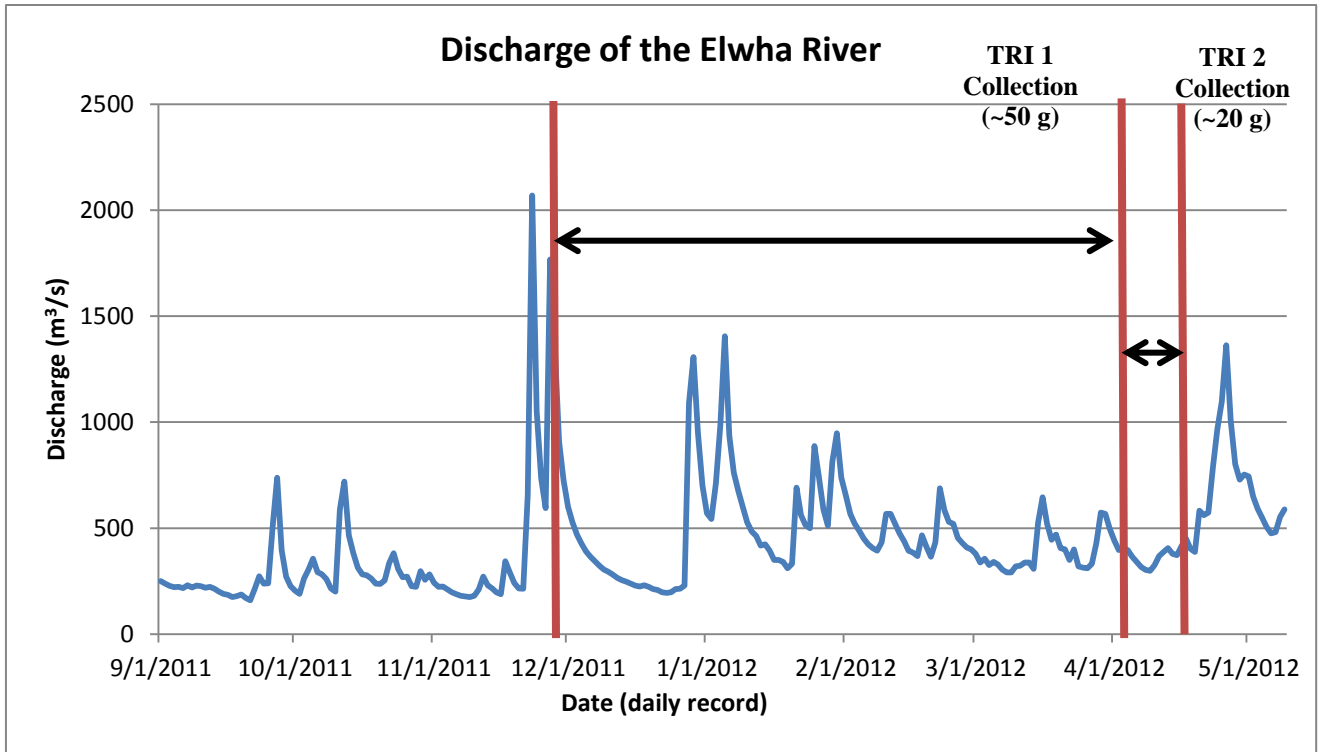
Sediment samples were taken at various sites along the Elwha River from the upper reservoir to the mouth of the river. The samples were collected during a week-long cruise to the Elwha watershed from April 2 to April 6, 2012 and an additional cruise on April 17, 2012. All collection sites were recorded using latitude and longitude coordinates, as well as an assigned waypoint number. Sediment samples were obtained using four different methods: (1) a scraper used to extract a surface sample from the various sites along the river (figs. 2 and 3); (2) a Shipek grab sampler to obtain seabed surface sediment from sites beyond the mouth of the Elwha river in the Strait of Juan de Fuca; (3) a Van Veen grab sampler to obtain bed surface sediment from sites in the Elwha river mouth; and (4) two cylindrical traps, each attached to a different instrumented tripods stationed at the mouth of the river. The tripods were positioned so as to collect sediment particles that settle out from the river's plume. Two tripod samples



**Figure 2.** Surface scrape sample measuring a cross-section of 20 cm × 20 cm and scraping off the first cm of sediment. Elwha River, former Lake Mills, WP 175.



**Figure 3.** Surface scrape, WP 178, collected in Altaire campground meadow. The dimensions used to collect the vegetation sample were the same as used for all surface scrapes (20 cm x 20 cm x 1 cm).



**Figure 4.** Elwha River discharge at McDonald Bridge, river gauge: 12045500. Blue line expresses daily discharge measurements in m<sup>3</sup>/s. Red lines indicate deployment time intervals for each tripod

were collected, one from each cruise. Along the river, samples were scraped approximately 1 cm deep in a 20 cm × 20 cm cross-section in order to have a high probability of <sup>7</sup>Be concentrations in the sediment (Fig. 2).

### *3.2. Radionuclide analysis*

Each sample was homogenized and approximately 100 g of the sample was sub-sampled, then weighed and put in an oven overnight to dry. Once dry, each sample was weighed again, and then ground into a fine powder using a mortar and pestle. They were then each placed in 60 ml straight-sided, high-density polyethylene counting jar to be analyzed through gamma spectroscopy using Low Energy Germanium Detectors (Sommerfield et al., 1999). The spectrum of <sup>7</sup>Be concentrations was not considerable enough to measure, so the presence or absence of the radioisotope (peak at 477 keV) at each site was recorded instead.

### *3.3. River discharge*

The tripod samples were collected two weeks apart from each other, one on April 5, 2012 and the other on April 17, 2012. River discharge was graphed for the Elwha River from September, 2011 to May, 2012 in order to correlate the tripod deployment time intervals with the episodic flooding of the river (Fig. 4).

### *3.4. Grain-size distribution*

Each of the samples was homogenized and sub-sampled again for grain size analysis. Approximately 40 g of wet sediment was taken from each sample and wet sieved in order to separate the mud from the larger size particles. The coarser sediment was then dried in an oven overnight and put through dry sieves ranging from -4 phi to 4 phi. Individual phi sizes within the mud fraction were measured using pipette analysis;

through settling velocity calculations a mud distribution from 4 phi to 8 phi was measured. An overall sample distribution from -8 phi to 8 phi was recorded and, from this distribution, the percentages of gravel, sand, and mud were found.

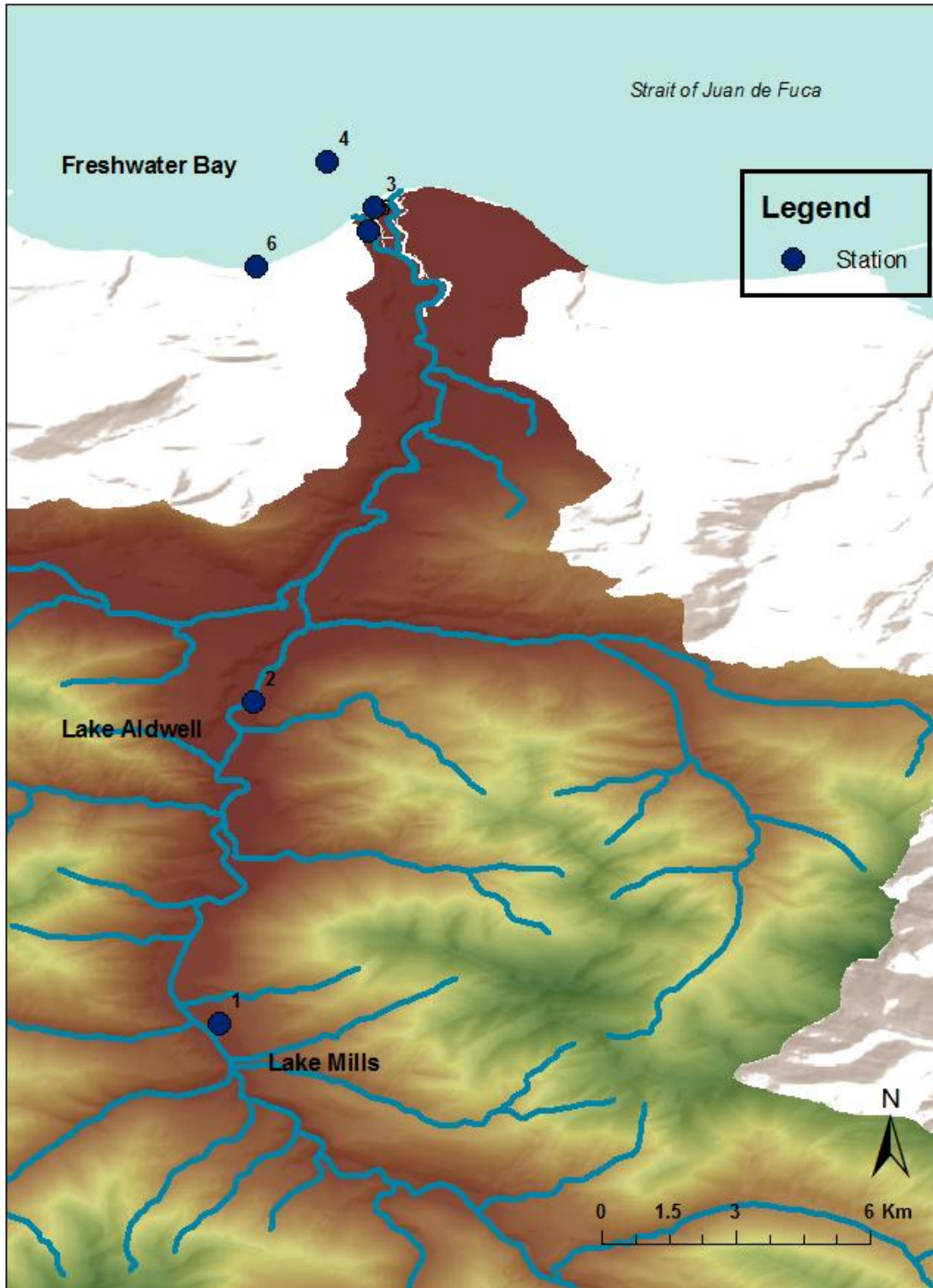
### *3.5. Sediment texture and mineralogy*

Six stations within the Elwha watershed and the Strait were examined under a dissecting microscope and analyzed for angularity, sphericity and mineralogy (Fig. 5). Using the classification scheme suggested by Folk, 1955, the spectrum of grain shape was recorded for each station, as well as mineralogy. For each sample, 100 individual grains were examined. Color determined the mineralogy of the individual particles, roundness was analyzed using a spectrum that ranged from very angular to well rounded, and sphericity was recorded using a range from discoidal to prismoidal, as discussed by Boggs (2001).

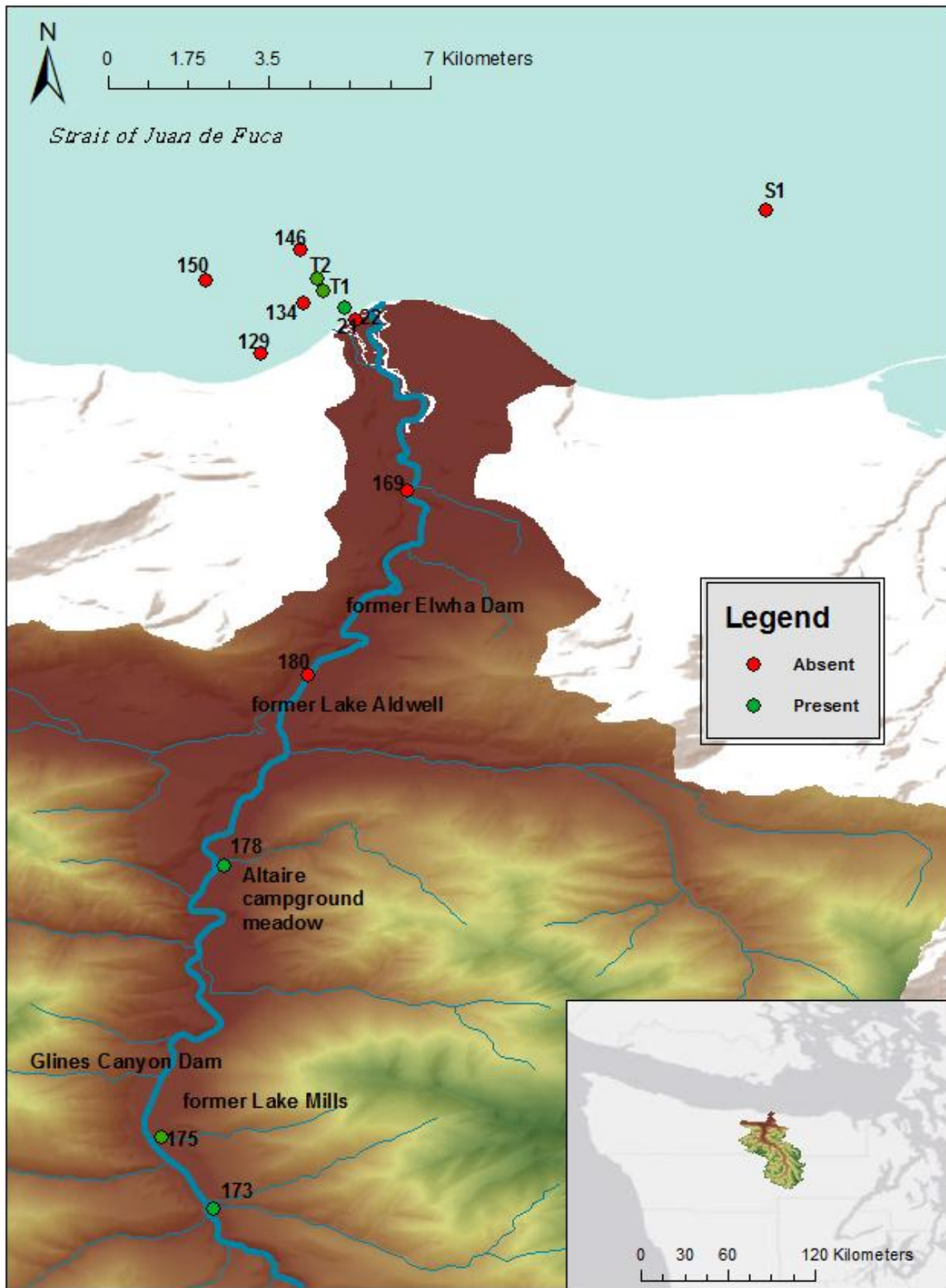
## **4. Results**

### *4.1. <sup>7</sup>Be signatures*

Beryllium-7 was analyzed on surface sediments from samples taken along the Elwha River and in the Strait of Juan de Fuca. At each site, the presence or absence of <sup>7</sup>Be was recorded (Fig. 6; Table 1). Throughout the sampling sites (from upper Lake Mills to offshore the river mouth), a patchy distribution of <sup>7</sup>Be was observed. The radioisotope was present in the now-exposed Lake Mills (WP 173, WP 175) and in a meadow beside the river (WP 178), however was absent farther north along the river (WP 180, 169, 22). A <sup>7</sup>Be peak was again seen in the river mouth (WP 21) and within the trap on the instrumented tripods (T1, T2), but the Shipek seabed samples collected



**Figure 5.** Six sampling stations for sediment texture analysis. At each site, grain sphericity, angularity, and mineralogy were examined. The station numbers coincide with the numbered labels on figures 4, 5, and 6. Basemap data courtesy of Western Washington University (<http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb/>).



**Figure 6.**  $^7\text{Be}$  presence or absence at each station on the Elwha River and in the Strait of Juan de Fuca. The green points mark where there was a  $^7\text{Be}$  in the sample, and the red dots indicate where there was no  $^7\text{Be}$ . Basemap data courtesy of Western Washington University (<http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb/>).

**Table 1**  
Summary of  $^7\text{Be}$  records and corresponding grain-size distribution.

WP	Location	$^7\text{Be}$ absent or present?	Grain distribution			Notes
			% Gravel	% Sand	% Mud	
173	Upper Lake Mills	present	0	96.3	3.7	<i>Southern end of Lake Mills.</i>
175	Lake Mills	present	0	47.2	52.8	<i>Surface scrape</i>
178	Altaire campground meadow	present	N/A	N/A	N/A	<i>Vegetation sample collected from meadow near river.</i>
180	Lake Aldwell	absent	2.9	69.3	27.8	<i>Surface scrape</i>
169	Foot bridge below dams	absent	0.2	14.1	85.6	<i>Surface scrape</i>
021	River mouth	absent	0.1	11.9	87.9	<i>Van Veen grab sample</i>
022	River mouth	present	0.1	44.7	55.2	<i>Surface scrape</i>
129	Offshore	absent	36.0	61.5	2.5	<i>Shipek grab sample</i>
134	Offshore	absent	56.8	40.5	2.7	<i>Shipek grab sample</i>
150	Offshore	absent	28.6	68.8	2.7	<i>Shipek grab sample</i>
146	Offshore	absent	70.5	25.7	3.8	<i>Shipek grab sample</i>
S1	Offshore	absent	85.3	13.2	1.5	<i>Shipek grab sample</i>
TRI 1	Below plume	present	N/A	N/A	N/A	<i>Trap collected particles (49.95 g), 11/30/2012 to 04/05/2012</i>
TRI 2	Below plume	present	N/A	N/A	N/A	<i>Trap collected particles, (19.38 g), 04/03/2012 to 04/17/2012</i>

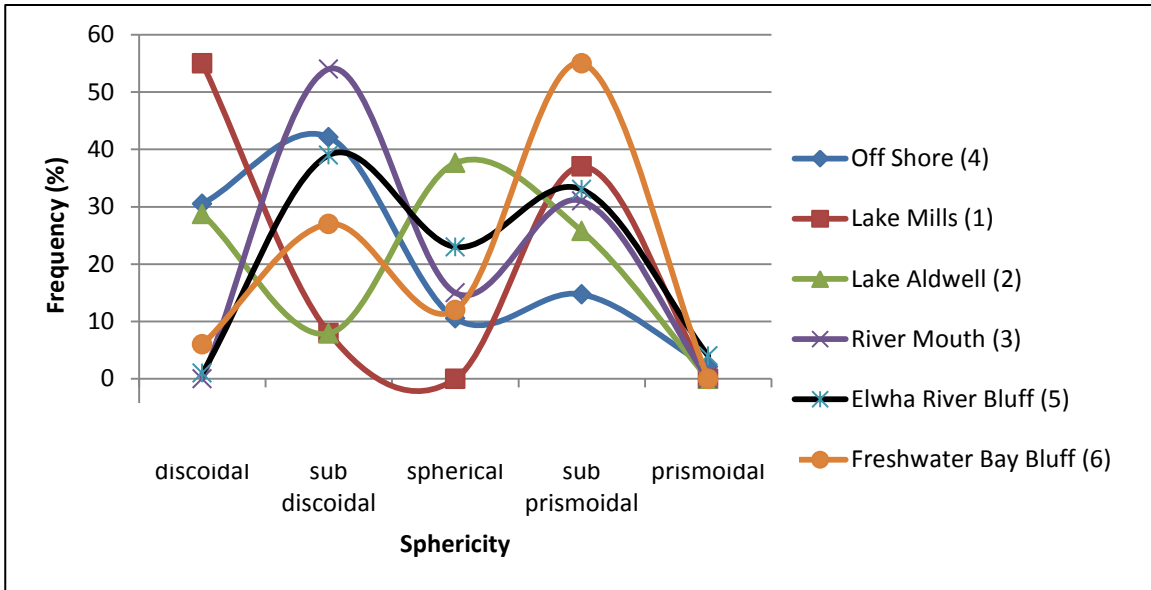
in the Strait of Juan de Fuca had no  $^7\text{Be}$  signature. The first tripod sample (T1) was extracted from the instrumented tripod on April 5, 2012 and had been collecting settled plume sediment since November 30, 2011. The second tripod sample (T2) was composed of sediment that had been trapped in the tripod from April 3, 2011 to April 17, 2011. The river discharge during these tripod deployment intervals can be seen in Figure 4. The river discharge during the collection interval of T1 displays several floods while the interval for T2 shows very little flooding. T1 had a weight of 49.95 g and T2 weighed 19.38 g, approximately 40% of the weight of T1 (Fig. 4).

#### *4.2. Grain-size distribution*

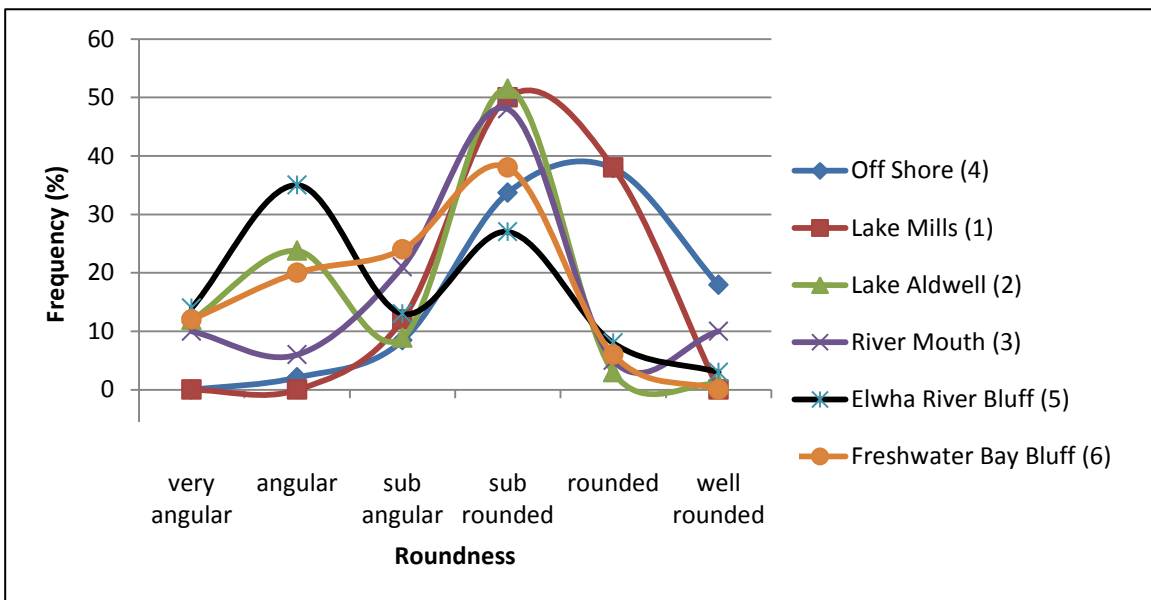
Grain-size distribution was analyzed for each sample that was collected for  $^7\text{Be}$  (Table 1). The five samples that were offshore of the Elwha River mouth (WP 129, 134, 146, 150, S1) had a minimal mud fraction and were mostly coarse sand, while the samples from the subaqueous delta (WP 021, T1, T2) were composed of much finer sediment and little sand. The samples from the Elwha watershed, with the exception of WP 173 in former Lake Mills, were mostly fine-grained as well.

#### *4.3. Sediment texture*

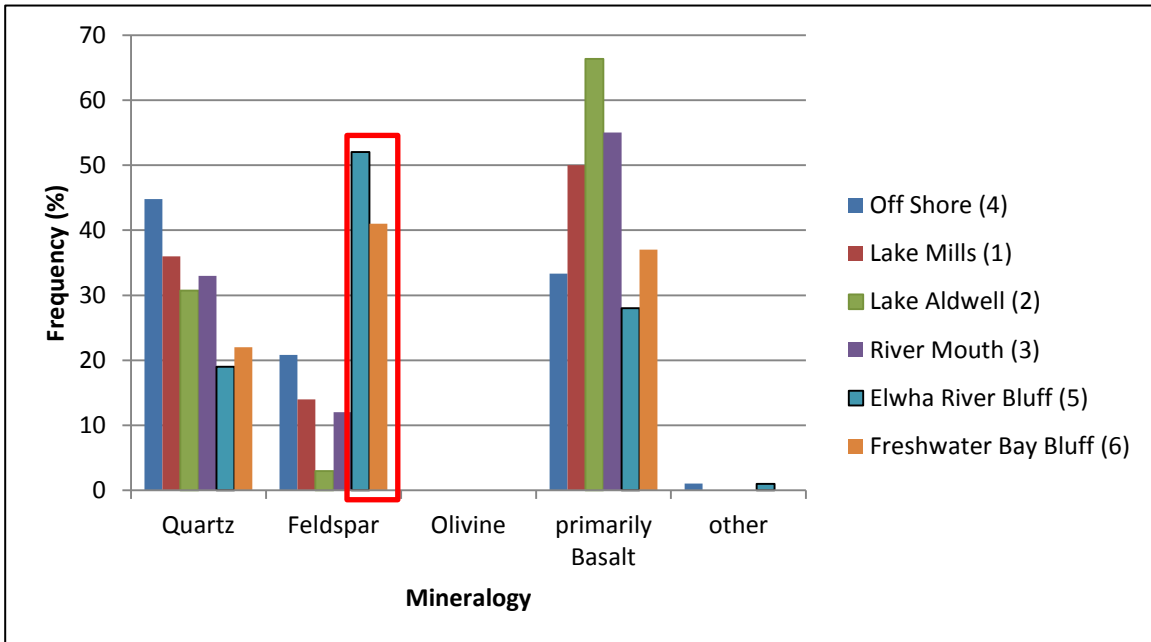
Analysis of sand grains consisted of a comparison between roundness, sphericity, and mineralogy at six different sampling stations (Fig. 5). Differences in sphericity were observed; grains from the now-exposed reservoirs were more frequently distal from a spherical shape, whereas grains from stations closer to the mouth of the river and the Strait of Juan de Fuca were more spherical (Fig. 7). A distinction in roundness between the bluff samples and the other four samples was observed. The majority of



**Figure 7.** Distribution of sphericity among grains at six locations. The x-axis represents the comparison to a sphere as a range from discoidal to prismoidal, a method suggested by Boggs (1995). The numbers next to each station label relate to the numbered stations in Figure 3.



**Figure 8.** Distribution of roundness among grains at six locations. The x-axis ranges from very angular to well rounded, a classification scheme by Folk (1955). The numbers next to each station label relate to the numbered stations in Figure 3.



**Figure 9.** Distribution of mineralogy among grains at six different locations. The x-axis lists four different types of compositions: quartz, feldspar, olivine, and basalt. The numbers next to each station label relate to the numbered stations in Figure 4. The red box highlights the change in mineralogy on the two bluffs compared to the other four stations.

grains found upriver, in the mouth, and offshore was sub-rounded while the grains observed in the bluffs were more angular (Fig. 8). Concerning mineralogy, basalt, quartz, and feldspar were observed at all six stations (Fig. 9). At the two bluff sites there was an increase in feldspar and a slight decrease in quartz.

## **5. Discussion**

### *5.1. $^7\text{Be}$ distribution*

An irregular distribution of  $^7\text{Be}$  was seen throughout the Elwha watershed and in the Strait of Juan de Fuca. No  $^7\text{Be}$  signature was detected on the river bank downstream of the two dams, nor was it seen beyond the delta in the basin of the Strait. However, the samples from farther upriver and the trapped sediment from the plume displayed a  $^7\text{Be}$  peak, and thus the overall  $^7\text{Be}$  record formed an inconsistent distribution (Fig. 6). The  $^7\text{Be}$ -laden sediment that reached the nearshore tripod site during the two tripod deployment intervals must have been carried from upriver because other sources along the coast would have lost their  $^7\text{Be}$  signature. While both tripod samples imply that the sediment came from upriver, we can infer different upriver sources based on the correlation between deployment time intervals and river discharge (Fig. 4). Within the first tripod sample (T1) collection dates, there were several discharge fluctuations, implying the sediment in the subaqueous delta came from rainfall and soil erosion acting on the river. T2 had collected for only two weeks and had 40% the weight of T1 which had been collecting for 4 months. The amount of sediment that had collected in these two weeks does not seem to match the amount of river discharge seen in that same time interval (Fig. 4). This disparity implies that the sediment reaching the Strait was not from

river discharge, rather from the reworking of the former reservoir sediments. From these findings, we can see that the source of sediment in the subaqueous Elwha delta is a mixture of soil deposition associated with fluctuations of river discharge and the erosion of former lake beds as the reservoirs reform into river systems.

This study also finds that  $^7\text{Be}$  can be an effective tool for tracing sedimentation after a dam removal. It has been proven that  $^7\text{Be}$  is a good tracer for episodic sediment transport (Sommerfield et al., 1998), however it was uncertain if this would hold true for dam removal projects. In such cases, the examined sediment has had atmospheric exposure for a short period of time so the amount of  $^7\text{Be}$  accumulation is unknown. Through this study, we see that sediment that had been exposed to the atmosphere for less than four months could obtain measurable amounts of a  $^7\text{Be}$  signal (WP 175). This confirms that  $^7\text{Be}$  has a rapid and constant fallout rate, and shows that it can be used as an effective tracer for events like dam removals.

### *5.2. Grain-size distribution*

The grain-size distribution for different sites is reflected on Table 1. We know that grain size impacts the ability for  $^7\text{Be}$  to adsorb to particles (Wallbrink et al., 1996) and we see a varied grain-size composition throughout the different sites. This shows limitations to the consistency of our study and can offer an explanation for the absence of  $^7\text{Be}$  at certain sites. The offshore samples collected via Shipek grab sampling were composed of mostly coarse sediment and had no  $^7\text{Be}$  signal, while the samples from upriver contained finer sediment and were more likely to obtain a  $^7\text{Be}$  signature (Table 1). Thus, this grain-size irregularity could contribute to the patchy distribution of  $^7\text{Be}$  seen throughout the watershed and in the samples collected in the Strait.

### 5.3. Grain texture and mineralogy

Six sites were examined for grain mineralogy along the Elwha River and on the coastal bluffs near the mouth (Fig. 4). Throughout the watershed and offshore the mouth of the Elwha River we found mostly basalt and quartz with some feldspar (Fig. 9). The site from the Elwha River bluff and the Freshwater Bay bluff (Fig. 5) had less quartz and more feldspar. This distinctive mineralogy in the bluffs could be the result of till formation from large ice lobes that migrated through the Puget Sound, bringing foreign sediment to the area (Anderson, 1967). The mineralogy from the reservoirs are parallel to the mineralogy from the delta, which is interesting when combined with the roundness data.

Differences in angularity or roundness were observed between the same six locations. We see a distinct difference in roundness in the bluffs compared to the roundness observed along the river and in the delta (Fig. 8). The grains found in the river have traveled farther and been impacted by fluvial processes that continuously round them, whereas the grains from the bluff were deposited from glacial movement and thus less rounded. The range of roundness observed on the delta was the same as the roundness observed upriver (Fig. 8). This finding combined with the similar mineralogy implies that the grains found in the delta are dominantly from sources upriver.

Sphericity has been argued to play the most important role when explaining different sources of grains based on texture (Barrett, 1980). There have been many studies examining the change in pebble shape throughout a river system, however there has been less analysis on sand-size grains. Because transportability varies with form, the pebbles that are seen higher up in a river system tend to be less spherical while the grains

that get carried all the way to the coastal environment tend to be more spherical (Boggs, 2001). The sand-grain analysis from this study follows that same trend (Fig. 7), implying that sand texture is affected by the same processes that affect larger gravels and pebbles. While this may be true, different studies have shown that the smaller a grain gets the harder it is for its shape to be affected by such processes (Santamarina et al., 2004). On top of this, our sphericity results are also not conclusive because the presence of the dams has prohibited sediment from undergoing this observed natural process.

Despite the changes in sphericity being inconclusive, we can draw conclusions based on the differences seen in mineralogy and roundness. Because the two samples from the bluffs have clear grain differences when compared to the samples from along the river and on the delta, we can conclude that the grains found in the mouth and offshore are primarily from upriver.

#### *5.4. Source of sediment in Elwha delta*

Based on our results from mineralogy, grain texture, and  $^7\text{Be}$  analysis, we are able to identify the sediment from the Elwha delta as sediment from upriver. The near century in which the presence of the dams prohibited the majority of river-supplied sediment to reach the marine environment caused the dominant source of sediment in the delta to be from the bluffs. However, based on our results from the two tripod samples, we can see evidence of the impact from the removal as the release of reservoir sediments is being carried to the delta. We can predict that the composition of sediment in the mouth will shift to a more balanced mixture of sediment from both the bluffs and from upriver.

## **6. Conclusion**

When identifying the source of sediment in the Elwha delta, we can use these two tracers to draw certain conclusions. First, we can say that sediment in the delta is a mixture of bluff erosion and sediment carried from upriver. Second, due to the comparison of the two tripod samples and corresponding river discharge records, we are able to conclude that the previously trapped sediment from the former reservoirs is being carried to the marine environment. Because these results provide an indication that such sediment is reaching the Elwha delta, we can expect to see interesting changes to the nearshore environment in upcoming months.

### **Acknowledgments**

I would like to thank my professors, Dr. Andrea Ogston and Dr. Charles Nittrouer, and my T.A. Emily Eidam for their font of knowledge and continuous support. I also want to thank NSF, Friday Harbor Labs, UW Provost, Holly and Henry Wendt for which their support made this project possible, and the UW sediment lab, especially Katie Boldt for helping with <sup>7</sup>Be analysis and Rip Hale for helping with data collection. Lastly, I want to thank my fellow research apprentices; I could not have asked for a better research team.

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