Predicting Secondary Reservoir Sediment Erosion and Stabilization Following Dam Removal

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Abstract

In the early 1900s two hydroelectric dams were built along the Elwha River in northwestern Washington State. In order to restore the Elwha River ecosystem and native anadromous fish runs, the dams are scheduled to be removed. During and after removal, accumulated reservoir sediments are expected to erode downstream. The exposed sediments remaining after the dam removals and initial erosion will be prone to continuing secondary erosion and should be stabilized as quickly as possible. Experiments were performed on both fine and coarse sediment from underneath Lake Mills (formed by the Glines Canyon Dam) to determine strategies to stabilize the sediments under moderately high rainfall. Two slopes (5° and 15°) and two rainfall intensities (high and low) were examined along with mulch, plants, or polyacrylamide (PAM) stabilization treatments. The Revised Universal Soil Loss Equation (RUSLE) was used in comparison with experimental results to refine predictions. In both the experiments and as modeled with RUSLE, the coarse sediment was much less erosive than the fine sediment. Comparing the controls, the experiments had a similar erosion rate to the RUSLE model. For fine sediment, the mulch treatment was much more successful in preventing erosion in the experiments whereas the plant treatment was more successful as modeled with RUSLE at 5° slopes, but not 15° slopes. Mulch reduced erosion up to 99%, PAM up to 87% and plants by 33% in the experiments. A combination of stabilization treatments may be the most effective method of erosion reduction.

Introduction

In the early 1900s two hydroelectric dams were built along the Elwha River on the Olympic Peninsula in northwestern Washington State. The 32 m high Elwha Dam was completed in 1913 only 8 km from the river's mouth and forms Lake Aldwell, which has a water storage capacity of 9.9 x 10^6 m^3. The Glines Canyon Dam was completed in 1927 approximately 22 km upstream from the mouth, stands 64 m high, and forms the Lake Mills reservoir with a water storage capacity of 5.0 x 10^7 m^3. Neither dam includes fish passage facilities, therefore runs of anadromous fish have been blocked from more than 112 km of the Elwha River and its tributaries, limiting fish to the lower 8 km of the river below Elwha Dam (DOI 1995a).

In 1992, Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, directing the Secretary of the Interior to fully restore the Elwha River ecosystem and native anadromous fisheries (DOI 2005). Subsequent analysis by the National Park Service (NPS) determined that the removal of both dams is necessary to restore the ecosystem and the fisheries (DOI 1995a, 1996a). Pursuant to the Act, the Secretary was authorized to acquire the Elwha and Glines Canyon dams; however, it was not until February 29, 2000, that the acquisition was completed. Dam removal is expected to begin within the next 10 years and will last approximately two years as the dams will be removed in controlled increments to manage sediment erosion (DOI 1995a).

During the removal of the Elwha and Glines Canyon Dams, much of the sediment trapped in the reservoirs behind the dams is expected to erode downstream. As of 1994, it was estimated that 10.6 million m^3 of sediment are trapped in Lake Mills (the upstream reservoir) and 2.98 million m^3 of sediment are trapped in Lake Aldwell (DOI 1996b). Of all the 13.6 million m^3 of trapped sediment, about half (52%) is fine ($\leq$ 0.075 mm) [silt- and clay-size particles] and the other 48% is coarse textured [sand, gravel, and cobbles] (Table 1; DOI 1996b). Computer models predict between 15-35% of the coarse sediment and approximately 50% of the fine sediment will be

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TABLE 1. Estimated sediment particle size and volumes for Lake Mills and Lake Aldwell (DOI, 1995b).

	Volume in 10^6 m^3				
	Clay & Silt <0.075 mm	Sand 0.07<5 mm	Gravel 5<75 mm	Cobbles 75<300 mm	Total Total
Lake Mills	5.10	3.90	1.40	0.15	10.6
Lake Aldwell	1.98	0.83	0.12	0.38	2.98
Total of Both Lakes	7.08	4.73	1.52	0.19	13.6

eroded from both reservoirs during and after dam removal (DOI 1996b).

The exposed sediments remaining after the lakes are drained will be prone to secondary erosion and therefore will need to be stabilized as soon as possible. Although the NPS intends to extensively plant with native species along the reservoir margin, much sediment will be exposed and subject to erosion until plants can grow to fully cover the site. Mulches or soil conditioners are sometimes used when vegetation cannot be established or is not established quickly enough to stabilize the soil. Mulch, in the form of wood chips, which is locally available, could be an economical way to prevent erosion. Chemical additives could also be used to stabilize the sediments in the most highly erosive areas. For example, polyacrylamide (PAM) has been shown to be effective in developing stable soil aggregates. Polyacrylamide is a synthetic polymer that binds soil particles and reduces crusting, thus increasing pore space and infiltration (Whisenant 2003). PAM can reduce soil loss, stabilize soil until seeds establish, reduce sediment runoff and runoff turbidity, and improve water infiltration (Ajwa and Trout 2006; Levy et. al 1991). Although a large application of PAM may not be economical, it has been shown that even small amounts are helpful in preventing erosion (Brady and Weil 2002). Physical barriers such as large woody debris or silt fences can also help avert erosion (Whisenant 2003).

Erosion prediction models can help predict erosion losses and compare alternative strategies (Whisenant 2003). The Universal Soil Loss Equation (USLE) is an equation designed to estimate the amount of soil loss in an average year caused by sheet and rill erosion at a given location (Wischmeier et al. 1965). USLE was revised and updated in the early 1990's (USDA-ARS 2001). The Revised Universal Soil Loss Equation (RUSLE) could be a useful tool for predicting soil erosion levels during and after dam removal.

Since it is expected that about half of the sediment will erode and half of the sediment will remain *in situ* it is important to predict what will happen to the sediment that both leaves and stays. Our objective is to demonstrate through a series of experiments, using three different treatments and controls, strategies to stabilize the sediments that remain after the initial major erosion. Such information can serve two purposes: first, to show which locations and textures of sediments may be most susceptible to erosion and, second, to demonstrate which treatments may be most effective in reducing erosion in the most susceptible areas.

Study Area

The study site is located along the Elwha River in the northeastern section of Olympic National Park approximately 22 km upstream of the mouth at Lake Mills. Lake Mills was created in 1927 after the Glines Canyon Dam was constructed. Since completion of the dam, the Elwha River has built a 914 m long, 20-24 m thick delta at the south end of the Lake Mills reservoir basin (DOI 1995b). According to the DOI (1995b) the main sources of sediment to the Lake Mills basin are fluvial erosion along the Elwha River and its major tributaries.

For this project, approximately 0.75 m^3 of fine sediment was removed by scuba divers from underneath Lake Mills. Coarser sediments were removed from the delta area which was accessed by boat.

Methods

Erosion Experiments

Two boxes of 84 x 28 cm were built to assess potential erosion. One narrow end of each box had a slightly lower wall to allow sediment to runoff but prevented slumping. Boxes were set upon tables allowing the boxes to be sloped at different angles. A plastic tub was placed on the ground under the opening of the box and reached the entire length of the box to catch sediment and water that eroded. Experiments were performed on both fine and coarse sediments at two slopes, two rainfall intensities, and with three stabilization treatments. Particle size of the fine and coarse material was determined using the hydrometer method with samples that were pretreated using hydrogen peroxide and citrate-dithionate to remove organic matter and iron (Gee and Bauder 1986). Two slopes of 5° and 15° were chosen to examine the effect of slope on erosion; a few experiments were performed at 1°. Three treatments were chosen as possible methods to reduce erosion: 1) mulch in the form of wood chips, 2) plants in the form of owlfruit sedge (*Carex stipata* Muhl. ex Willd.) and 3) PAM. Four replicates were completed for each set of experiments. After each replicate, the old sediment was removed and replaced with new sediment. Sediment was stored in covered buckets prior to use in erosion experiments. Pictures were taken before and after each precipitation event. A bulk density sample and a moisture content sample were taken from each box before and after the precipitation event. The sediment that ran off during the experiment was poured into containers and dried at 105°C for ≥ 24 hours and weighed.

High and low rainfall intensities were chosen based on information from the Elwha Ranger Station precipitation data (WRCC 2006). The daily precipitation average and extremes were used to determine two approximate rainfall intensities. The high-intensity rainfall was chosen to mimic a short, intense storm while the low-intensity rainfall mimicked a heavy, steady rainfall. Six beakers for each box collected a representative amount of precipitation and were measured and averaged to determine the exact rainfall amount. The high-intensity precipitation was produced by a sprinkler which ran for 10 minutes on each box. The average cumulative amount was 3.13 cm at a rate of 18.8 cm/hr. The low-intensity precipitation was produced using 3 Raindrip (Fresno, California) landscape misters which were placed in each box. These operated for 45 minutes and the average rainfall amount of 3.98 cm at a rate of 5.3 cm/hr. The total rainfall amount was approximately equal for both intensities; however, there was a range in rainfall rate possibly due to changes in water pressure to the experiment site. Precipitation ranged from 1.60 cm to 5.46 cm for experiments, with 1.60 to 4.78 cm for the high-intensity experiments, and 2.16 to 5.46 cm for the low-intensity precipitation experiments.

Experimental treatments were conducted on fine or coarse sediment, with 5° or 15° slope, and with both low and high precipitation intensity (Table 2). Slopes, one low and one moderate, were chosen based on what could be expected after dam removal. As limited plants and coarse-textured sediment were available, and as most reservoir sediments are fine textured, only one experiment was conducted using planting in the coarse-textured sediment. For the fine sediment experiments, the sediment was left overnight in the box before the experiment was run in order to allow settling. Also, some of the fine sediment experiments were run over a period of two days. On the first day, one run of the experiment was performed, then it was covered and left to sit overnight again, and then run the second day. This was done to examine the effect of erosion over time and determine the effect of the natural organic debris contained in the sediment to reduce erosion when exposed.

TABLE 2. Erosion experiments performed on both fine and coarse sediments at each slope with various treatments. C = control; P = plants, M = mulch, and A = PAM.

	Slope gradient	Low-intensity rainfall	High-intensity rainfall
Fine	5°	C, P, M	C, P, M, A
sediment	15°	C, P, M	C, P, M, A
Coarse	1°	C, M	
sediment	5°	C, M	C, M
	15°	C, M	C, P, M

The plant treatment experiments were conducted on fine sediment at 5° and 15° slope, and both low- and high-intensity rainfall (see Table 2). The plant treatment was only conducted on the coarse sediment at 15° and high-intensity rainfall as the 5° slope and low-intensity rainfall were not expected to show substantial erosion. The plants were allowed to remain *in situ* for approximately 72 hours to allow roots to adapt to the soil. For this project, owlfruit sedge was used to emulate one of many types of sedges that will be planted in the Lake Mills area by the NPS. The plants used were approximately one year old and 14-18 cm tall. They were planted at the density suggested by the NPS of approximately 500 plants per hectare, which resulted in two plants per box. For the fine sediment, one run of the experiment was performed, then left to sit overnight, and repeated to examine the effect of erosion over time.

Mulch in the form of wood chips (arborist mulch) was applied at a depth of 2.5 cm to the entire box. Experiments with mulch were performed on all the same conditions as with no stabilization treatments (see Table 2).

Polyacrylamide was applied in a dry, granular form (Soilfloc DryTack, Hydrosorb Inc., Orange, California) at a standard rate of 11-33 kg ha^{-1} as recommended by the manufacturer to reduce sediment runoff and improve water infiltration into the soil. Experiments with polyacrylamide were performed on fine sediment with 5° and 15° slopes that were exposed to a high-intensity rainfall (see Table 2). The sediment was allowed to sit overnight for sediment to settle and PAM to equilibrate before the experiment was performed.

Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) is an updated equation that is based on USLE. The six major factors causing erosion are quantified by the universal soil-loss equation (USLE) (USDA-ARS 2001):

$$Soil\ Loss = RKLSCP \qquad \text{(Eq. 1)}$$

where R = rainfall erosivity, K = soil erodibility, L = slope length, S = gradient, C = cover, P = erosion control practices (see Tables 3 and 4 for estimated parameter values).

Rainfall erosivity (factor *R*) refers not only to the total rainfall, but also to the intensity and seasonal distribution of the rain and therefore is the driving force for sheet and rill erosion (Brady and Weil 2002). Soil erodibility (factor *K*) refers to the soil's inherent susceptibility to erosion. The two most significant characteristics influencing erodibility are (1) infiltration capacity and (2) structural stability (Brady and Weil 2002). Texture, organic matter content, permeability, and seasonal changes affect erodibility. A high content of silt, which is prevalent in the fine reservoir sediments, contributes to high *K* values. The topographic factors *L* and *S* include the length and steepness of slope. The longer the slope, the greater the opportunity for concentration of runoff water, which leads to more erosion (Brady and Weil 2002). The *C* factor is a ratio of soil loss with the current vegetative condition to what would occur with continuously bare soil. A low ratio (<0.10) indicates dense vegetation or plant residue left on the land and a higher ratio indicates little soil cover. Supporting practices (factor *P*) include erosion augmentation practices.

RUSLE2, a computer software program developed and maintained by the USDA-Agricultural Research Service (ARS), the USDA-Natural Resources Conservation Service (NRCS), and the University of Tennessee (USDA-ARS 2006), was used to calculate soil loss with several parameters. RUSLE2 was used in conjunction with erosion

TABLE 3. Parameters used in RUSLE equation to compare erosion experiments to RUSLE2 modeling results.

Factor	Fine Texture	Coarse Texture
R	1670 (MJ mm)/(ha h yr)	1670 (MJ mm)/(ha h yr)
K	0.061 (metric ton ha hour)/ (ha MJ mm)	0.026 (metric ton ha hour)/ (ha MJ mm)
L	72.6 meters and 152 meters	72.6 meters and 152 meters
S	1°, 5°, and 15°	1°, 5°, and 15°
C	Smooth bare, no disturbance; blade fill, wood fiber 2.2 metric tons/hectare; blade fill, wood fiber 4.5 metric tons/hectare; long term veg, range grass 4 years after last disturbance; long term veg, range grass 15 years after last disturbance	Smooth bare, no disturbance; blade fill, wood fiber 2.2 metrictons/hectare; blade fill, wood fiber 4.5 metric tons/hectare; long term veg, range grass 4 years after last disturbance; long term veg, range grass 15 years after last disturbance
P	None	None

TABLE 4. Rainfall amount (mm) by month used to calculate R factor.

Month	Rain (mm)
January	200
February	165
March	150
April	100
May	68
June	50
July	33
August	30
September	62
October	143
November	200
December	240

experiment results to refine predictions for variable site factors to demonstrate how different treatments may be used to minimize sediment losses. Using average monthly rainfall in the lower Elwha River Basin (Table 4), a rainfall erosivity value of 1670 (MJ mm)/(ha h yr) was calculated to compare erosion experiments results to RUSLE results (see Table 3 for RUSLE parameters). Cover and management parameters used were: smooth, bare no disturbance; blade fill, wood fiber 2.2 metric tons/hectare; blade fill, wood fiber 4.5 metric tons/hectare; long term veg, range grass 4 years after last disturbance; long term vegetation, range grass 15 years after last disturbance. These parameters were chosen to mimic the treatments used in the experiments to allow comparisons. However, since RUSLE2 is typically used in agricultural situations some conditions are slightly different than what will occur during the dam removal.

Statistical Analysis

One-way Analysis of Variance (ANOVA) was used to compare stabilization treatment effects on erosion using SPSS. Tukey's test was used to determine differences among means in each group with outlier tests were performed on the sediment data. Due to an uneven experimental design, average levels of erosion due to slope, rainfall intensity, and texture were compared using paired t-tests. Linear regressions were performed to test the relationship between rainfall amount and erosion. A 0.05 significance level was used.

Results and Discussion

Bulk Density, Moisture Content, and Texture

Bulk density generally remained the same throughout most of the experiments. The fine sediment bulk density averaged 1.09 g m^{-3} before the simulated rainfall and 1.10 g m^{-3} after for an average 0.86% change. The coarse sediment bulk density averaged 1.42 g m^{-3} before and 1.47 g m^{-3} after simulated rainfall, for an average 3.20% change. Fine-textured soils such as silt loams generally have a lower bulk density than coarser-textured soils. There were a few instances of bulk density increasing after a precipitation event which could indicate that settling was occurring.

The fine sediment had a particle size of silt loam with 82% silt and 18% clay, and represents the majority of the reservoir sediments. The coarse sediment had a texture of loamy sand with 4% clay, 11% silt, and 85% sand. Moisture content for the fine sediment was high, averaging 48.39% before and 48.43% after the precipitation event. Moisture content for the coarse sediment averaged 11.30% before to 15.34% after. Some sediments had the same moisture content before and after added precipitation. The fine sediment has small particles which can hold more moisture than the coarse sediment. The fine sediment was almost completely saturated before precipitation even occurred and therefore infiltration may have been limited. The high moisture content of the fine sediment is likely to cause excess water to pond or run off. Conditions near saturation can reduce infiltration rates, resulting in little water content increase and more surface flow. The coarse sediment was much less saturated than the fine sediment allowing for better infiltration and drainage. Coarse sediments are unlikely to be saturated under field conditions due to their high sand content and large pore size.

Silt exhibits little or no stickiness or plasticity and therefore can crack as it dries. Soil within the aggregates between cracks could retain more water, despite drying of the aggregate surface. If water enters cracks between aggregates, the silty material could rapidly erode, creating rills where concentrated water flow will enlarge cracks, washing away more of the silty material (Brady and Weil 2002). This could cause substantial erosion of the fine sediment over time as the sediment trapped behind the dams dries out.

As mentioned, the fine sediment was classified as a silt loam and the coarse sediment was classified as loamy sand. However, there is a gradation of textures present in the reservoir in addition to the silt loam and loamy sand textures that we focused upon in our study. Most of the coarse sediment that was gathered for this project was loamy sand, but we encountered a less coarse sand in the field. Because of this, one of the experiments for the coarse sediment included sediment material resulting in a statistical outlier due to an unusually high amount of silt and was excluded from further statistical analysis.

Erosion Experiments

For every treatment, drastically less erosion occurred with the coarse sediment than with the fine sediment (Table 5). This was expected because finer particles such as silts are easily transported by water (Brady and Weil 2002). In general, erosion was higher under high-intensity rainfall across all treatments, but the differences were not statistically significant (T-tests, all *P's* ≥ 0.05).

As expected, experiments using fine sediment with no treatment had the most erosion at higher slopes (Table 5). Experiments performed on fine sediment at both slopes at high-intensity rainfall showed significant differences (ANOVA, 5° P = 0.015, at 15° P = 0.001) between the control and the stabilization treatments. Experiments with low-intensity rainfall were significantly different (ANOVA, 5° P = 0.001, at 15° P = 0.0001). Surprisingly, the long mist at 15° slope with no treatment had more erosion than the shorter hard rain at the same conditions. The high erosion rate of the fine sediment suggests that treatments will be necessary on this material to reduce surface erosion to the Elwha River channel. It may be necessary to use silt fences in some of the most unstable areas to control erosion.

Coarse sediment experiments at 5° slope with both low- and high-intensity rainfall experiments showed little erosion. Coarse sediment erosion with high-intensity rainfall did not differ with slope (ANOVA, P = 0.343). There was not a substantial amount of runoff in any of the coarse sediment experiments. This lack of erosion with the coarse sediment is undoubtedly due to the large pore size and high infiltration rate of this sediment. Unless this material reaches saturation, it is not likely to have a high erosion rate unless slopes are extremely steep.

TABLE 5. Average sediment runoff from erosion experiments in g m^{-2} along with standard deviation.

	Volume of Sediment in g m^{-2}		
	Slope gradient	Low-intensity rainfall	High-intensity rainfall
Control (day 1 and day 2 averaged together)			
Fine Sediment	5°	434 ± 183	764 ± 591
	15°	1,710 ± 399	964 ± 486
Coarse Sediment	1°	n/a	14 ± 5
	5°	2 ± 1	43 ± 62
	15°	8 ± 4	17 ± 4
Planted (day 1 and day 2 averaged together)			
Fine Sediment	5°	343 ± 42	474 ± 49
	15°	802 ± 359	1,010 ± 171
Coarse Sediment	15°	n/a	4 ± 1
Mulch			
Fine Sediment	5°	10 ± 3	9 ± 5
	15°	10 ± 4	16 ± 8
Coarse Sediment	1°	n/a	3 ± 1
	5°	2 ± 1	12 ± 8
	15°	8 ± 4	3 ± 1
PAM			
Fine Sediment	5°	n/a	103 ± 21
	15°	n/a	215 ± 110

Stabilization Treatments - Plants

Plants generally did not substantially reduce erosion in these experiments (see Table 5), except in the case of the fine sediment at 15° slope with a low-intensity rainfall (T-test, P = 0.003). This could be due to the fact that the plants were small and covered little of the surface area (20% cover). This treatment would be indicative of the initial effects of revegetation. Over time, plants will grow to cover more of the sediment surface area and as their shoot and root systems spread through the sediment and they would be expected to decrease erosion. However, the sediments need to be stable sufficiently long for this plant growth to occur; erosion needs to be slow enough that plants are not removed and root systems are not damaged. The plants used in this experiment were an example of a sedge that may be planted, however, the revegetation activities planned by NPS include over 60 species of trees, shrubs and herbaceous plants which will eventually result in substantially greater surface cover and therefore will have more of an impact on erosion. Revegetation will be completed in phases and treatments will be tailored to broad geomorphic zones: valley bottom, valley wall and the transition in between. Some key areas will be planted densely to establish islands of more developed vegetation to serve as seed sources for surrounding areas, and to attract birds for additional seed dispersal, to limit erosion, and to limit invasion of exotic plants. Planting density will be variable; high density in some patches, low density in most of area. Actual plantings will be mostly trees and shrubs. Seeds of grasses, sedges, and forbs will be broadcast over most of the valley bottom zone. Live stakes of willows (*Salix* sp.) and cottonwoods (*Populus balsamifera* ssp. trichocarpa) will be installed close to the river. Plants can reduce flow velocities, protect the soil surface from raindrop impact, increase soil stability, and increase the amount of water infiltrating into the soil (Whisenant 2003). However, the vegetation most likely to inhabit the newly exposed surface includes invasive and non-native species. It is feared that the extensive, bare-surface sediments may provide a substrate that will favor weedy, non-native plants (Whisenant 2003). The physical and chemical character of sediments transported downstream through erosion may be different from conditions that existed before dam removal, which may affect species of plants colonizing soil in the downstream deposits or the former reservoir (Brown and Chenowith 2008).

Although weeds may also be effective at reducing erosion, once weedy, non-native plants are established, they may inhibit the growth of native species (Whisenant 2003). Two possible ways to deal with this issue are 1) plant the entire site immediately with native plants and 2) stabilize the sediments by using mulches or other treatments to control erosion and invasive species, followed by planting of native species.

Stabilization Treatments—Mulch

The mulch treatment had the most substantial impact on reducing erosion. When mulch was applied to fine sediment at 15° slope with low-intensity rainfall, there was 99% less erosion, which is a significant decrease (ANOVA, $P = 0.002$). Using fine sediment at both 5° slope ($P = 0.019$) and 15° slope ($P = 0.002$) with a high-intensity rainfall, the mulch treatment had significantly less erosion than using no treatment (Table 5). Using the two slopes on the fine sediment but with a low-intensity rainfall, the mulch treatment also had a significant impact on preventing erosion for both slopes (at 5° $P = 0.001$, at 15° $P = 0.048$). Even for the coarse sediment at 15° slope with high-intensity rainfall, which had little erosion with no treatment, mulch made a significant reduction in erosion ($P = 0.0001$). The mulch treatment did not significantly reduce erosion for the coarse sediment at 5° slope, however there was little erosion under these conditions with no treatment. Mulch was the most successful treatment for preventing erosion. Overall, there was no substantial sediment runoff at either slope or rainfall intensity from fine or coarse sediment when mulch was applied.

Stabilization Treatments—Polyacrylamide (PAM)

Polyacrylamide had a significant impact on reducing erosion at both slopes for the fine sediment (ANOVA, at 5° $P = 0.034$, at 15° $P = 0.035$) (Table 5). PAM was only applied to the fine sediment with the high-intensity rainfall as these sediments had the greatest erosion in controls and PAM is most effective on fine textured soil (Whisenant 2003). It appeared as though slope altered the effectiveness of the PAM application since less erosion occurred at 5° than 15° but it was not statistically different (ANOVA $P = 0.054$). Compared with controls, PAM reduced erosion at 5° by 86.5% and by 77.7% at 15° slope. Suspended sediments from PAM treated sediments visually exhibited increased flocculation over untreated sediments. Although PAM substantially reduced erosion in these experiments, it was not as effective as mulch.

Erosion over Time

Some of the experiments for the fine sediment were run over a period of two days to evaluate potential changes in erosion over time. Between the first day and the second day of each experiment, the soil was covered to avoid possible confounding from natural precipitation. There was significantly less erosion the second day of all experiments performed on the same soil (T-tests, all P's $\leq$ 0.05). This could be due to the large amount of organic debris that is present in the reservoir sediments. This material was exposed after the first day of treatment which may have helped keep soil in place by increasing surface roughness and exposing barriers to surface water flow.

There was a significant difference between the first day and second day for fine sediment within controls (T-tests, P's ≤ 0.03) except for 5° with high-intensity rainfall ($P = 0.12$). Although there was not a significant difference between controls and the plant treatment there was a decrease in erosion and a significant difference between day 1 and day 2 (T-tests, P's ≤ 0.05). Fine sediment experiments with PAM treatment were conducted with a high-intensity rainfall at both slopes. The experiment was done over two days and there was less erosion the second day suggesting that PAM will continue to be effective.

RUSLE

Using parameters that are suitable for the Elwha River area, calculations were conducted using RUSLE2 to predict erosion at specific slope length and gradients. Slope gradients of 1°, 5°, and 15° were used in performing the calculations, both to correspond with experiments and as an expected range of slopes for the sediments. Using a longer slope length increases the amount of erosion because water flowing down longer slopes can accelerate more and has more energy to erode soil, therefore two slope lengths were compared. Comparing a slope length of 76.2 m, which represents ¼ of width of the narrowest part of the reservoirs with a slope length of 152 m, which represents ¼ of the width of the widest part of the reservoirs, erosion was substantially higher with a longer slope length (Table 6). Slope gradient also increased erosion. With both a steeper and longer slope length, a greater amount of erosion is predicted. The USDA considers 11 Mg ha^{-1} yr^{-1} to be the maximum tolerable loss of soil for any agricultural field or construction site (USDA-ARS 2001).

As expected based upon the erosion experiments, texture was a major factor in the calculations. The textures used in the calculations had the same clay, silt, and sand percentage as that used in the erosion experiments. Only the coarse texture at 1° slope gradient at both slope lengths had predicted soil loss amounts that were under the tolerable loss of 11 Mg ha^{-1} yr^{-1}. However, higher slopes greatly increased the amount of erosion. The bare, fine texture at 5° for both slope lengths had predicted soil loss between 120 and 230 Mg ha^{-1} yr^{-1}, while at 15° amounts were > 500 Mg ha^{-1} yr^{-1}. Mulch greatly reduced this amount, especially with the higher application rate of 4.5 metric tons/hectare which reduced erosion by half. An application of 19.5 tons/hectare would approximately equal a 2.5 cm application depth. Range grass was chosen to best represent the vegetation used in the erosion experiments. Calculations were made for use of range grass 4 and 15 years after disturbance. Use of range grass nearly cut in half the amount of erosion compared to bare soil. Surprisingly, there was not much difference in the results for range grass four years

TABLE 6. Modeled RUSLE erosion in Mg ha^{-1} yr^{-1} with slopes used for erosion experiments, parameters as given in methods and Table 3 with slope lengths of 76.2 meters and 152 meters.

Texture	Slope gradient	Bare	Mulch (2.2 metric tons/ha)	Treatment Mulch 4.5 metric tons/ha)	Range grass 4 yrs after disturbance	Range grass 15 yrs after disturbance
Slope length = 76.2 m						
Silt	1°	18	16	8.1	11	11
Loam	5°	160	120	56	88	82
	15°	760	570	280	410	390
Loamy	1°	6.8	6.1	3.2	4.1	4.0
Sand	5°	54	46	23	31	30
	15°	260	230	110	150	140
Slope length = 152 m						
Silt	1°	22	21	10	13	13
Loam	5°	230	200	95	130	130
	15°	1,200	1,100	560	680	640
Loamy	1°	7.5	7.3	3.8	4.6	4.5
Sand	5°	71	69	33	41	40
	15°	380	390	190	220	210

after disturbance and 15 years after disturbance. This may be because after four years, the grass is already well established.

When the erosion experiments are converted into Mg ha^{-1} yr^{-1} using the annual average rainfall of 142 cm at the Elwha Ranger Station for both low and high-intensity rainfall, the low-intensity results are much lower than the high-intensity results as more erosion is likely to occur during a high-intensity storm than a low-intensity rainfall (Table 7). Comparing the erosion experiments (also using the annual average rainfall of 142 cm at the Elwha Ranger Station in Mg ha^{-1} yr^{-1} as used in RUSLE2) with modeled erosion using RUSLE2, the controls had similar results (Table 8). However, the experimental mulch treatment was much more successful in preventing erosion than predicted by RUSLE2, whereas the plant treatment was more successful in the RUSLE2 model at 5° but not 15° slope (for fine sediment) . Surprisingly, when converted to Mg ha^{-1} yr^{-1}, PAM did not reduce erosion to below the tolerable soil loss of 11 Mg ha^{-1} yr^{-1}.

Conclusions

Following dam removal, large amounts of reservoir sediment are expected to erode downstream into the Elwha River. In order to limit erosion, the National Park Service could use a combination of stabilization treatments. These experiments and modeling suggest that mulch was the most effective treatment for reducing erosion. Mulch reduced erosion by as much as 99%; PAM reduced erosion by an average of 82% and plants on average reduced erosion by 33%. However, with the large area being exposed, covering the entire site with mulch may not be practical. Using a combination of plants and mulch supplemented with a temporary silt fence may be the most effective method of erosion reduction. Large woody debris, which is predicted to be available in large quantities in both reservoirs, may also act as aboveground obstructions which will slow water movement and decrease sediment erosion. Although erosion will naturally occur as the dams are removed, substantial erosion could be prevented by using the RUSLE2 model to predict the location of and the amount of erosion from the most susceptible areas, and then focusing amendments in these areas.

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TABLE 7. Estimated annual erosion in Mg ha^{-1} yr^{-1} for low- and high-intensity precipitation from experimental results with annual Elwha River precipitation.

		Treatment and Rainfall Intensity						
	Slope	Control		Mulch		Planted (500 plants/ha)		PAM
Texture	Gradient	Low	High	Low	High	Low	High	High
Silt	5°	150	350	4	4	120	210	45
Loam	15°	610	440	4	7	280	460	98
Loamy	1°	n/a	6	n/a	1	n/a	n/a	n/a
Sand	5°	1	20	1	5	n/a	n/a	n/a
	15°	3	8	1	1	n/a	2	n/a

TABLE 8. Comparison of experimental and RUSLE results for no treatment, mulch, and planted sediments (using 500 plants per hectare) with low-intensity rainfall using slope length of 76.2 meters in Mg ha^{-1} yr^{-1}. Day 1 and day 2 results are averaged.

		Treatment					
	Slope	Control		Mulch		Planted	
Texture	gradient	RUSLE	Measured	RUSLE	Measured	RUSLE	Measured
Silt	**5°**	160	153	120	4	88	120
Loam	**15°**	760	610	570	4	410	280
Loamy	**5°**	54	1	46	1	31	n/a
Sand	**15°**	260	3	230	1	150	2

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