Suction dredge mining impacts on Pacific lamprey populations and habitat in Washington State: A case study of the Entiat River

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Jaime Lee Liljegren

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We hereby approve the thesis of

Jaime Lee Liljegren

Candidate for the degree of Master of Science

APPROVED FOR THE GRADUATE FACULTY

______________ ______________________________
Dr. Anthony Gabriel, Committee Chair

______________ ______________________________
Dr. Karl Lillquist

______________ ______________________________
Dr. Clay Arango

______________ ______________________________
Dean of Graduate Studies

ABSTRACT

SUCTION DREDGE MINING IMPACTS ON PACIFIC LAMPREY POPULATIONS AND HABITAT IN WASHINGTON STATE: A CASE STUDY OF THE ENTIAT RIVER

by

Jaime Liljegren

Suction dredge mining is a largely unregulated recreational activity in Washington State with potentially significant impacts to aquatic habitat. Although dredging has the potential to cause widespread ecological effects, only impacts to select species have been thoroughly assessed. Due to their reliance on freshwater habitat throughout multiple life stages, Pacific lamprey are significantly vulnerable to impacts from dredging practices. This thesis focuses on assessing the effects of dredging to lamprey habitat within state-owned aquatic lands of Washington. Pacific lamprey are anadromous, utilizing freshwater habitat throughout key life stages including spawning in substrate ranging from coarse gravel to fine sand, and burrowing into streambeds as larvae to grow for a maximum of seven years (Pirtle et al., 2003; Graham and Brun, 2006). By conducting a controlled dredging experiment along the Entiat River and comparing alterations to water quality and stream morphology before and immediately after dredging, two months later, and at the beginning of the following season, changes to habitat were quantified. When water quality was assessed, no significant impact to parameter levels were observed. Although changes to overall grainsize proportions were small, distributions showed coarser material directly at dredged sites, while finer material increased downstream. Channel profiles showed reductions in material following dredging, as well as minimal recovery two months after the activity and at the beginning of the following season. Artificially created tailings piles were observed to experience a 55.40% reduction in material volume over two months, while total hole volume showed a contrasting increase of 8.10%. Additionally, tailings experienced a 100% reduction in volume 11 months following dredging activity while dredge holes were reduced by 9.6%. Results can be related to habitat preferences of other aquatic species to determine ecosystem-wide impacts as well as providing necessary data to extrapolate impacts to similar systems throughout the state. Using these results, I provided recommendations to apply throughout management decisions and developed further recommendations for research.

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CHAPTER 1

INTRODUCTION

Problem

Suction dredging is a recreational mining activity that is well-established throughout aquatic systems of Washington State. Dredge mining began in the early 1900s following the large-scale removal of easily accessed gold deposits during the Gold Rush of 1849 (Delcotto, 2010; Harris, 1993). Original dredges were composed of multi-story floating barges that mined deposits within channel beds of large river systems (Harris, 1993). Since then, modernization of mining technology has led to the development of small-scale suction dredges commonly used today in aquatic systems throughout the West. Due to their increased efficiency in processing large amounts of material as well as providing the ability to access previously inaccessible deposits, small-scale suction dredges have gained popularity among prospectors. Through the mechanization of traditional mining practices such as rocker boxes and gold panning, suction dredging provides an efficient and time-effective alternate technique.

Dredging is a popular prospecting activity known to occur in Washington, as well as Colorado, Oregon, Alaska, Idaho, and California. Occurring on marine beaches as well as various sized freshwater creeks, streams and rivers, this activity is widely distributed throughout many systems across Washington State. The large distribution of dredging practices has increased the amount of aquatic habitat impacted from mining along with increasing the potential for negative effects on native aquatic species.

A suction dredge is composed of floating pontoons equipped with an electric or gasoline motor and a water pump to lift submerged bed materials through hydraulic suction (Washington Department of Fish and Wildlife [WDFW], 2018). Suction dredging takes place directly within the channel bed and focuses on placer deposits of gold and other minerals of interest including platinum and silver. Placer deposits are secondary deposits created after fluvial processes erode metals from superficial bedrock (Healy, 1978). During dredging, material moves through an attached trough called a sluice box concentrator with riffles along the bottom to recover gold and other heavy materials (R2 Resource Consultants [R2RC], 2006). A motorized pump lifts sediment from a river system containing minerals of interest, and in doing so, has the potential to negatively affect sensitive species by simultaneously displacing fish larvae and eggs through the dredge system (Harvey and Lisle, 1998). Once clear of the dredge, individuals are suspended in the water column, increasing their vulnerability to predation (Harvey and Lisle, 1998). Processed sediment is expelled back into the river system and has been shown to result in large plumes of suspended sediment that are slow to dilute and that reduce oxygen levels for sensitive redd habitat (United States Department of Agriculture [USDA], United States Forest Service [USFS], 1997). Dredging activity has also been shown to result in the simplification of a river system through the removal of woody debris and boulders (R2RC, 2006).

Despite displaying significant negative impacts to natural ecosystems, dredge mining is largely unregulated in Washington State. Unlike Oregon, California, and Idaho, Washington currently allows suction dredge mining without requiring annual written permits or fees. The 2018 WDFW Gold and Fish Pamphlet provides general rules for prospecting and serves as the approved pamphlet Hydraulic Permit Approval (HPA) for small-scale dredging in Washington State. This pamphlet allows dredging activity in all specified locations and timeframes without any permit application and requires that the dredge operator have it in their possession and follow all guidelines when dredging. With the exception of required HPA applications to dredge outside approved timeframes or locations, no cumulative permitting system or inventory exists leaving dredging intensity and distribution throughout the state virtually unknown.

Previously documented impacts on aquatic ecosystems and the overall lack of regulation has put multiple species being at risk of increased habitat destruction and mortality rates. Current anti-dredging campaigns are focused on listed Endangered Species Act (ESA) species including steelhead and salmonids, subsequently focusing less on other species similarly dependent on stable stream bed substrate including native freshwater bivalves, sculpin, dace, sturgeon, and multiple species of lamprey (Kreuger et al., 2007; R2RC, 2006). Pacific lamprey, *Entosphenus tridentatus*, is a native anadromous species of Washington State that depends on stable sediments for spawning and rearing. Emerging 450 million years ago, Pacific lamprey are known to be the oldest species of vertebrates still present (McIlraith, 2015). Due to their ability to inhabit both marine and freshwaters lamprey have been identified to effectively reduce predation on recovering salmonids as well as provide a significant indication of aquatic habitat health (Close, 1995). Unique life history patterns combined with low population counts has limited the current knowledge of Pacific lamprey populations, although anecdotal observations and discrete individual counts suggest decreasing populations throughout the West (Columbia River Inter-Tribal Fish Commission [CRITFC], 2011). The identification and mitigation of factors limiting towards juvenile lamprey spawning and rearing habitat has been identified as a significant topic of concern and a goal for further study (CRITFC, 2011). Large periods of time spent within shallow water regions subject juvenile lamprey to direct and indirect effects from human activities including recreational gold mining. Although briefly identified in previous studies (R2RC, 2006; Oregon Chapter American Fisheries Society [ORAFS], 2013), evidence is largely lacking on dredging impacts specifically to Pacific lamprey and their preferred habitat.

Purpose

The purpose of this research was to evaluate the effects of small-scale suction dredge mining on Pacific lamprey populations and habitat within the Entiat River located in the Eastern Cascade Mountains of Washington State. Working in collaboration with the Washington Department of Natural Resources (WDNR), the overarching research intent focused on assessing the amount of impact from dredging to Pacific lamprey habitat specifically within state-owned aquatic lands (SOAL), with the Entiat River serving as a representative river system. SOAL includes all aquatic lands deemed ‘navigable’ and not within private ownership (WDNR, 2012). WDNR currently manages 2.6 million acres of designated state-owned aquatic lands and is responsible for balancing the protection of state resources with the appropriate level of public access to state-owned lands for water-dependent activities (WDNR, 2012). The agency is therefore interested in the assessment and regulation of activities potentially detrimental to public lands including suction dredge mining. The Entiat River was identified as an appropriate study site due to the previous identification of this river within SOAL boundaries, the present documented lamprey habitat, the presence of similar habitat characteristics to commonly dredged river systems, and minimal mining activity present for a more accurate pre- and post-dredging analysis.

Research was completed by assessing changes in water quality, channel morphology, and substrate composition that resulted after suction dredge mining within an identified site in the Entiat River. This project provided an opportunity to monitor the impacts of suction dredging activities to a river system and the potential to extrapolate impacts to similar aquatic habitat in Washington State. The main questions addressed in this research include: 1) how does small-scale suction dredge mining alter the water quality of habitat units in natural aquatic environments of this size and composition? 2) how does small-scale suction dredge mining alter the morphology and substrate grain-size distribution of habitat units in natural aquatic environments of this size and composition? 3) does dredge mining significantly reduce the availability of habitat characteristics required by Pacific lamprey populations and other aquatic species? Survey objectives determined to answer the identified research questions included: 1) collecting baseline habitat conditions of sample reaches along the Entiat River in Washington's Northeast Cascade Range, 2) conducting a controlled dredging experiment at one sample reach within the Entiat River, 3) comparing post-dredging to baseline conditions in order to quantify change in substrate composition and water quality, and estimate related impacts to preferred habitat of Pacific lamprey and other associated species; and 4) utilizing research findings to provide recommendations to state agencies in regards to inventory and regulation of suction dredge mining activities occurring within Washington State.

Significance

This analysis quantifies specific impacts of suction dredging to aquatic habitat in Eastern Washington and provides necessary data to extrapolate impacts to similar systems throughout Washington State. Previous reports on suction dredging impacts to ecosystems have focused on salmonids, macroinvertebrates, and freshwater mussels (R2RC, 2006; Krueger, 2007; Maiyou and Moreau, 2015; Prussian et. al., 1999). Although many reports rely on secondary data to assign general dredging effects, few specific experimental dredge studies have been completed and none have been directly related to Pacific lamprey. Serving as a predation buffer to salmonids, an effective indicator of ecosystem health, and an important cultural resource to tribal nations, the Pacific lamprey is an essential species to the Northwest and impacts deemed significant to populations and habitat should be mitigated. These data will contribute to the limited Pacific lamprey knowledge dataset with the potential to strengthen the push for listing protection under the ESA.

By capturing geomorphic factors and water quality measurements in the Entiat River before and after dredging, results can be compared to habitat preferences of multiple species to determine impacts within the entire aquatic ecosystem. Through specifically identifying habitat conditions of interest and creating a sampling frame that replicates recreational suction dredging activity and has the potential to be repeated, this assessment will provide a framework for further monitoring studies within various environments where dredging occurs in Washington State.

Suction dredge mining policies in Washington State are currently being assessed by state agencies including the WDFW and WDNR with the potential for increased regulation if deemed appropriate. By providing primary data through research directly completed in waters of the state, impacts to various sized systems can be addressed. Through the collection and spatial analysis of at-risk regions in public lands, state agencies can apply results throughout current and future land management decisions and can provide further recommendations for research. In addition, these data established methods for further suction dredging experimental research and contributed to a growing scientific dataset on which to base policy decisions including the permitting and regulation of small-scale mining within Western states.

CHAPTER 2

LITERATURE REVIEW

The following is a literature review of dredge mining history in the United States, suction dredging equipment and methods, current policies for regulation, a summary of dredging impact studies on sensitive species, and a description of Pacific lamprey life history and potential threats to current populations.

Placer Mining History and Development

Gold and other minerals of interest are found throughout many Washington streams and as a result, prospecting activities are common throughout the state. Mining practices focus on either placer or lode deposits with suction dredge mining targeting placers in both marine and freshwater aquatic systems. Placer deposits are created through the erosion of lodes and the eventual deposition as alluvial material (WDNR, 2010). Placer deposits accumulate heavy minerals and can settle where velocities decrease rapidly including eddies, pools, and downstream from channel obstructions (McCracken, 2006). Minerals such as gold are designated as ‘heavy’ due to the substance having greater weight than equal volumes of other minerals (WDNR**,** 2010).

California Gold Rush

Mining in the West began largely during the California Gold Rush between 1848 and 1855 which largely contributed to the formation of the state (Harris, 1993; Delcotto, 2010; Horizon Water and Environment, LLC [HWE], 2009), and led to the creation and initiation of mining regulations within the mining community (Rickard, 1966). California had been recently acquired from Mexico and the state was controlled by the military.

Although the mines were within the boundary of public lands, therefore under ownership of the U.S. government, it was determined to be directly beneficial for the economy of the country to allow miners to extract the valuable metal independently (Rickard, 1966). Rules were created and self-regulated within the initial mining camps, eventually becoming the basis of the Mining Law of 1866 enacted by U.S. Congress (Rickard, 1966). The idea of mining claims was brought to California through foreign prospectors and many were established to create a system of property rights. Within each claim the first locator of the site could hold an area ranging from 30 to 100 square feet depending on the size of the deposit, until abandoned (Rickard, 1966).

Mining in Washington

Mineral prospecting in the Northwest was largely attributed to the growing fur trade and expansion of missionaries (Rickard, 1966). Placer gold was initially discovered in Washington in the 1850s, but placer mining did not become active until discoveries were made in the 1860s on Peshastin and Swauk Creek (Moen, 1979). The first recorded discovery of gold in Washington occurred in September of 1953 by a party of surveyors led by George McClellan who were surveying for potential routes for the transcontinental railway (Tozer, 1965). The party made camp at the Yakima River across from the mouth of Manastash Creek near present-day Ellensburg and found the first traces of gold (Tozer, 1965). Into the early 1900s prospecting occurred throughout Washington, and many streams were explored for placer deposits (Moen, 1979).

Evolution of Mining Technology

During the California Gold Rush, rocker boxers, or hand-powered concentrators to wash the gravel and separate gold, became popular within the mining community (Rickard, 1966; USFS, 2015). Rocker boxes utilized riffles along the bottom of the box to capture gold in the transverse cleats and release unwanted material (Rickard, 1966). Once most of the easily accessed gold was removed, mining was largely centered around commercialized companies (HWE, 2009; Delcotto, 2010; USFS, 2015). Large floating dredge systems were created in the early 1900s to mine deposits along rivers and outwash fans using large steel buckets to collect gold and dump removed sediment back into the river as large mounds downstream (Figure 1) (HWE, 2009).

Figure 1. Gold dredge in Fairbanks, Alaska operated by the Fairbanks Exploration Company. Photo adapted from: https://alaskatours.com/day-tours/gold-dredge-no-8-tour/.

Dredges were also known to be utilized along the marine beaches of Nome, Alaska in 1899 to extract large quantities of gold following the subsequent rush in the north (Rickard, 1966). Although commercial dredging continued to grow until the Great Depression, large expenses associated with dredging coupled with low prices for recovered gold led to a decline in the industry (HWE, 2009).

Suction Dredge Types

Dredge mining technology eventually re-emerged in the 1960s when the suction dredge was initially developed by individuals as a way to access river deposits and later became produced commercially for small-scale dredge mining, allowing the processing of significantly larger amounts of sediment at a faster rate (HWE, 2009; Delcotto, 2010; USFS, 2015). Suction dredges are composed of a flotation device such as a pontoon framework, a water pump, a suction hose, and a sluice concentrator, and are driven by small gasoline or diesel engines. Suction is created using a high-pressure water pump that produces a powerful vacuum effect to uplift streambed substrate for filtration (Figure 2) (WDFW, 2018).

Figure 2. 5-inch Keene suction dredge with a pontoon framework, gasoline motor, water intake pump, and a header box to transport substrate over the attached sluice box for sorting. Photo credit: Jaime Liljegren.

Dredges typically utilize sluices as a concentrator to separate the minerals of interest from the channel material. Within the sluice system, vacuumed substrate is uplifted through the suction hose and transported to the concentrator equipped with riffles along the bottom. Each riffle forms a small eddy current, allowing gold and other heavy minerals to fall out of suspension at the bottom while lighter sediments are discharged back into the stream as tailing piles and sediment plumes (USFS, 2015; Harris, 1993). Header boxes are also used in conjunction with sluice systems as a separator to break up consolidated material upon leaving the hose and entering the sluice (Harris, 1993). As the water and substrate enter the header box, particles are loosened and released into a classifier screen in which separates the heavier material before entering the riffles (Harris, 1993).

Dredge size is based on the nozzle diameter of the suction intake hose entering the sluice box (McCracken, 2006; WDFW 2018). Non-commercial dredges range from two to eight inches in diameter with the most commonly used ranging from two to five inches, and they include engines up to 15hp (ORAFS, 2017). The diameter of the suction hose directly affects the amount of material processed. Increasing the hose diameter by one inch doubles the available suction and increases the depth of excavation by a foot per inch (McCracken, 2013). In addition, doubling the intake diameter also increases the amount of processed substrate by a factor of four (Harris, 1993).

The two-inch suction dredge is a small system that can be quickly and efficiently transported to a waterbody as a backpack and is typically used for small regions that larger dredges cannot access (Harris, 1993). Due to the small capacity, the two-inch dredge is not typically used for production dredging and rather is used for sampling an area to determine paystreak locations (HWE, 2009).

The four and five-inch dredge are most commonly used by small-scale production dredge miners (Harris, 1993; HWE, 2009). Although requiring more effort to assemble than smaller dredges, they are designed to be transported moderately easily while still allowing the ability to process large amounts of substrate from channel beds (Harris, 1993). Dredges four inches in diameter and larger can use a double or triple sluice set-up to more efficiently process sediment; however, the standard set-up uses a single sluice concentrator (Harris, 1993; McCracken, 2006). Large 6 to 8-inch dredges are typically used for commercial gold mining purposes and require a significant amount of people, effort, and special permitting within certain states to be successfully operated (Harris, 1993). In addition, many large dredge systems include an air compressor as an air supply system for diving in deeper water or working down to the bedrock. These systems are referred to as ‘hookah’ air systems in which the compressor delivers air from the surface to the diver using an air hose and regulator, allowing for a less-costly option when compared to SCUBA diving (Delcotto, 2010; Harris, 1993).

Suction Dredge Mining Techniques

Dredging occurs typically during summer low flows to allow operators safe access to streams and when required permits allow mining (R2RC, 2006; HWE, 2009). According to a study on California suction dredging, recreational suction dredgers represent approximately 90 percent of all suction dredgers and spends on average 5.6 hours a day dredging an area ranging from one to ten square meters (California

Department of Fish and Game [CDFG], 1994). Dredge systems are commonly tied to boulders, vegetation or other stable structures to maintain proper placement and orientation in the channel (R2RC, 2006; McCracken, 2006).

When dredging, operators target placer deposits for gold and other valuable minerals. Although possible for gold to reside on the surface of the streambed, the most productive sediments are present at depth in the channel bed not usually mobilized during floods (McCracken 2006, USFS 2015). Initial testing is completed through dredging small holes, then surficial substrate is removed to access sediments deeper in the channel where significant amounts of gold are available (McCracken, 2006).

Production dredging is focused on the recovery of a discovered deposit and is the main technique once a paystreak is found using sample holes (Harris, 1993). To reach significant paystreaks in a substrate transition zone, operators will dredge to bedrock or hard-packed layers often removing all rocks and boulders (Marvin-DiPasquale et al., 2011; McCracken, 2013). When working downward through channel substrate above bedrock, operators may intercept 'flood gold' deposits residing above crevices in layers that have been deposited through flooding and other precipitation events (USFS, 2015). Streambed materials that exceed the intake pipe diameter are manually piled downstream or adjacent to the dredging (ORAFS, 2017; Evans, 2017). Once processed, sediment is released downstream and, if present, fine material is transported in a plume a further distance down the channel.

Regulations in the American West

Mining Claims

Under regulation by the Bureau of Land Management, individuals are allowed to stake a claim to any permissible public land in the United States for surface mining purposes (Moen, 1962; USDOI, 2016). Although citizens receive the right to mine within the surface, a claim does not allow the claimant sole use of the land and can therefore be used for any activity available on other public lands as long as it does not interfere with mining activities (USDOI, 2016). Many individuals and prospecting clubs work under claims in order to secure particular locations of interest. Claims are regulated using the General Mining Law of 1872 and the Federal Land Policy and Management Act of 1976 on federal lands, and are based on the Public Land Survey System (PLSS) using township, range, and section as the location identifiers (Moen, 1962). When receiving a claim, users must pay a fee and are required to regularly utilize the area as well as follow policies particular to the state (USDOI, 2016). Placer claims for individual claimants cannot exceed 20 acres while an organizational claim cannot exceed 160 acres. Multiple placer and lode deposits cannot be within the same claim (USDOI, 2016).

Federal Lands and Regulations

Various designated federal lands are subject to different regulations regarding mineral prospecting. Lands managed by the National Forest Service (NFS) are open to mining claim ownership as well as mineral prospecting outside of claims (WDFW, 2018). In contrast, no new mining claims can be established in National Parks following the Mining Law of 1872 and mineral prospecting is allowed only in pre-existing claims

(WDFW, 2018; Moen, 1962). In regard to wildlife protection, all activities with the potential to impact resident fish, plants or animals are under the authority of the United States Fish and Wildlife Service (USFWS) while activities that can impact anadromous species such as the Pacific lamprey have the potential to be regulated by the National Marine Fisheries Service (NMFS) (WDFW, 2018). Both agencies are responsible for the appropriate application of the Endangered Species Act (ESA), which requires agencies to protect and conserve listed species.

State Regulations

Although small-scale suction dredge mining occurs throughout the American West, policies regarding the activity significantly differ among states. Under the Mining Act of 1872, a private citizen is allowed to 'explore potential mining opportunities on federal land' and allows citizens the right to stake a claim to any available land (United States Government Publishing Office [USGPO], 2011). Dredge mining is included within the Mining Act of 1872 and therefore falls under federal regulation; however, certain states including California, Oregon, and Idaho have taken responsibility to impose additional local rules regarding approved locations, timeframes, and permitting processes in order to accurately track activity and allow further environmental protection to state resources.

In 2009, California passed Senate Bill 670 in which placed a temporary moratorium on all dredging activity throughout the state until a final comprehensive environmental review could be completed documenting all known impacts (CA S.B. No 670). Once completed, it was determined that if the ban was lifted, dredging would cause significant environmental harm to the state of California. Therefore, Senate Bill 637 was implemented issuing a ban on suction dredging until a thorough and appropriate regulatory system could be implemented (CA S.B. No.637). Under state law, it is a criminal penalty for illegally operating a dredge and offenders could face fines of up to $1000, a six-month incarceration, or both (Arsenault, 2019).

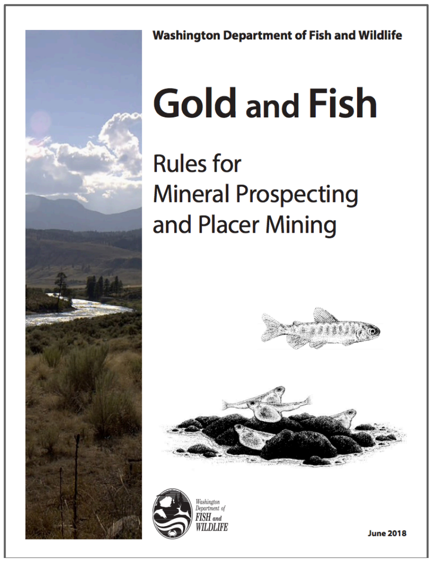
Although requiring state permits to dredge in specified locations under the Stream Channel Protection Act (SCPA), Idaho has relied primarily on federal regulations regarding enforcement within the state (Arsenaut, 2019). Under the Clean Water Act (CWA), the Environmental Protection Agency (EPA) has issued a generalized National Pollution and Discharge Elimination System (NPDES) permit for all suction dredging activity within the state and all permitting is enforced under the authority of EPA (EPA, 2018). In the state of Idaho, illegal dredging is a civil penalty subject to fines of up to $500 for violation of the SCPA (Idaho Department of Water Resources [IDWR], 2018). With state permits costing $250 to obtain and the EPA focusing more attention on industrial violators of the CWA, illegal dredging in Idaho is more likely to occur without further enforcement of state law (Arsenaut, 2019).

The state of Oregon has taken a more balanced approach in an attempt to appeal to both the mining and environmental communities. In 2013, a moratorium was temporarily enacted while the state assessed known impacts to the environment of Oregon from dredging (OR S.B. No. 838). The ban was lifted in 2017, and State Bill 3 was passed restricting mining to specific locations throughout the state (OR S.B. No. 3). In the new legislation, all habitat deemed necessary for native anadromous salmonids was off limits to dredge mining, creating legislation that moderated mining activity with critical habitat (Arsenault, 2019).

Regulations in Washington State

All stream and river channel habitat located below the mean high-water mark is designated state-owned land; therefore, all instream activities are regulated through state agencies (WDFW, 2018; Ivey, 2012). Designated state-owned aquatic land is managed by the WDNR which is responsible for balancing the mitigation of water quality issues, protection of aquatic habitat, and public access for recreational opportunities (WDFW, 2018). SOAL includes all land present in freshwater rivers and lakes deemed 'navigable' that are present below the designated ordinary high-water line (Moen, 1962). Within state-owned aquatic land, WDFW coordinates with WDNR in order to conduct ESA compliance work, provide public access, provide enforcement, and assist in protecting species and local habitat (Joint Legislative Audit and Review Committee [JLARC], 2008).

Mineral prospecting policies for Washington State are located within the Washington Administrative Code ('WAC') under both 220-660-030 and 220-660-300. The codes require all activities in Washington State that "use, divert, obstruct or change the natural bed or flow of state waters" apply for an HPA through WDFW to ensure no damage occurs to public shellfish and fish resources (WDFW, 2018). The Gold and Fish pamphlet is recognized as the appropriate HPA for any mining or prospecting in compliance with all pamphlet rules (Figure 3) (R2RC, 2006).



Washington Department of Fish and Wildlife

Gold and Fish

Rules for
Mineral Prospecting
and Placer Mining

Washington Department of FISH and WILDLIFE

June 2018

Figure 3. The 2018 Gold and Fish HPA pamphlet serves as the approved HPA permit for all prospecting completed in compliance with the stated guidelines.

No application or fees are required, although miners must follow the rules outlined in the pamphlet and carry it with them in the field while performing mining activities (WDFW, 2018). Prospectors must have the pamphlet on hand and follow all policies regardless if they are working an established claim or within unclaimed public lands. Regulations state when an applicant wants to work outside the pamphlet guidelines in work period, timing method or location, written HPAs are available for approval (WDFW, 2018). Applications must be completed and submitted to WDFW online and will be approved unless determined that the activity will directly or indirectly negatively affect fish life and an appropriate mitigation strategy cannot be identified (WDFW, 2018). Mineral prospecting performed under the general approval of the Gold and Fish HPA are not inventoried, making documentation of mining frequency and location largely absent (R2RC, 2006).

Regulations were updated through the Washington State Legislature in May 2018 which remove suction dredging from the approved Gold and Fish pamphlet HPA and requires all suction dredge miners to apply for individual HPA applications for review. The new policy will be enacted beginning November 1, 2019 and will allow for a more accurate inventory of current dredge mining activity in Washington State. Although a more detailed look at dredging hotspots will be identified following the increased regulation, mining will still be allowed in many aquatic systems that serve as critical habitat for vulnerable species.

Placer and Suction Dredge Mining Distribution

A significant portion of current suction dredge mining overlaps critical fisheries habitat in Washington (Trout Unlimited, 2017). Previous HPA applications for suction dredging activity have locations widespread across Washington from marine regions along the West Coast at Long Beach, Ocean Shores, and near Grays Harbor to the San Juan Islands and freshwater reaches within the Skagit Valley, along the Cascade Mountains, and many locations in Eastern Washington (Figure 4) (WDFW HPA APPS database).

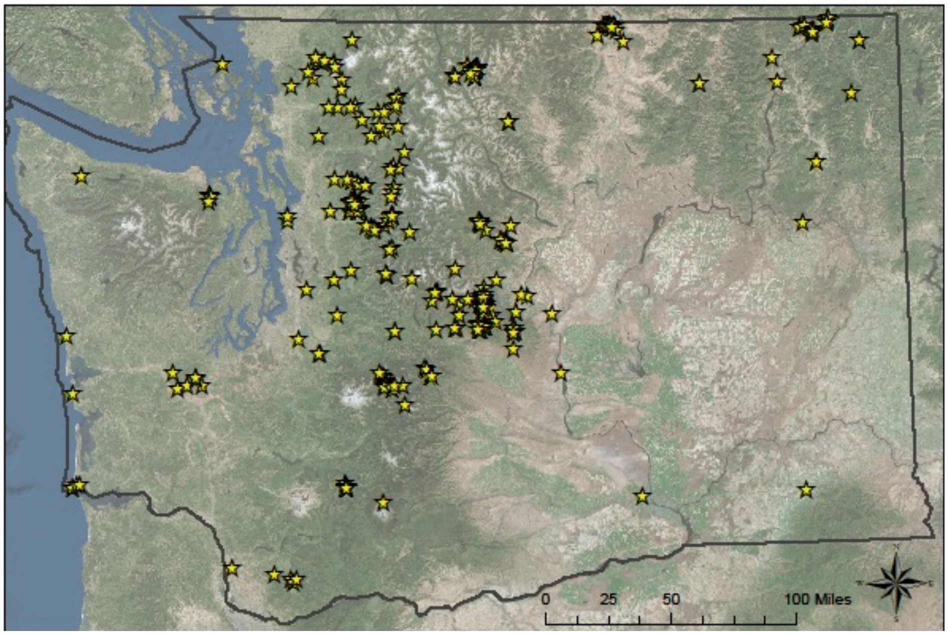


Figure 4. Sites of known dredging locations throughout Washington State. Locations were identified based on previous HPA applications via the WDFW APPs database as well as using a layer provided by Trout Unlimited on dredging hotspots.

According to the WDFW APPS database, HPA permits for mineral prospecting have been approved for many regions across Washington State with the most locations occurring in Chelan, Skokomish, and Whatcom Counties based on 2014-2018 HPA application data (WDFW APPS). Although written HPA permits provide a portion of general areas where dredging occurs outside of approved timeframes or locations, complete data on all dredging locations are unknown. Current HPA permits for suction dredge activity outside the approved windows is estimated to encompass only 5% of the total dredging occurring in Washington State (Davis, J. WDFW; personal interview with Trout Unlimited, 2016).

Impact Studies of Suction Dredge Mining to Channel Geomorphology

Suction dredge mining alters natural stream channels and disrupt channel-forming processes (ORAFS, 2017). Dredging activity typically focuses on depositional regions within aquatic systems including riffles, lower pool sections, channel margins and other features creating slack water (Harvey and Lisle, 1998). These features are locations where gold deposits are likely to occur. Large impacts to the channel have been identified as a result of dredging including displaced boulders, cobbles, and logs along with the creation of holes and substrate piles along stream channels (Evans, 2017). Habitat alterations that mobilize channel substrate can result in the continued destabilization of the streambed and increased channel erosion over time (Wilcock and DeTemple, 2005; Parker and Klingeman, 1982). A study on suction dredge mining in Canyon Creek, California identified the average hole depth to be four feet in 1984 and five feet the following year with 9% of created tailings and holes still present at the beginning of the next season (Stern, 1988). Similar research in Victoria, British Columbia found holes ranging from two to six feet in depth following dredging (Hall, 1988).

In addition to directly observed impacts within the dredged region, processed material has the ability to change channel morphology downstream by depositing tailings in pools that can remain until a significant high-flow with sufficient flow to transport gravel, which can have low recurrence interval in small streams (R2RC, 2006). Significant sediment deposition has been shown to result in a depth decrease and width increase of the channel (Thomas, 1982). Velocity reductions and adjusted riffle-pool interactions have been observed following deposition downstream of dredging activity, leading to a decrease in the overall number and depth of pools (Rulifson, 1979). The capability of suction dredges to move large amounts of substrate can significantly alter features within a channel reach, subsequently impacting the species that rely on the impacted habitat.

Dredging Effects to Species and Habitat

Ofent, the same areas of interest to gold miners also provide habitat for native fishes and macroinvertebrates (ORAFS, 2015). This overlap in use increases the likelihood of direct and indirect impacts to multiple species within the system. Suction dredging has been shown to significantly affect channel morphology, resulting in reduced spawning and rearing habitat of multiple species within a river system (Harvey and Lisle, 1999). During a dredging event stream habitat simplification can occur, increasing negative effects by removing items that reduce water velocity including boulders and large wood, as well as altering riffles that are essential to fish and aquatic insect habitat (North, 1993; Quinn, 2005). A study performed on species diversity found the number of species of fishes present was most strongly correlated with stream depth, suggesting deep pools are extremely important to fish (Sheldon, 1986). Fine gravels released downstream create substrate piles that are redistributed below the dredged region with the potential to fill pool features used for habitat in less than a year (Thomas, 1982). These unconsolidated, loose tailings piles may be utilized to construct spawning redds, making them more prone to being washed downstream (Delcotto, 2010).

In addition to the direct alterations within the channel following dredging, many other less visible yet equally significant effects to aquatic organisms can occur. While the dredge is running, processed sediment is released onto undisturbed substrate downstream along with a plume of fine sediment, dependent on the composition of the channel.

Released sediment has been shown to cover downstream spawning gravel habitat resulting in direct burial as well as deposition of fine sediment within interstitial spaces in gravels that can cut off pathways for flushing metabolic wastes produced by larvae and eggs (USFS, 2015; Somer and Hassler, 1992; Kreuger et al, 2007). Fine sediment deposition can also affect permeability within gravel and dissolved oxygen levels, affecting egg and embryo stages of salmonids that develop within gravel substrate (Thomas, 1982). Sediment burial harms the development of fish eggs, reduces cover, and increases the predation vulnerability of juvenile fish and macroinvertebrates (USFS, 2015).

The persistence of sediment plumes is dependent on sediment characteristics, dredge operation, and stream flow. Previous studies identified water quality effects from sediment plumes over 500 ft below dredging activity (Prussian et al., 1999). In addition, sediment with larger proportions of clay content will have lower-density particles and therefore more persistent sediment plumes (Marvin-DiPasquale, 2011). Increased suspended solids can directly impact fishes and invertebrates by clogging gills and other respiratory surfaces as well as impacting the uptake of filter-feeding species (Birtwell, 1999). A California study documenting dredge operation impacts found chinook salmon avoided silted areas downstream from mining and concentrated in clear tributaries resulting in overlapping redds and increased egg mortality (Sumner and Smith, 1939). Later studies found high mortalities of salmonid fishes and macroinvertebrates downstream from suction gold dredges (Campbell, 1953).

Like fish, benthic aquatic insect distributions within lotic ecosystems are also strongly dependent on present grain size (Cummins and Lauf, 1969). A study focusing on substrate changes from dredging in multiple California streams was found to significantly influence macroinvertebrate density and diversity following dredging activity (Harvey, 1986). Suspended particles have the potential to affect the respiratory systems of aquatic organisms or remove vegetation and insects from the channel (Thomas, 1982). Previous studies identified reduced populations of aquatic insects below silt outflows (Bjornn et al., 1975; Nuttall and Bielby, 1973). A decrease in invertebrate populations over a continuous timeframe would have significant implications to local aquatic health (Thomas, 1982).

Cumulative Effects of Dredge Mining

Multiple dredge operators often work the same site on a designated claim and it is common to repeatedly return to the same location (Delcotto, 2010). Significant disturbance of streambeds resulting after dredging within a broad area or from the activity of multiple dredges can persist over long periods (ORAFS, 2015). Dredged sites where large amounts of boulders and cobbles are removed and piled in a concentrated area or sites located away from the thalweg may affect streambeds for a longer duration (Thomas, 1985; Harvey et al., 1982; Stern, 1988; Prussian et al., 1999). Multiple dredges are more likely to affect the channel over a larger timeframe, diminishing its capacity to support organisms (ORAFS, 2017). Persistent effects can result from dredging annually at the same site or from multiple mining activities occurring within a specific area (ORAFS, 2015). Little research has been completed on the physical and biological effects of multiple dredges operating concurrently and should be a focus of further study (Harvey and Lisle, 1998).

Pacific Lamprey Distribution

Pacific lamprey historically occupied a range from Mexico to Japan along the Pacific Rim (USFWS, 2004). Currently, lamprey are present in streams and rivers along the West Coast of central and northern California, Oregon and Washington as well as inland rivers throughout eastern Oregon, Washington and Idaho (Figure 5) (USFWS, 2015).

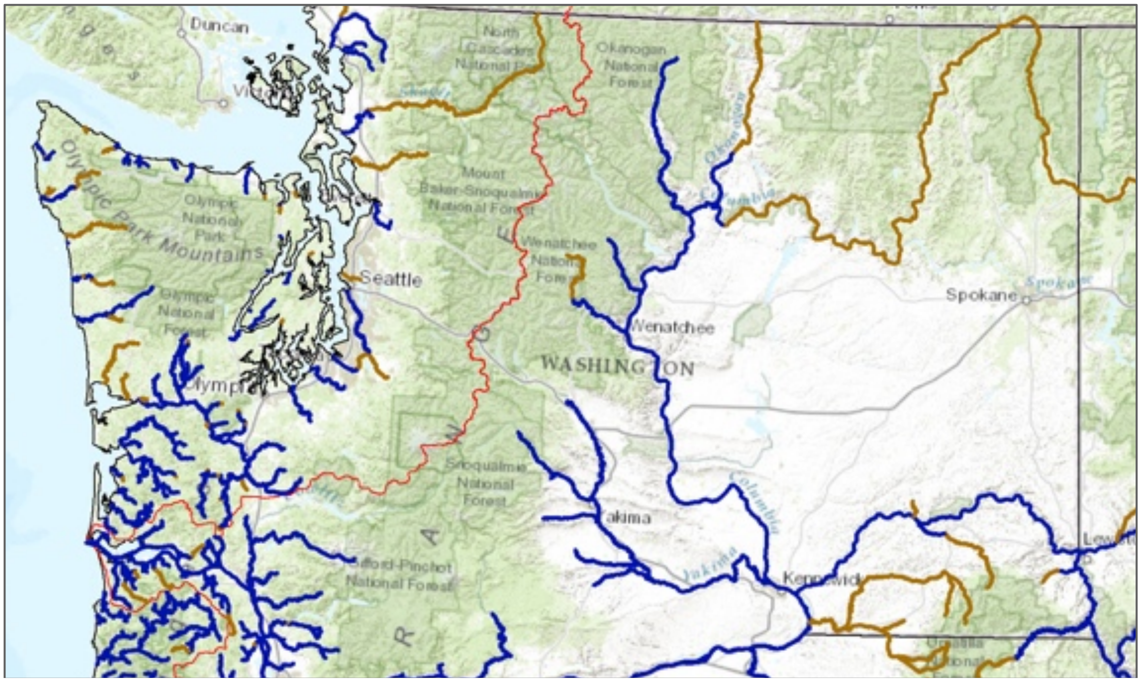


Figure 5. Current and historic distributions of Pacific Lamprey populations within Washington State. Blue represent current distributions while brown represent historical locations. (Map modified from original by U.S. Fish and Wildlife Columbia River Fisheries Program Office, 2015).

Observations have identified declining populations in streams along the Pacific Coast from Washington to California south of Point Conception as well as within the Columbia River Basin (Close, 2001; Luzier et al. 2009; Swift and Howard, 2009; Moyle et al. 2009). Pacific lamprey were eradicated from multiple rivers throughout coastal Washington, Oregon, and California (USFWS, 2004), above dams and barriers in west coast streams, and above dams in the Columbia and upper Snake Rivers (Streif, 2007). Within the South Fork Clearwater River sub-basin in Idaho, the abundance of lamprey populations were documented to be dramatically reduced from historic populations (USFS, 2016).

The NatureServe ranking system is a world-wide program developed to assign conservation status using known science for further protection. Within the system, Pacific lamprey populations within the Mid-Columbia and Upper Columbia River are designated at ‘high risk’ while populations in the Lower Columbia are at lower risk, although facing larger, continuous threats (Luzier, 2011). The Upper Columbia region represents all Columbia River tributaries including the Wenatchee, Yakima, Entiat, Naches, Okanogan, and Methow Rivers. Although accurate counts of the Pacific lamprey are difficult to attain due to their complex life history, discrete counts at dams in conjunction with observations have identified a dramatic decline in western populations.

Pacific Lamprey Life History

The Pacific lamprey is a unique anadromous fish species native to aquatic systems throughout the Northwest (Figure 6). Although minimal information is known regarding certain life stages, the lamprey has been identified as a species required for proper ecosystem functions throughout the West. Lamprey utilize freshwater systems for spawning, rearing, and juvenile development, followed by migration to marine systems throughout maturation, and finally return to available freshwater reaches for spawning (Figure 6).

Figure 6. Adult Pacific lamprey. Photo adapted from: United States Fish and Wildlife Service.

Developmental stages of distinct lamprey populations are similar; however, variation occurs between and within basin environments (Clemens et al., 2009). Spawning generally occurs throughout the late spring and early summer in the Columbia River Basin when temperatures reach 10°C to 15°C (Beamish, 1980; Luzier et al., 2011; Moser et al., 2007). Similar to salmonids, Pacific lamprey spawn in habitat within gravel streams in low-gradient stretches, upstream of riffle crests, and in downstream portions of pools (USFWS, 2011; Stone, 2006; Moser et. al., 2007; USDA, 2016). When constructing redds, lamprey move individual grains using sucking discs called buccal funnels located on their mouths to clear the area and to deposit substrate around the redd **(**Crandall and Wittenbach, 2015; Pletcher, 1963).

Larvae hatch after approximately three weeks, traveling in the downward flow until appropriate habitat is present for burrowing or spring flows are reduced (Dawson et al, 2015). Once emerged, juvenile ammocoetes remain three to seven years buried in channel material typically at a depth of less than 20cm, feeding on microscopic algae and organisms in the water column (Dawson, 2015). Although fine sediment is preferred, ammocoetes can use small gravel and cobble material for rearing if habitat provides limited availability (Crandall and Wittenbach, 2015). Rearing habitat is typically within close proximity to spawning habitat (Moser et al., 2007). Ammocoetes are commonly found in pools, eddies, and along stream edges that provide low water velocity; however, juveniles cannot tolerate areas of high anoxic conditions commonly found in regions of high organic matter if unsuitable velocities are present (Crandall and Wittenbach, 2015; Pirtle et al., 2003). Downstream regions of logs, boulders, and other channel obstructions create suitable rearing habitat (Crandall and Wittenbach, 2015).

When individuals emerge from rearing habitat and outmigrate to the ocean following maturation, Pacific lamprey will spend one to three years in the marine environment feeding on various fish (Beamish, 1980; Kan, 1975). Once sufficiently developed and matured, lamprey will stop feeding and return to freshwater systems for overwintering and spawning (Cummings, 2007). Due to their unique life history patterns, Pacific lamprey can be present within the channel bed at all times of the year, increasing their vulnerability to human activities including dredging.

Dredging Effects to Pacific Lamprey

Several meetings of the Pacific Lamprey Conservation Initiative identified specific threats to lamprey from human activities within aquatic systems including the dewatering of rivers and reservoirs, navigational and recreational dredging, unscreened surface water diversions, reduction of vegetation, channelization, large woody debris removal, and the introduction of toxic contaminants and predatory fish (Luzier et al., 2009).

Minimal information is present regarding small-scale mining impacts on non-salmonid fishes; however, lamprey habitat is known to significantly overlap with common dredge mining streams (R2RC, 2006). Species with a spring spawning timeframe including resident lamprey, rainbow, steelhead, trout, west slope cutthroat, sturgeon, and cade species have a higher likelihood of being exposed to small-scale mineral prospecting (R2RC, 2006).

Impacts identified from dredging activity with the potential to affect lamprey include the uptake of individuals through the system, burial of eggs and larvae by fine sediment, alteration of available food sources, reduction of nesting and rearing habitat, increased vulnerability to predation, and re-mobilization of heavy metals to larval habitat (ORAFS, 2015; HWE, 2009; Bettaso and Goodman, 2010). Like salmonids, lamprey are affected by impaired water quality conditions and streambed instability during both larval/juvenile migration downstream and adult migration upstream (CRITFC, 2011). The simplification of channel habitat, increased streambed instability and gravel embeddedness, and the discharge of fine sediment can impact present lamprey spawning, holding, and rearing habitats (Stern, 1988). Pacific lamprey restoration goals have been established in tribal management plans and are identified as a priority species for recovery (CRITFC, 2011).

High variation in water quality are common throughout the Upper Columbia tributaries with levels of dissolved oxygen, pH, pollutants, chemicals, along with agricultural and sediment runoff (Luzier et al., 2011). Degradation of water quality from either external environmental conditions or direct dredging activity have the potential to significantly affect lamprey throughout all freshwater life stages. A survey completed by the Fish Ecology Division in the National Marine Fisheries Service and the Umatilla Tribal Fisheries Program assessed thermal stressors to Pacific lamprey (Moser et al., 2017). Groups of larvae were separated and assessed for their response to changes in temperature according to different amounts and timeframes. In the study, larvae were resilient to slow thermal changes with a 100% survival when increased from 13℃ to 19℃ in 1.5 hours and then returned to 13℃ (Moser et al., 2017). Larvae experienced slightly higher rates of mortality in abrupt temperature shocks with 96% survival after an increase from 13℃ to 20℃ in 10 minutes and returned back to 13℃ after one hour (Moser et al., 2017). Aquatic systems that experience dredging have the potential for rapid alterations to ambient temperature during dredging activity. Another survey completed by the Fish Ecology Division in the National Marine Fisheries Service (NMFS) analyzed minimum oxygen levels required for the transport and holding of translocated Pacific lamprey (Moser et al., 2018). Results showed larvae were overall resistant to low levels of dissolved oxygen with dramatically lower consumption rates than adults with a mean oxygen consumption ranging between 0.2 to 2 mg/kg/hr when exposed to dissolved oxygen levels ranging from 4.3 to 9.1 mg/L (Moser et al., 2018). In contrast, adults experienced higher stress when dissolved oxygen fell below 2mg/L, and they were less resistant to depleted oxygen conditions with a mean oxygen consumption ranging between 5-600mg/kg/hr when exposed to dissolved oxygen levels ranging from 1-8.0 mg/L (Moser et al., 2018). In addition, adults could reduce respiration rates when oxygen levels were low, whereas larvae continued similar levels of consumption (Moser et al., 2018). Due to the potentially significant effect of altered temperature and oxygen levels to lamprey, it is necessary to monitor this parameter during dredging to identify any detrimental effects present. In addition, when mature individuals experienced increased levels of turbidity in holding tanks, behaviors of distress were identified including climbing the sides of the tank (Moser et al., 2018). Dredging has a potential to increase turbidity, conductivity, and suspended sediment levels within a system in a short period of time through the uptake and release of substrate from the channel bed. It is necessary to identify alterations to these parameters during dredging in order to identify potential effects on lamprey populations

CHAPTER 3

STUDY AREA

Geographic Setting

Located within the Eastern Cascade Mountains of Central Washington, the Entiat River watershed is surrounded by the Entiat Mountains along the southwest, and the Chelan Mountains and Lake Chelan drainage on the northeast (Sixta, 2010). The watershed width ranges from five to 14 miles along the valley with a drainage area of approximately 1080 km^2 (Chelan County Conservation District [CCCD], 1999). A tributary to the larger Columbia River, the Entiat River flows southeast from the headwaters located at the Cascade Crest approximately 53 miles to the confluence near Entiat (Figure 7) (Sixta, 2010; Entrix, 2003).

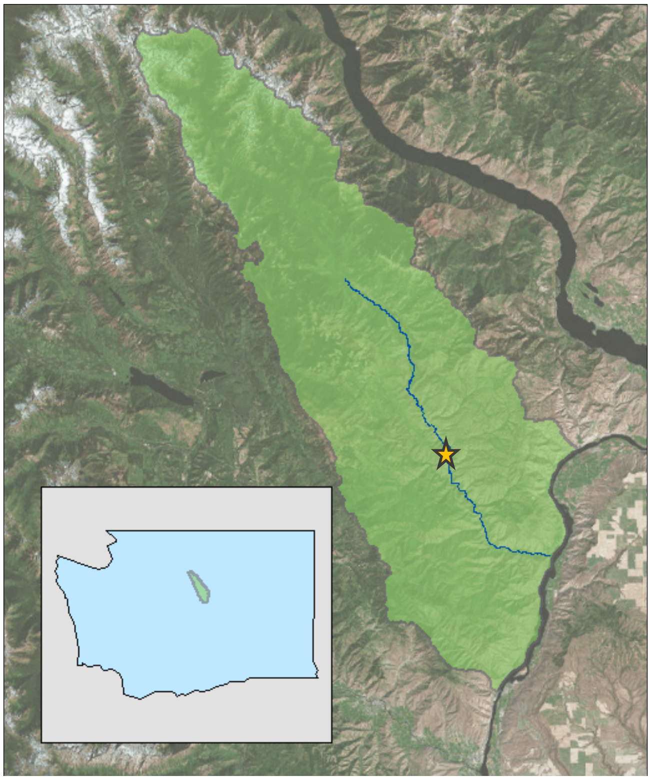


Figure 7. Entiat River watershed, Washington State. The gold start represents the approximate survey site location.

Elevation extremes range from the headwaters at 9,000 feet to approximately 700 feet near the river confluence (Kirk et al., 1995; Andonaegui, 1999). Disregarding the lower floodplain, the overall terrain of the watershed is mountainous and mostly forested (Kirk et al., 1995).

Watershed Geology and Geomorphology

Bedrock composed of crystalline minerals is present throughout the watershed with glacial and alluvial deposits along the valley that vary significantly with depth (Kirk et. al., 1995). Crystalline rocks, common throughout the Chelan and Entiat Mountains, include gneiss and schist, quartz diorite and granodiorite (United States Forest Service [USFS], 1979). Within the watershed there are multiple terranes present including the Mad River Terrane, Chelan Mountains Terrane, and Swakane Terrane (Figure 8) (Tabor et al, 1987). Present terranes have experienced significant metamorphism and intrusion events during the Late Cretaceous and outcropping of bedrock is common throughout the Entiat River (Inter-Fluve, 2013; Tabor et al, 1987).

Glacial deposits are poorly sorted and typically consist of sand, cobbles, and gravel with lower amounts of silt and clay while alluvial deposits are stratified (Kirk et. al., 1995). Although now considered inactive, tephra from the previous volcanic activity of Glacier Peak covers a large portion of the watershed (Tabor et al, 1987).

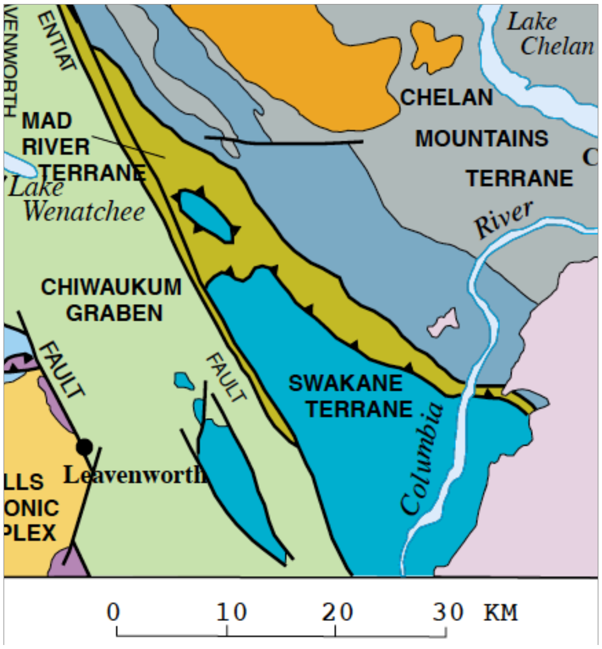


Figure 8. Geologic terranes within the Entiat River watershed. The Chelan Mountains Terrane is composed of Entiat pluton (blue), migmatite, and tonalite (gray), the Swakane Terrane is composed of biotite and gneiss (turquoise), and the Mad River Terrane is made of heterogenous schist and gneiss (yellow-green). (Map modified from USGS, 2001).

Composition of the Chelan Mountains Terrane is a mixture of plutonic and metamorphic rocks and includes the Chelan Complex that was metamorphosed during the Late Cretaceous (Inter-Fluve, 2013). Chelan Complex rocks are present along the Entiat River from river mile (RM) 18.5-21.0 and are composed of gneiss and amphibolite (Tabor et al, 1987). Entiat Pluton is an igneous intrusion composed of granitic rocks and is present within the entire valley stretch from the Columbia River to the headwaters (Tabor et al, 1987).

Previous glacial erosion of the surrounding mountains as well as current stream flows contribute significant sediment to the watershed (Kirk et al., 1995). During the Pleistocene Epoch, a thirty-mile-long glacier was present in the upper Entiat valley (Long, 1969). The glacier extended from Mt. Maude to RM 15.1, five miles north of the town of Ardenvoir where a terminal moraine is present (Figure 9) (Long, 1951; Andonaegui, 1999).

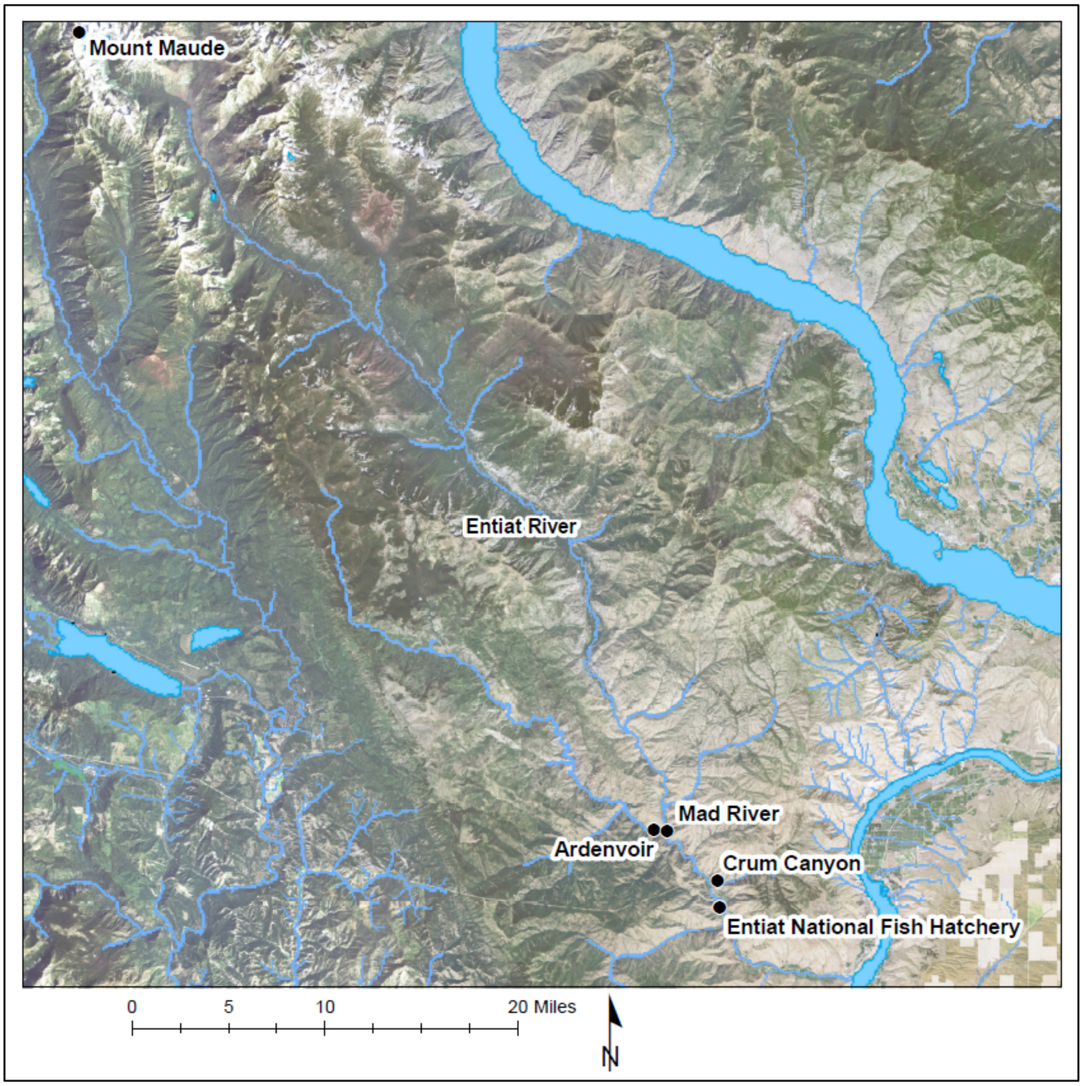


Figure 9. Points of interest along the Entiat River, Washington.

Ice scoured the valley into a U-shape creating a wide floodplain. Below the region of glacial activity, the Entiat valley has a typical V-shaped, incised stream habitat created from downcutting and other processes (Andonaegui, 1999; United States Department of Agriculture [USDA], 1979). Debris flows along hillslopes from erosional slope processes are an important contributor of sediment to the river channel (Bureau of Reclamation [BOR], 2009). Sediment is fed into rivers through rock fall and mass wasting events throughout the valley (BOR, 2009). Although certain reaches have compositions capable of eroding fine sediment to the river, the majority of grains present in hillslopes adjacent to the channel are composed of coarse rock that is transferred through mass wasting to create steep slopes (BOR, 2009). Tributaries and debris flow have transported sediment within the Entiat floodplain through a natural cycle of fill and scour as alluvial fans during past flood events and are well sorted (Andonaegui, 1999; USDA, 1979).

The Entiat River was classified in 1996 using the Rosgen Classification system in which the entire system from RM 0-53 was classified into Rosgen streamtypes as well as into general ‘depositional’, ‘transitional’, or ‘transport’ zones based on present channel characteristics (CCCD, 2002; USFS, 1996). Figure 10 depicts a diagram of the Entiat River identifying features along the mainstem as well as present spawning habitat with the most suitable substrate composition, gradient, and pool-riffle channel habitat for anadromous spawning occurring at RM 16 to 26 (Andonaegui, 1999).

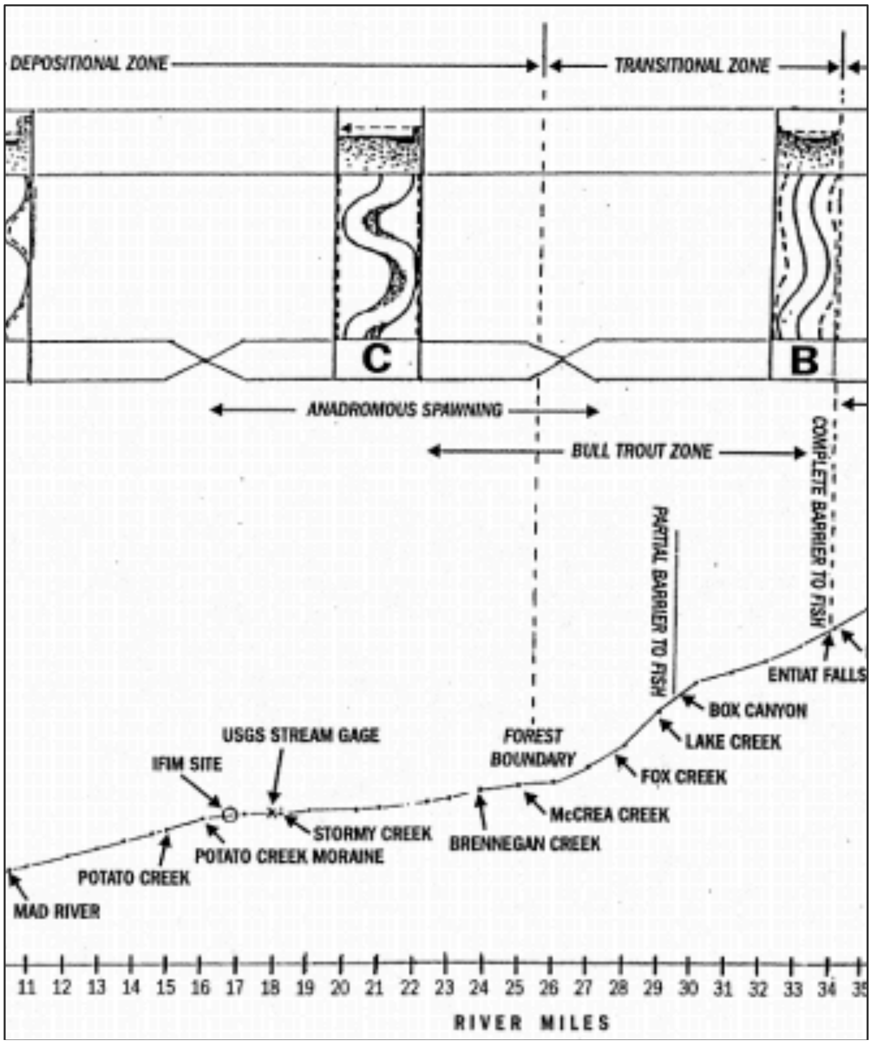


Figure 10. Diagram of the Entiat River outlining channel gradient, dominant Rosgen channel classifications and fish use (Modified from USFS, 1996).

For this study, the experimental site was located within the depositional zone at RM 19, identified as Rosgen type ‘C’ with high suitability for anadromous spawning (Figures 7 and 10). This zone experiences deposition as a dominant channel process with periodic flooding from thunderstorms as an important method of substrate transport (Andonaegui, 1999).

Fishes

Ecological processes within the watershed are influenced by present and historic morphologic and climatic conditions. Sediment transport, channel slope, habitat complexity and present streamflow are all factors that can affect fish populations present (USFS, 1996). The Entiat River provides a large amount of spawning, rearing, and predation cover habitat for various fishes including steelhead and salmon as well as multiple populations of native, non-salmonid fishes (Entrix, 2003). Fish species inhabiting the Entiat River that have received further protection under the Endangered Species Act include the Columbia River bull trout (*Salvelinus confluentus*), Upper Columbia steelhead (*Oncorhyncus mykiss*), and Upper Columbia spring chinook salmon (*Oncorhyncus tshawytscha*) (USFS, 2004). According to the Washington State Salmon and Steelhead Stock Inventory (SASSI) completed in 1992, the Entiat River has one stock of spring chinook, and it is listed as 'depressed' due to consistently low numbers and reproduction (Andonaegui, 1999). Other native salmonid species of management focus include summer chinook salmon, west slope cutthroat trout (*Oncorhyncus clarki lewisi*), rainbow trout (*Oncorhyncus mykiss*), and a small sockeye (*Oncorhyncus nerka*) population (USFS, 2004). Coho salmon (*Oncorhyncus kisutch*) no longer occur in the Entiat watershed, having been extirpateded from the upper and middle segments of the Columbia River basin (Andonaegui, 1999). Recent spawner surveys performed in the summer of 2018 directly in the survey site by the USFWS have identified several chinook redds located upstream and downstream of the experimental region (Fraser, G. and Grote, A. personal communication, 2018).

Pacific lamprey still exist in the Entiat River system, but distribution and abundance information is largely absent (Peven et al., 2004). According to a report by the USFWS and the Pacific Lamprey Conservation Initiative in 2011, when compared with other Upper Columbia watersheds and based on professional judgments, both the Wenatchee and Entiat watersheds were presumed to have higher population counts ranging from 250-1000 (Luzier, 2011). Within the same study, populations in the Upper Columbia Region experienced a decline of 10% over 27 years (Luzier, 2011). Due to declining populations of Pacific lamprey throughout the West as well as the absence of accurate population data, a high level of effort to monitor and enhance these populations is recommended (Peven et al. 2004). Recent USFWS lamprey surveys directly adjacent to the study area have identified probable nests immediately upstream and downstream of the experimental stretch, confirming the presence of lamprey and appropriate habitat (Anne Grote, personal communication, 2018).

Weather and Climate

The variation in topographic setting along the Entiat River watershed creates extreme variation in precipitation, temperature, and weather events (Entrix, 2003). Due to the location of the upper watershed at a higher elevation within the Cascade Mountains, this region is subject to orographic effects and subsequent colder temperatures and wetter conditions than the lower watershed (Erickson, 2004).

High variation in temperature occurs seasonally between the upper and lower regions of the Entiat Watershed. In the summer, average temperatures at elevation usually remain around 50°F while high temperatures in the lower watershed commonly reach

70°F (Andonaegui, 1999). At the Entiat River Hatchery located in the lower watershed, average temperatures range from 21.9-86.8°F annually (Figure 11).

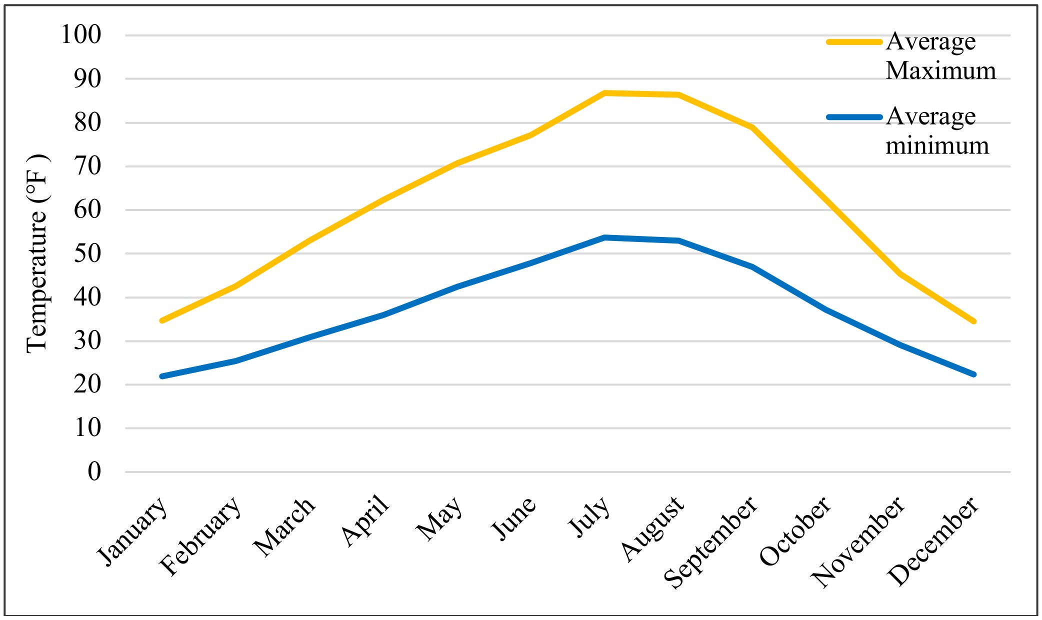


Figure 11. Average minimum and maximum monthly temperature for the Entiat River Hatchery in the lower watershed between 1989-2012 (Data obtained from the Western Regional Climate Center, 2018).

Average annual precipitation varies significantly throughout the valley with approximately 100 inches in the northwestern region of the watershed to approximately 10 inches at the river confluence (Kirk et al., 1995; Andonaegui, 1999). The main precipitation input occurs as winter snow, which in turn increases streamflow when high temperatures of spring and early summer melt the snowpack (Kirk et al., 1995). Precipitation is cyclic throughout the year with minor amounts during summer months, increasing significantly in the winter with much of the precipitation occurring as snowfall, and then decreasing in the spring (Figure 12) (Kirk et al., 1995).

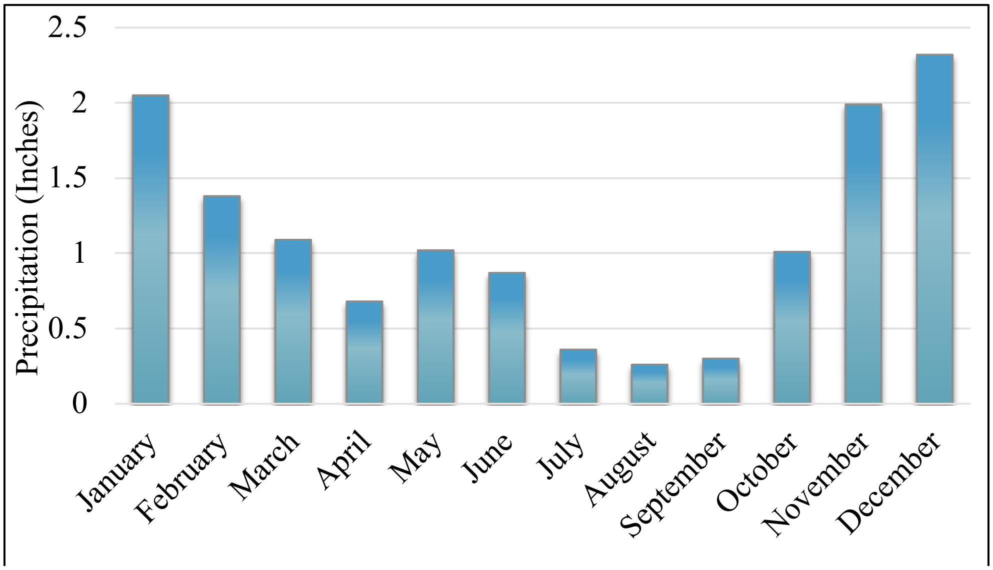


Figure 12. Monthly precipitation averages for the Entiat River Hatchery between 1981-2010 (Data obtained from the Western Regional Climate Center, 2018).

Heavy rainfall events are associated with high intensity thunderstorms common in the watershed during summer months that have resulted in flash flooding in the narrow canyons (USFS, 1996). Thunderstorms are known to cause major fires in the region by striking steep or otherwise inaccessible locations of the valley. During the past 30 years, 60% of the watershed has experienced a burn (USFS, 1996). Consequently, the total sediment yield and annual runoff occurring in the valley varies considerably with precipitation amounts and fire prevalence (Entrix, 2003).

Hydrology

The accumulation and melting of snow in the upper watershed experiences interannual variation with weather, significantly influencing hydrology and runoff occurring within the Entiat River. Most precipitation comes in the winter and spring as snow, resulting in late spring and early summer snowmelt (Figure 13).

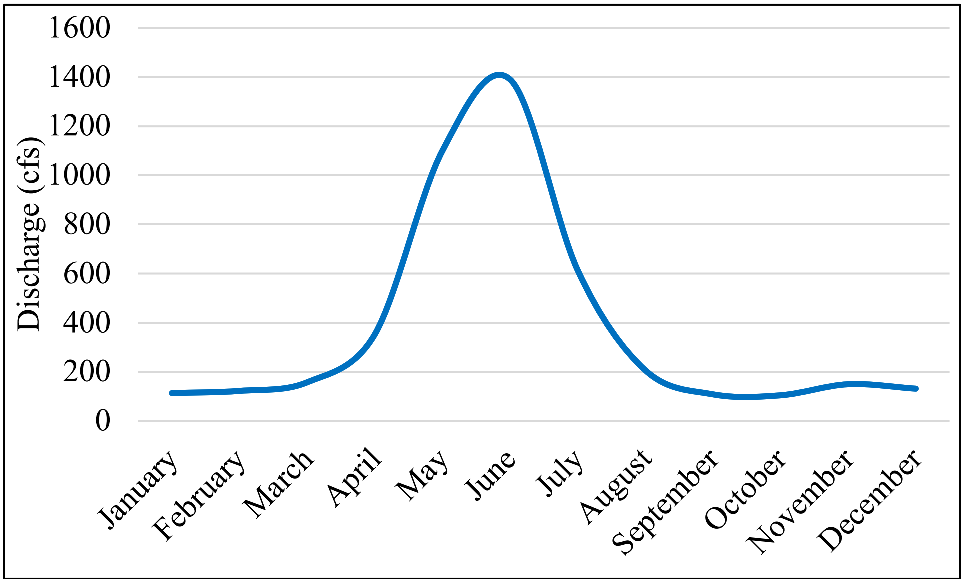


Figure 13. Average monthly stream flow for the Entiat River at river mile 18. (Data attained from USGS steam gage 12452800).

According to USGS flow data from 1957 to 2017, the average annual flow in the Entiat River site located approximately one mile downstream of the survey site is 379cfs (USGS, 2018). Peak discharge is dominated by the amount of surface runoff that occurs in the valley. Many perennial and intermittent tributaries exist within the watershed that provide significant amounts of streamflow to the main stem Entiat. The north fork meets the main stem at river mile 33 and provides 20% of flow to the Entiat River while the Mad River provides 14% of flow to the Entiat at river mile 10.5 (Figure 9) (Andonaegui, 1999). Present glaciofluvial and alluvial material deposited throughout the valley in the watershed acts as the main aquifer and provides the majority of groundwater (Kirk et al., 1995). Due to the sloped floor, the aquifer discharges to the Entiat River, leading to increased streamflow (Kirk et al., 1995).

Ownership and Land Use

The watershed is located within Chelan County between the city of Wenatchee and just south of Lake Chelan. Approximately eighty-seven percent of the land is publicly-owned and located within the upper watershed in the National Forest boundary (Entrix, 2003). In contrast, a majority of the lower valley is privately-owned along the lower 25 river miles including approximately 1,300 acres of orchards (Entrix, 2003). In the watershed, the main land uses include timber, agriculture, recreation, and rangeland (Kirk et al., 1995). With the growing season generally between March through September in the lower region, off-stream water demand for irrigation contributes a separate stressor towards healthy water levels in the Entiat River ecosystem. Orchard crops are the main use of irrigation with the largest demand typically occurring in late June through August (Entrix, 2003).

Located in the lower watershed at RM 6, the Entiat National Fish Hatchery operates as one of multiple impact mitigation facilities for establishment of the Grand Coulee Dam through the Columbia Basin Project (Figure 9). The initial plan included trapping mature steelhead and salmon at the lower Rock Island Dam to be transported for spawning and holding within the hatchery (USBOR, 2009). In addition, the hatchery began raising summer Chinook salmon in the fall of 2009 with the primary objective of maintaining a separate summer Chinook harvest program (USBOR, 2009).

Sources of Disturbance in the Watershed

Disturbance processes observed currently and historically in the watershed include wildfire, flooding, mass wasting, and various land uses (Nelle et al. 2009).

Changes to the watershed from human land use activities include river channel modifications, grazing, road and residential development, agriculture, timber harvesting, log transportation using the river channel, splash dams for log storage ponds and hydropower generation, and recreation (Sixta, 2010). Before the orchard industry, the most common economic activities in the watershed included mining, logging, and grazing (Erickson, 2004). Mineral extraction was present but not extensively popular in the Entiat River, in contrast to many productive adjacent watersheds (Erickson, 2004). Gold and other minerals of interest were mined between 1885 and 1910 throughout the watershed with most attention on the Crum Canyon (Figure 8) (CCCD, 2002). According to “Western Mining History”, small gold and platinum placer deposits throughout the Entiat River were previously mined, however production was minimal; therefore, placer mining is not known to be a significant aspect within the history of the Entiat River (Koschmann and Bergendahl, 1968). Mining activity was further reduced after the early 1900s following the increase in lumber and agricultural industry in the valley (CCCD, 2002). The lack of small-scale mining makes the Entiat River a preferred location for the highest accuracy of habitat alteration pre- and post- dredging.

CHAPTER 4

METHODS

Survey Site Location

For purposes of this study, site locations were identified and referred to based on valley and reach segment identifications previously designated within the *Entiat River Assessment Report* completed by the Bureau of Reclamation (BOR) in 2009. Under this assessment, the Entiat River was characterized for prioritizing restoration activities based on multiple factors from river mile 0 to 26. Within the BOR assessment, three valley segments were identified based on general channel gradient, morphology, and present geologic controls while reaches within each valley segment were identified based on smaller scale specific habitat characteristics (BOR, 2009).

The longitudinal profile of the Entiat River from river miles 1 through 26 is shown in Figure 14 and displays the change in elevation between the three identified valley segments. The identified dredge study site is located within the second valley segment at reach 2C near river mile 20 that experiences low gradient, moderate sinuosity and alternating erosional and depositional stretches (Figure 14).

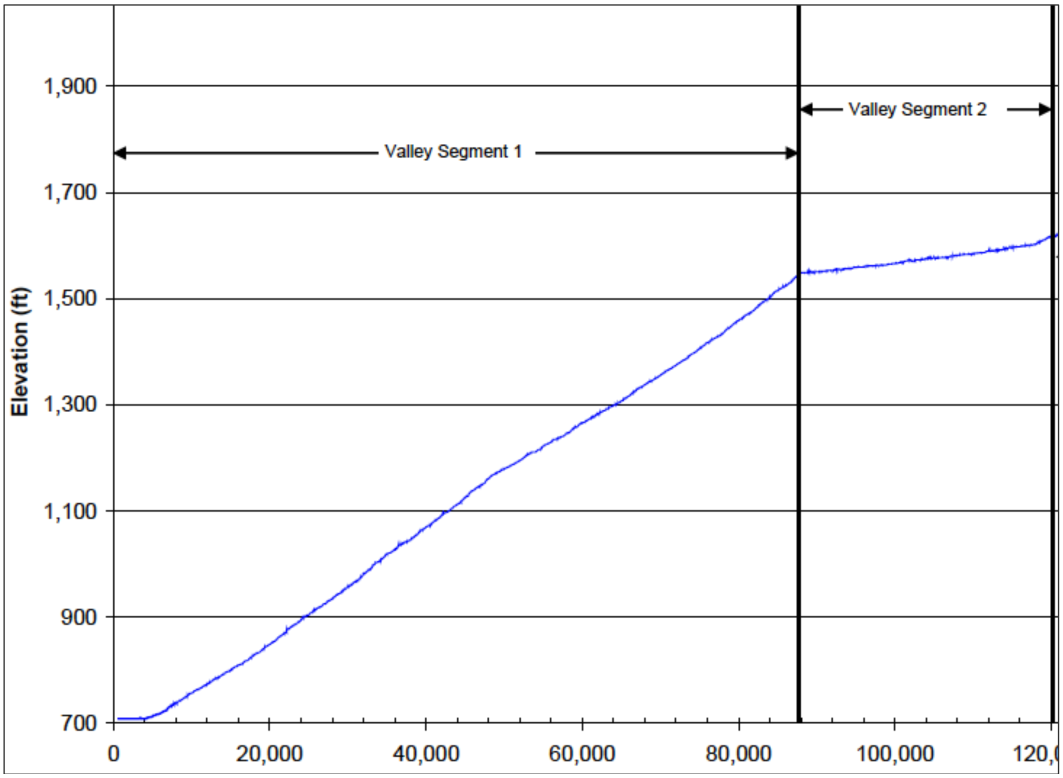


Figure 14. Longitudinal profile of the Entiat River from approximate river miles 0 to 26 using present channel elevations from a 2006 channel survey. Values on the x-axis represent distance (in feet) from the mouth located at the intersection with the y-axis. (Modified from USBOR, 2009).

The site was located within the upper region of section 2C at a sufficient distance from the upstream levee and offered approximately 1500 m of workable area. Due to its low gradient, unconfined river channel and active floodplain, this stretch of the Entiat River adequately represents preferred mining areas. The reach is contained in the upper river segment identified by the USGS gage site location at river mile 18 and is composed of more typical sequences of pools and riffles as well as sediment bars composed of gravel and cobble (Kirk et al., 1995). Flows during the experiment ranged between 199-215cfs and allowed safe access to the channel bed (Figure 15) (USGS flow gage station 12452800).

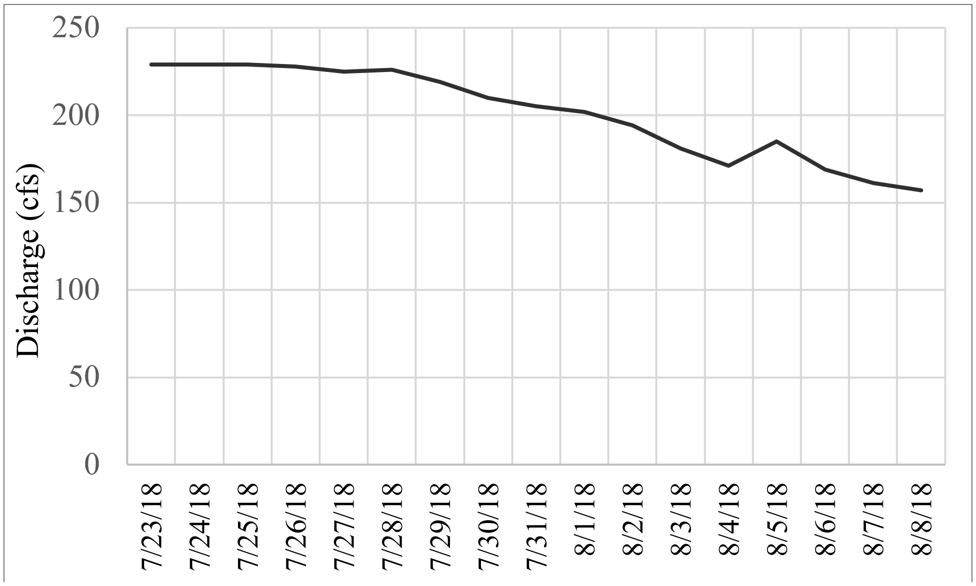


Figure 15. Flow rates associated with all survey timeframes. Data obtained by the USGS flow station near Ardenvoir (USGS, 2018).

All pre-dredge surveys and dredging experimental days were between July 25th-August 1st, 2018 as present flows were during the approved timeframe stated in the Gold and Fish HPA and were following the large surge of snowmelt earlier in the season. Present flows allowed safe access to the channel bed while still providing appropriate levels of flow for dredging equipment.

Habitat Characterization

Before any dredging occurred, both the designated experimental and control reaches were characterized for existing conditions before dredging on July 25th and 26th, 2018 at a stream flow of approximately 225cfs, similar to flows during the dredging experiment. Through establishing a baseline of pre-existing data, effects to the system resulting from dredge activity can be quantified. The longitudinal extent of each sample reach characterized was based on a traditional method using a standard 20 times bankfull width metric to include at minimum one meander wavelength and approximately three to four replicate habitat features (Fitzpatrick et al. 1998; MacDonald et al. 1991; Pleus and Schuett-Hames, 1998). Utilizing the 20 times bankfull width method allows an appropriate distance to be covered for an accurate representation of the channel system without oversampling and creating a reduction in surveying efficiency (Fitzpatrick et al., 1998).

Approximate longitudinal distances for each reach were estimated by measuring channel cross-sections within ArcMap and Google Earth software as well as measuring three cross-sections in the field at equal distances within the experimental reach for bankfull width to confirm a representative distance (Arend and Bend, 1999). The wetted channel width was also measured across the streambed perpendicular to the flow at the edge of the water/air interface. Average bankfull width for the survey region was measured at 29.7 m while average wetted width was 24.3 m. Longitudinal distance characterized was therefore approximately 609.6 m for both the control and experimental reaches (Figure 16).

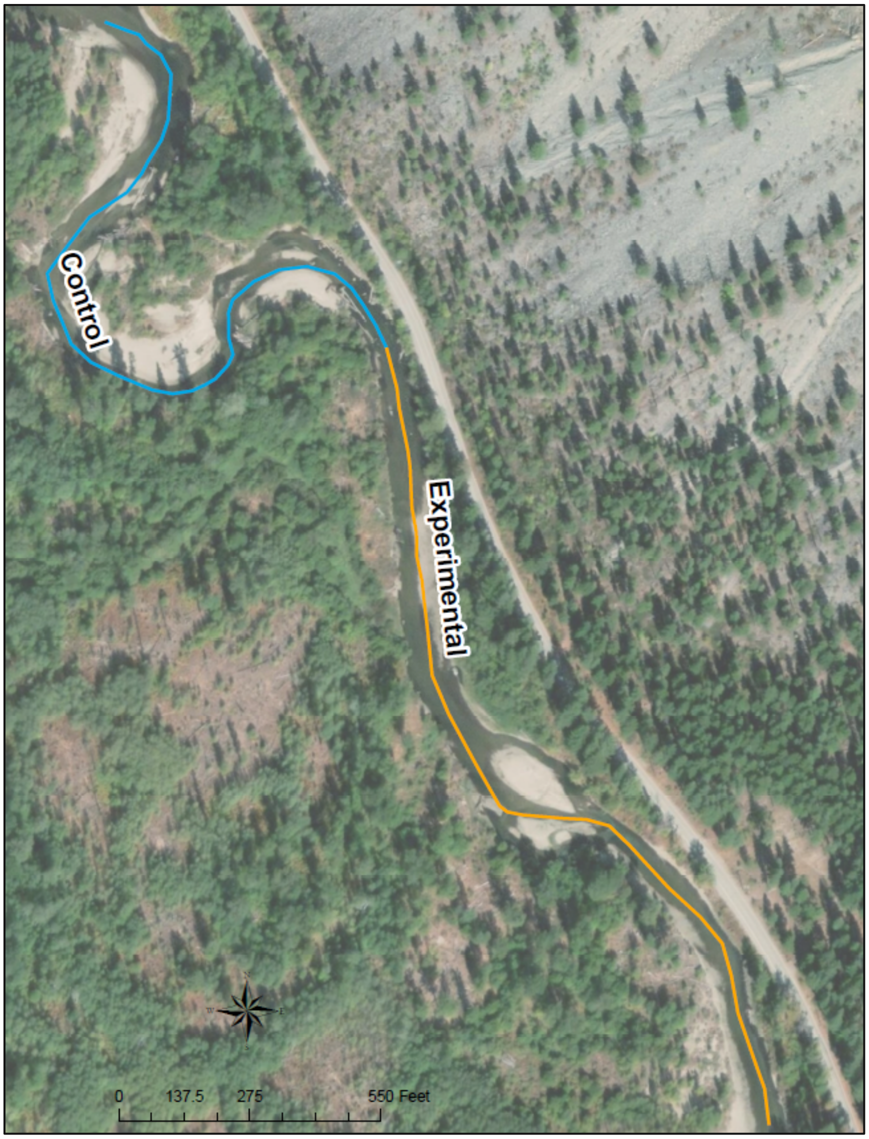


Figure 16. Longitudinal profiles of both control and experimental reaches. Each profile was characterized for present habitat features and distances were determined to be approximately 609.9m for each reach.

All pool, riffles, and glide habitat features were inventoried along the established longitudinal distances for both reaches. A riffle is composed of steep slopes and shallow depths with turbulent water, typically having a poorly defined thalweg (Vermont Agency of Natural Resources [VANR], 2004). A glide has no turbulence, fast water velocities, and is usually present in transition points between features or downstream of pool habitat

(VANR, 2004). Pools are commonly found at the deepest points within a channel reach with slow water flow. Pool features are delimited by a crest at the upstream transition in channel bed slope as well as a downstream change in slope at the crest of the present tail (USFS, 1997). Throughout both reaches each habitat unit was given a unique identification number and documented for the total length covered in the channel using upstream and downstream GPS waypoints. Within each characterization all identified pools and riffles were counted and measured for width, length and maximum depth (Pleus et al. 1999). Width and length measurements were collected using a 200m measuring tape while depths were collected using either a meter stick or a survey rod.

One sediment sample was collected at each pool near the maximum depth to establish a grain size distribution (Pleus et al. 1999). Surficial bulk samples were collected from the channel bed surface using a trough shovel pointed into the flow, slowly raised to the surface, and collected in labeled one-gallon Ziploc bags (Figure 17).

Figure 17. Shovel used for bulk sediment sampling. Large edges helped minimize loss of fine sediment during collection.

The shovel was equipped with large edges to minimize loss of fine sediment from the sample. Once collected, all sediment samples were returned to Central Washington University for post-processing.

Wolman pebble counts were collected in the field at riffles and glides to measure grain size distribution (Wolman, 1954). Pebble counts were conducted by measuring 100 randomly chosen particles from the streambed within each habitat feature. At the beginning of each survey, the surveyor chose a rock at random from the channel bed and tossed it without looking within the feature to establish a random starting point. Once a starting location was identified, the surveyor worked upstream in an alternating diagonal pattern along the feature and collected particles located at the surveyors' toe following every step (Wolman, 1954). Each particle was then measured along the intermediate axis or if the grain was embedded and unable to be fully removed the shortest axis showing was measured, following the established guidelines for completing a Wolman pebble count (Wolman, 1954). All measurements were transferred verbally to another surveyor on the shore to be recorded.

Finally, water quality measurements were also collected in the center of each pool and riffle for dissolved oxygen in both units of mg/L and percent saturation, temperature (°C), turbidity (NTU), pH, and specific conductance (µS/cm). State requirements for Class A water systems including the Entiat River have limits on water quality parameters to maintain a healthy ecosystem (CCCD, 2004). In these requirements, temperature should not reach levels above 18°C, dissolved oxygen should not fall below 8mg/L, pH values should be within the range of 6.5-8.5, and turbidity must not exceed 10 NTU above background levels when current levels are 50NTU or lower (CCCD, 2004). Due to their direct effects on channel biota, it is important that these parameters were monitored throughout the entire study. Suspended sediments typically show similar trends with turbidity levels and were therefore also included in the monitored parameters. Temperature, dissolved oxygen, and specific conductance were collected using a YSI 85 meter with the associated sensor submerged at approximately 60% water depth in the water column in appropriate flow until readings stabilized. Turbidity and pH samples were collected by hand using a sample jar submerged at 60% water depth until filled. Through collection and inventory of habitat characteristics of each reach a baseline could be established for use in quantifying impacts to the river system during and following dredging.

Sample Sites

Cross-sections were established in the experimental reach to approximate dredging and monitoring locations. Although current regulations in Washington State restrict the distance between dredges working in a river system to a minimum 61.0 m (200 ft) apart (WDFW, 2018), previous studies have documented impacts from suction dredge mining over 152.0 m downstream from the dredged portion of a waterbody (Prussian et al 1999). Survey transects were spaced at 15.2-30.5 m intervals for an approximate total distance of 198.1 m downstream from dredging in order to assess the effectiveness of current regulations and to apply results towards potential cumulative impacts from multiple dredges. By utilizing intervals at smaller distances than 61.0 m required in regulations, any existing changes to the water quality were identified on a smaller scale and the total distance affected in the survey area by dredging was captured. All established transects were set in a cross-sectional pattern and spanned the width of the river channel. Five were established in the uppermost region of the experimental section to identify the dredged region (DR_1 through DR_3) and were monitored for direct, specific alterations to the channel habitat (Figure 18).

Figure 18. Established experimental transects within the survey site located at river mile 19 of the Entiat River, Washington. Dredging activity occurred between transects starting at Dredge 1 (DR_1) upstream to immediately below the control transect (CO_1).

One cross-section (CO_1) was established 26 m upstream of the dredged region and was monitored as a control (Figure 18). Five transects were established at 15.2 m intervals below the dredged region (identified as G-C) as well as two transects spaced at 30.5 m intervals (identified as A and B) to capture downstream impacts for a total distance of approximately 213.4 m (Figure 18). Three survey points were identified along each transect at 25%, 50%, and 75% channel width to be used as locations for point sampling and monitoring throughout the study. Through capturing three separate points along each survey transect, specific regions of impact could be identified and a more complete coverage of the transect as well as the downstream region was attained.

Dredging Experiment

The majority of known dredging activity occurs in the summer months when low flows allow operators to safely access a larger amount of sites. In order to best mimic dredging impacts to a system in comparative flows, the experiment took place within the months of July and August 2018. According to the WDFW Gold and Fish pamphlet HPA guidelines, the allotted timeframe for dredging from the Entiat River mouth to Entiat Falls is from July 16th to 30th. An HPA application was previously submitted to WDFW and following a site visit with a regional fish biologist, was approved for this research to be extended through August 10th within the 2018 year and every year during the same timeframe through 2023.

Dredging was delayed one week due to high flows and therefore was completed over three days on July 30th, 31st, and August 1st, 2018. The dredge began just upstream of Dredge 1 on Day 1, at Dredge 2 on Day 2, and just upstream of Dredge 3 on Day 3 (Figure 19).

Figure 19. Monitored profiles over the three survey days. Dredge 1 was the general starting location for Day 1 along with Dredge 2 for Day 2, and Dredge 3 was for Day 3.

Dredging began at approximately 10am every day with the dredge placed near the beginning transect and moved upstream as each survey day progressed. Monitoring and dredging assistance were provided by CWU staff, Mid-Columbia Fisheries Enhancement Group interns, fellow CWU graduate students, and other volunteers. A 5” diameter Keene suction dredge was acquired for purposes of this study using funds attained from the Kittitas County Audubon Society Scholarship as well as the CWU School of Graduate Studies Research Support Award (Figure 20).

Figure 20. Trial run of the 5" suction dredge within the Little Naches River, Washington. Photo credit: Jaime Liljegren.

The 5” intake nozzle is the largest dredge permitted in the Entiat River and was attained to assess the maximum potential impact available to a river system of this size. Equipped with an 8hp gasoline Honda motor, a water pump, and a sluice, this dredge is capable of moving a substantial amount of material within an aquatic system.

Dredging Techniques

Each survey day the dredge was transported from the road access point into the river channel, tied to the banks using two upstream and one downstream rope for stabilization of the dredge within the river, and run at designated dredge transects working upstream according to proper dredging techniques outlined in literature including “The Gold Dredger’s Handbook” and “Suction Dredging for Gold”, both written by Dave McCracken, “The Gold Miner’s Handbook” by Bruce Harris, and “Suction Dredging Techniques” from Dredger’s Digest. Dredging began just above the Dredge 1 transect on Day 1, directly at Dredge 2 on Day 2, and above Dredge 3 on Day 3 with each day working both laterally and upstream from the starting point. Dredging events were completed every day for three days to best mimic common group dredging situations and assess cumulative impacts within a specific region. The dredge was run for five hours the first two survey days to closely mimic the average timeframe spent dredging per day (5.6 hours; CDFG, 1994); however, due to the approaching Cougar Creek fire dredging had to be completed early on the third day, reducing total dredging time for the day to three hours.

After tying off the dredge to the channel banks in order to maintain a proper position in the river, the water pump was primed and the engine was run at low speeds until properly warmed up. Once prepped, the dredge engine was accelerated to full operating speed. During dredging, one person operated the suction nozzle directly in the channel while the other assisted in removal of large material too large for the nozzle as well as removing plug-ups created from oversized material and maintaining overall proper operation of the dredge (Figure 21).

Figure 21. While the engine was in operation, two people were working the dredge with one person operating the suction hose while the other would move large material out of the dredge hole by hand and assist in the proper functioning and management of the dredge. Photo credit: Scott Kugel.

Dredging was completed in an upstream direction in order to drop tailings downstream from the region being dredged. The survey site in the Entiat River encompassed a variety of grain sizes with the main channel bed being composed of cobbles and boulders with sand and gravel present filling interstitial spaces. Dredge holes were initially started at the dredge transect, being widened along the channel, and then once established were dredged both forward in an upstream direction and downward vertically (Figure 22).

Figure 22. Once the dredge hole was established and widened laterally, the hole would simultaneously be moved both in an upstream direction and deepened vertically. Photo credit: Scott Kugel.

A pry bar was utilized to loosen hard-packed material in the streambed for suction or removal by hand. Production dredging was followed in which substrate was moved through the nozzle at an efficient speed and was accomplished by widening the created dredge hole to appropriately remove oversized rocks (Harris, 1986; McCracken, 2006).

Multiple dredge holes were created to mimic assessments of dredge operators towards determining and maintaining the paystreak as the dredge is moved upstream. Effective dredging involves the creation of holes both closer towards the streambank as well as the center of the waterway if possible (McCracken, 2006). Dredging locations varied among each survey day with most activity focused in the central region of the channel, the second day focusing both centrally and near the eastern streambank, and the final dredging day focused entirely on the center.

Water quality and sample collection

While the motor was running, two people operated the dredge and approximately seven other individuals were deployed downstream at set transects to capture and record water quality measurements and collect water samples during dredging. Water quality measurements and samples were collected before, during, and after dredging along transects to gather sufficient background data on downstream impacts. Water samples, flow rates, and depths were collected three times a day. All measurements and sampling occurred at three locations of 25%, 50%, and 75% channel width along each surveyed transect for comparison of impacts along the channel (Figure 23). Water quality measurements continued to be collected for approximately one hour after the dredge was stopped to capture the return to baseline levels within the river.

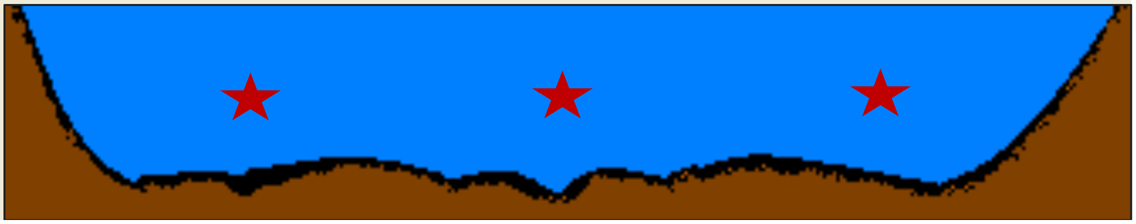


Figure 23. Channel cross-sectional diagram of approximate water quality measurement and turbidity sampling locations per identified transect. Vertically, samples were collected at 60% water depth of the water column. Horizontally, samples were collected at the 25%, 50% and 75% channel width distances. A total of three locations were measured and sampled per transect.

Water samples for suspended sediment were collected using 500 mL containers attached to two DH-48 suspended sediment samplers identified as the preferred method for sample collection in wadeable streams by multiple federal agencies (Federal Interagency Sedimentation Project [FISP], 2018). At each collection point, the DH-48 sampler would be placed directly into the upstream flow and slowly submerged from the water surface at a constant rate to the channel bed interface and back towards the surface in order to collect a representative sample of the entire water column. Once collected, all samples were post-processed at the Hydrology Lab within Central Washington University.

In addition to the collected suspended sediment sample, a second water sample for turbidity and pH measurements was also collected at each of the three sample points at 60% water depth for a total of six water samples collected at a time per cross-section (Figure 19). Samples were collected by hand using the same 500 mL containers and were analyzed in-situ using a portable Orbecco-Hellige 966 portable turbidimeter and a portable IFSET pH meter.

Water quality measurements of temperature, dissolved oxygen, and specific conductance were collected along all transects at hour intervals using a YSI 85 meter. Measurements were collected at all three locations along each transect for a total of three sample points per transect. Parameter levels were collected by submerging the sensor to a 60% water depth and were recorded directly in the field (Figure 24).

Figure 24. Survey assistants were deployed downstream at designated transects to monitor water quality parameters during dredging using a YSI 85 meter. Photo credit: Scott Kugel.

Bulk sediment samples were collected before and immediately following completion of dredge activity along all transects at the 25%, 50%, and 75% channel width to identify potential alterations of present grain size distribution. In addition, Wolman pebble counts were completed at transects Dredge 1, Dredge 2, and Dredge 3 immediately following dredging to be compared against the collected value before dredging. Samples were collected according to the same procedure outlined in the 'Habitat Characterization' section.

Cross-Sectional Profiles

Cross-shore elevation profiles were collected directly in the dredged region before, immediately after, two months following completed dredging activity, and at the beginning of the following season to capture vertical morphological changes to the system. Profiles were completed by walking across the channel width at one-meter intervals to identify point elevations using a TopCon GPT 3007 total station and prism (Figure 25). Profiles were collected at the Control, Dredge 3, Dredge 2, Dredge 1A, and Dredge 1 transects.

Figure 25. Elevation profiles were collected at five survey transects before, after, two months following the dredging experiment, and at the start of the next season in July 2019. These were visually assessed for direct vertical changes to the channel bed. Photo credit: Jaime Liljegren.

Transect elevation profiles were collected immediately before dredging and immediately after at the control and dredged transect regions to minimize external inputs and to allow a more direct comparison between sites. Once collected, profile elevations for each transect were plotted against one another from each timeframe at 1-meter intervals using Microsoft Excel to visually determine the amount of change.

In addition, stream power was calculated to assess the amount of 'work' capable of being completed within the channel. This measurement was used to help determine the amount of reworking in a system that occurs following a particular flow. This was determined using the cross-section wetted perimeter, area, and slope of the channel. Transects were collected again two months following dredging as well as after the spring snowmelt in the following year to capture the amount of change occurring at specific timeframes. Anecdotal arguments by dredge miners argue impacts from dredging are similar to natural storm events. Although storms cause a large amount of natural erosion and bedload movement, timing is a significant factor in the amount of impact that occurs to a region. Because dredging mainly occurs in the summer months with low flows, channel alterations have the potential to cause more significant impacts to biological habitat. Thunderstorms within the Entiat River watershed are common in summer months, making higher flows and rates of erosion more likely, although many riverine habitats in Washington generally experience moderate weather with low flow events in the summer and are thus more vulnerable to channel alterations. Monitoring the experimental site at various timeframes can help isolate and quantify erosional effects observed temporally at the dredged region.

Feature Measurement

On the final survey day, all tailings pile and dredge hole locations were collected using a GPS unit along with feature measurements to attain an overall footprint of the disturbed material. Every tailings pile was measured for the width, total length, the length of the sediment 'tail' that had been sorted downstream from the main pile, and water depths from the pile edges in all cardinal directions as well as a center depth (Figure 26).

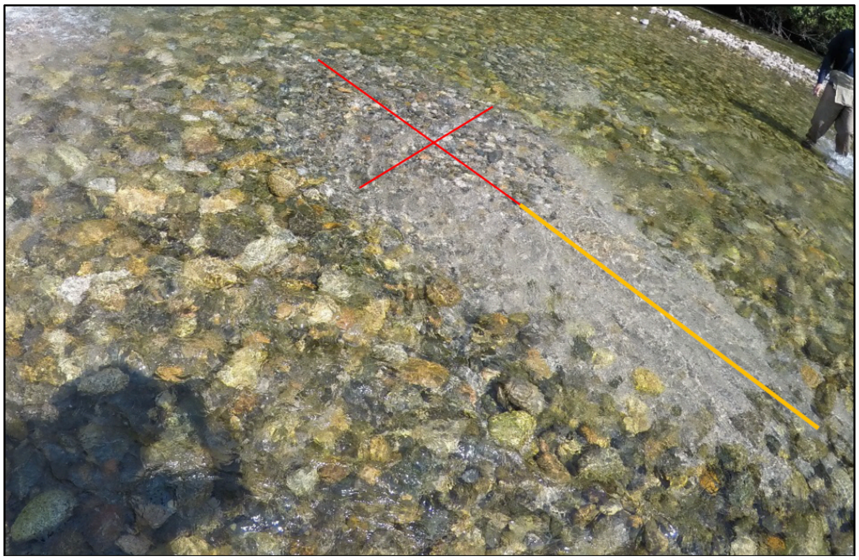
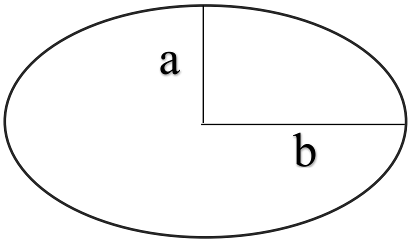


Figure 26. Length and width measurements of tailings pile created following dredging activity on Day 1 in the Entiat River, Washington. Grain sizes are sorted by water flow according to weight, with finer material transported further downstream. Photo credit: Scott Kugel.

In addition, the location of every created dredge hole was collected along with the length, width, and maximum depth. The same measurements were collected again for both tailings piles and pools in October to identify how much change occurred in the two-month timeframe.

The amount of surface area disturbed per tailings pile and dredge hole was determined using the ellipse formula:

$$Ellipse\ Area = \pi * a * b$$



Where ‘a’ is equal to half the total width and ‘b’ is equal to half the total length. The volumetric amount of substrate disturbed was determined using the adjusted ellipsoid formula to account for the create holes and piles being essentially equal to half of an ellipsoid:

$$(Ellipsoid\ Volume = \frac{4}{3}\pi * a * b * h)/2$$

Where ‘h’ is the height of tailings pile, essentially equal to half a full ellipsoid. Surface area and volume amounts were calculated for all piles and holes in August 2018, October 2018, and July 2019 and compared for the amount of material loss over the associated timeframe. This quantified the amount of recovery that occurred in between the initial dredging and varying flows.

Post-Processing and Statistical Analyses

All samples were processed in CWU's Hydrology Lab. Suspended sediment water samples were processed using a New Star V3000 vacuum pump and Rocker filtration glass set, and an Ohaus AdventurerPro AV212 analytical balance with a precision of 0.01g to attain a representative dried sample of present suspended sediment in the water column at a specific location and time. Samples were filtered through previously weighed 27.5mm diameter glass fiber filters using enhanced suction from the vacuum pump, dried overnight at room temperature, and re-weighed for a final weight. The difference between filter weights before and after filtration identifies the amount of suspended sediment present in the system downstream following dredging activity.

Bulk sediment samples were processed using a Ro-Tap sieve shaker to attain grain size distributions. Each sediment sample was removed from the freezer, placed in labeled aluminum trays and allowed to completely dry at room temperature for 1-5 days, depending on the moisture present within the sample (Figure 27). The entire collected bulk sample was processed to attain a representative distribution of substrate.

Figure 27. A subset of surficial bulk sediment samples collected during the study. Samples were dried at room temperature and then sorted to attain a present grain size distribution. Photo credit: Jaime Liljegren.

Once dried, each bulk sample was weighed, poured into sieves with measurements ranging from 2.5in to <0.0025in, placed in the Ro-Tap sieve shaker for five minutes, and then each subsample within each size category was weighed to attain proportions (Figure 28).

Figure 28. All bulk samples were processed through various sized sieves using a Ro-Tap sieve shaker in the Central Washington University Hydrology Lab. Photo credit: Jaime Liljegren.

Bulk sediment samples were weighed on a Tree LW Measurements HRB-10001 analytical balance with a precision of 0.1g. Due to the eight-sieve capacity limit in the Ro-Tap, the sieves were separated into two stacks of relatively fine and coarse groupings and the entire process was performed twice.

The first research question addressed how small-scale suction dredge mining alters the morphology and substrate grain-size distribution of habitat units in natural aquatic environments of this size and composition. This question was addressed through visually comparing collected cross-shore profiles before and after dredging and quantifying the amount of sediment disturbed to determine the larger-scale changes to channel bed elevations. In addition, grain size distributions and Wolman pebble counts were compared before and immediately following dredging to identify any observed effects. Finally, bulk grain size distributions were compared before and after dredging to determine how sediment proportions changed.

The second research question addressed how small-scale suction dredge mining alters the water quality of habitat units in natural aquatic environments of this size and composition. All collected water quality and suspended sediment datasets from the dredged sites were analyzed against baseline conditions using the *Statistix* statistical software to determine any significant effects to the system.

Results were further isolated into spatial or temporal effects to the system from dredge mining using various statistical tests. In order to determine if a significant temporal difference occurred throughout each day for every parameter, raw datasets from pre-, during, or post-dredging timeframes for each transect were run using a non-parametric Kruskal-Wallis test for independent sample groups. The Kruskal-Wallis test was run at each transect comparing the three sample groups with raw measurements for each of the time frames. Kruskal-Wallis tests were run at each transect using all parameters for each individual survey day as well as a combined dataset over all days. This test was used to determine any association or relationship between parameter levels and the time since dredging.

Individual transects were then consolidated into spatial groups based on distance downstream and were compared temporally using the same timeframes used in the previous analysis including pre-, during, and post-dredging to assess the presence of significant differences between specific timeframes. The non-parametric Wilcoxon signed ranks test was used to run the averaged parameter measurements at all timeframes of before, during and after dredging per day as well as cumulative measurements over all three days. This test was an appropriate addition to the temporal assessment completed using Kruskal Wallis as it further isolates any significant differences between each two specific timeframes, rather than the entire survey day. Spatial groups were composed of a control group including the control transect, a near group consisting of transects Dredge 3 through F, and a far group consisting of transects E through A. All three times for each group were then compared against each other using multiple analyses of pre- vs. during, pre- vs. post, and during vs. post dredging to further determine significant differences between specific timeframes. This test can determine if collected parameter levels are significantly related to the amount of dredging activity present within the system.

The non-parametric Mann-Whitney U test for independent groups was utilized to determine significant spatial differences between measurements within designated site groups at each time segment. This assessment shows the amount and distance of impacts present from dredging to the system, if any. For this test, all individual transects were consolidated spatially in the same site groups consisting of a control group including the control transect, a near group composed of transects Dredge3 through F, and a far group consisting of transects E-A. In addition, each survey hour was similarly grouped into 'Pre-dredging', 'Dredging', and 'Post-dredging' groups. Within each test, two site groups were compared against one another using all raw parameter measurements collected at each temporal group using a Bonferroni correction to determine if there was a significant difference. The Bonferroni correction adjusts the alpha value to a stricter standard and is used to reduce the potential for type I error when multiple statistical tests are run on the same variable (Statistics Solutions, 2019). All spatial groups were compared against one another for each timeframe to identify differences throughout the experimental reach for each day. All spatial groups for each timeframe were compared against each other using multiple analyses of control vs. near, control vs. far, and near vs. far to determine differences between specific locations. By assessing significant differences between designated locations in the reach, the distance of affected area from dredging activity can be further isolated.

Finally, individual datasets collected at every hour were assessed spatially using the non-parametric Spearman Rank analysis to determine correlation between parameter levels measured at each survey site and the associated distance to dredging activity. In the analysis, each transect served as an independent variable and was run against all others using averaged parameter levels for a correlation assessment. Raw data collected at the 25%, 50%, and 75% channel width points per transect were averaged per hour and then all measurements were assessed statistically to determine if dredging activity was correlated with resulting parameter levels. A Spearman Rank analysis was run at every survey hour per day using averaged values from all three sample points along the channel width for each transect. This analysis assisted in linking any present changes to water quality conditions downstream with dredging activity.

CHAPTER 5

RESULTS

The following analyses of collected data focus on water quality, sediment grain size distributions, cross-shore elevation profiles, and observed morphological alterations of channel features. Statistical results are reported for each water quality factor analyzed including any significant spatial or temporal differences between transects for each survey day. Pertinent tables and graphs are included in-text for illustrative purposes while the remainder of graphics are found in the Appendix for further review.

Habitat Characterization

Control Reach

Within the control reach, there were a total of seven pools, two riffles, and one glide present within the longitudinal distance of approximately 610 m. The average pool length was 26.8 m with a range of 14.9-65.5 m, average width was 11.9 m with a range of 7.9-13.4 m, and average depth was 1.39 m with a range of 0.96-1.83 m (Table 1).

Table 1. Summary table of all identified habitat features in the control reach in the Entiat River, Washington. Habitat characterization was completed July 25th, 2018.

Feature	Type	Width (m)	Length (m)	Max Depth (m)	Temp (°C)	DO (%)	DO (mg/L)	SpCond (µS/cm)	pH	Turb (NTU)
1	Pool	12.8	65.5	1.53	15.5	105.1	10.48	39.3	7.6	0.2
2	Pool	7.9	23.5	0.96	16.4	102.1	10.01	39.3	7.5	0.2
3	Pool	11.6	25.9	1.05	17.3	105	10.70	39.3	7.5	0.1
4	Pool	12.5	14.9	1.39	17.8	107.7	10.10	39.2	7.6	0.2
5	Pool	10.7	15.8	1.46	18.1	106.6	10.50	39.3	7.6	0.1
6	Pool	13.4	23.2	1.53	18.4	105.1	9.71	39.4	7.7	0.3
7	Pool	13.4	19.5	1.83	18.3	103.3	9.69	39.4	7.6	0.1
8	Riffle	10.7	37.8	0.30	17.4	109.4	10.48	39.2	7.5	0.3
9	Riffle	8.8	22.6	0.24	18.7	104.4	9.73	39.2	7.6	0.1
10	Glide	15.5	41.1	0.89	16.4	108.2	10.54	39.1	7.5	0.3

The average riffle length was 30.2 m with a range of 22.5-37.8 m, average width was 9.8 m with a range of 8.8-19.7 m, and average depth was 0.27 m with a range of 0.24-0.30m (Table 1). Only one glide was present with a length of 23.5m, a width of 15.5m, and a depth of 0.89m (Table 1).

Pool temperatures ranged from 15.5-18.4°C with a median of 17.8°C. Dissolved oxygen percent levels ranged between 102.1-107.7% saturation with a median of 105.1%. When assessed in mg/L, dissolved oxygen ranged from 9.69-10.7mg/L with a median of 10.1mg/L. Specific conductance ranged from 39.4-39.2µS/cm with a median of 39.3µS/cm. Readings of pH had a small range between 7.5-7.7 and a median of 7.6. Turbidity was low in the pools with a range of 0.1-0.3NTU, and a median of 0.2NTU. Velocity measurements collected between all features ranged from 0.31-1.31m/s in the control reach.

Between the two measured riffles temperatures ranged from 17.4-18.7°C with a median of 18.1°C. Dissolved oxygen percent saturation varied from 104.4-109.4%, and a median value of 106.9%. Dissolved oxygen ranged from 9.73mg-10.48mg/L with a median of 10.1mg/L, while both specific conductance readings measured at 39.2µS/cm. The riffles experienced an even smaller range in pH from 7.5-7.6, and a median at 7.55. Like the pools, riffle turbidity ranged from 0.1-0.3NTU, with a median of 0.2NTU.

Only one glide was present in the control reach with one temperature reading measured at 16.4°C. Dissolved oxygen registered at 108.2% and 10.54mg/L. Specific conductance was 39.1µS/cm, turbidity was low with a reading of 0.3NTU while pH showed a similar reading to the pools and riffles with a measurement of 7.5.

Experimental Reach

Within the experimental reach there were three pools, one riffle and four glides present within the 20x bankfull width longitudinal distance of approximately 609.6 m. The average pool length was 35.4 m with a range of 25.6-46.9 m, average width was 11.3 m with a range of 10.1-11.9 m, and average depth was 1.22 m with a range of 1.05-1.40 m (Table 2).

Table 2. Summary table of all identified habitat features in the experimental reach in the Entiat River, Washington. Habitat characterization was completed July 26th, 2018.

Feature	Type	Width (m)	Length (m)	Max Depth (m)	Temp (°C)	DO (%)	DO (mg/L)	SpCond (µS/cm)	pH	Turb (NTU)
1	Pool	11.9	33.5	1.40	14.2	88.2	9.03	39.4	7.4	0.4
2	Pool	11.6	25.6	1.05	14.1	87.3	9.00	39.4	7.3	0.2
3	Pool	10.1	46.9	1.21	16.4	103.5	10.13	39.1	7.2	0.3
4	Riffle	16,8	82.0	0.24	14.5	89.1	9.09	39.3	7.4	0.3
5	Glide	14.9	93.0	0.35	14.1	87.5	8.98	39.4	7.4	0.1
6	Glide	26.8	96.0	0.53	14.7	89.3	9.04	39.3	7.4	0.4
7	Glide	16.8	106.1	0.71	15.3	89.8	8.98	39.2	7.4	0.3
8	Glide	21.3	182.9	0.64	15.6	102.5	10.18	39.2	7.2	0.4

Only one riffle was present with a length of 82.0 cm, a width of 16.8 cm, and a depth of 0.24 cm (Table 2). The average glide length was 119.5 cm with a range of 93.0-182.9 cm, average width was 20.1 cm with a range of 14.9-26.8 cm, and average depth was 0.56 cm with a range of 0.35-0.71 cm.

Pool temperatures experienced a range of 2.3 °C in temperatures from 14.1-16.4 °C with a median value of 14.2 °C. Dissolved oxygen (%) levels in pools ranged from 87.3-103.5 % with a median value of 88.2 %. Minimum dissolved oxygen levels (in mg/L) in pools ranged from 9.0-10.13 mg/L, with a median value of 9.03 mg/L. Specific conductance ranged between 39.1-39.4 µS/cm with a median of 39.4 µS/cm. Turbidity was low ranging from 0.20-0.4 NTU and a median of 0.3 NTU. pH was relatively stable among pools ranging from 7.2-7.4 and a median of 7.3.

Only one riffle was present with a temperature value of 14.5 °C. Dissolved oxygen was present at 89.1 % and 9.09 mg/L. Specific conductance measured at 39.3 µS/cm, turbidity was low registering 0.3 NTU, while pH was measured at 7.4.

Glide temperatures had a wider range of 1.4 °C with 14.1 °C in the coolest glide to 15.5 °C in the warmest with a median value of 15.0 °C. The median value for dissolved oxygen percent levels was highest in the glide features at 89.6 % with a wide range in values from 87.5-102.5 %. When measured in mg/L, the dissolved oxygen values ranged from 8.98-9.90 mg/L, and the median was 9.01 mg/L. Specific conductance ranged from 39.2-39.4 µS/cm with a median of 39.25 µS/cm. Turbidity was low ranging from 0.1-0.4 NTU and a median of 0.35 NTU. Readings of pH within the glides were relatively stable ranging from 7.2 to 7.4 with a median of 7.4. Flow measurements in the experimental reach ranged from 0.3 m/s to 1.29 m/s. Typical flow velocities over lamprey nests have been found to range between 0.5-1.0 m/s (Kan, 1975; Pletcher, 1963).

Control and Experimental Grainsize Distributions

Grainsize data from all pool samples (n=7 for control; n=3 for experimental) were averaged for each of the two reaches surveyed, showing a greater amount of coarse material in the control with 5 % cobbles, 49 % pebbles, 11 % granules, and 36 % fines while the experimental reach had a higher amount of finer material with no cobble material present, 5 % pebbles, 22 % granules, and 72 % fine material (Figure 29).

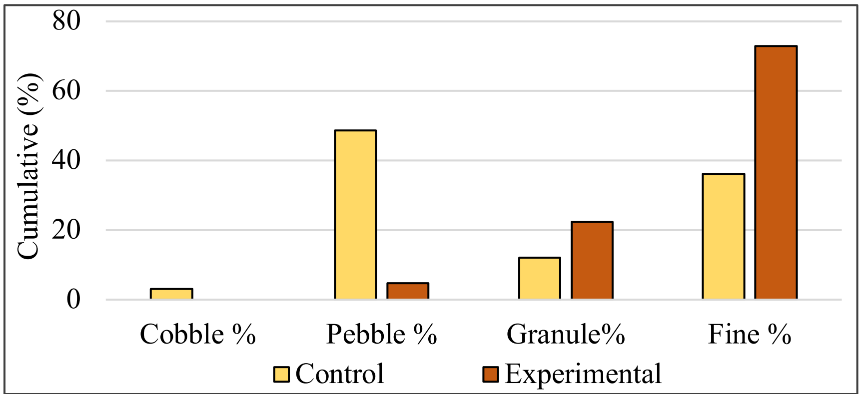


Figure 29. Averaged sediment distributions within the control and experimental reaches in the Entiat River, Washington. Surveys were completed over July 25th and 26th, 2018.

Wolman Pebble Counts

Control Reach

Wolman pebble counts showed coarser material present in the glide feature when compared to substrate collected at both riffles in the same stretch (Figure 29). Boulders were present at a low amount in the glide at 5 %, while neither riffle had any boulder material in associated pebble counts. In contrast, no granule or fine material was present in the measured glide while both were present in the first measured riffle, although at low amounts of granules (3 %) and fines (3 %) (Figure 30). The majority of distributions were between cobble and pebble amounts for all features.

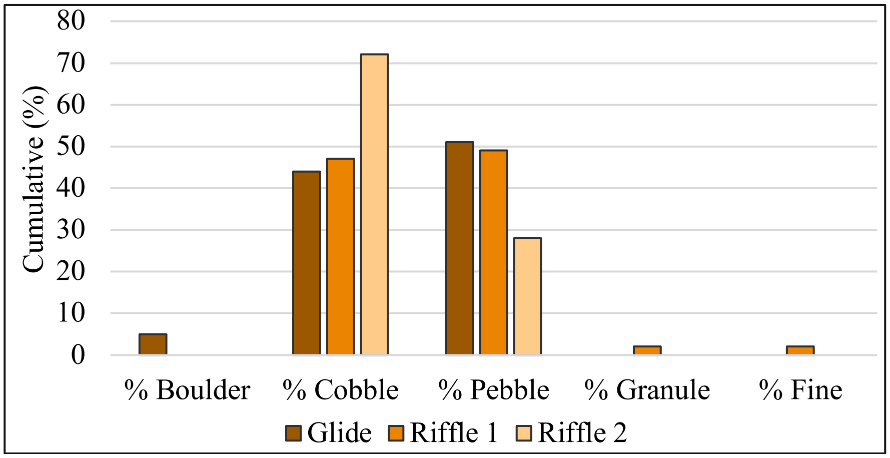


Figure 30. Grainsize distributions of three Wolman pebble count datasets collected at one glide and two riffles identified within the control reach in the Entiat River, Washington. Surveys were completed on July 25th, 2018 before the dredging experiment.

Experimental Reach

The distributions collected between the present glide and riffle in the experimental stretch showed slightly higher amounts of cobble material in the measured glide of 42 % compared to 35 % in the riffle, although distributions were similar (Figure 31).

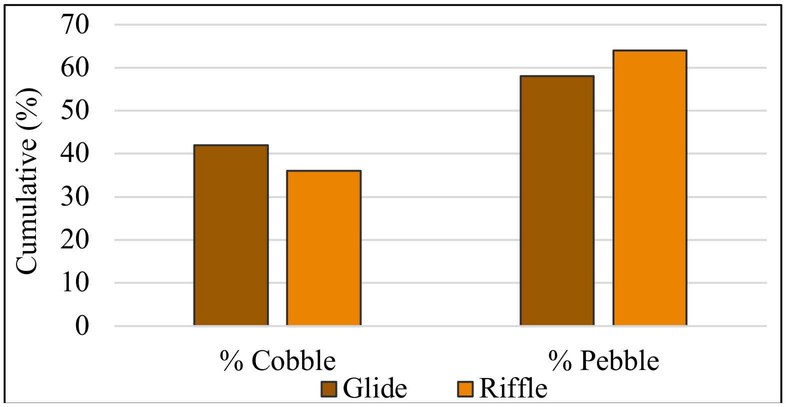


Figure 31. Grainsize distributions of two Wolman pebble count datasets collected at one glide and one riffle identified within the experimental reach in the Entiat River, Washington. Surveys were completed on July 26th, 2018.

In contrast, higher amounts of pebble material were present in the riffle at 64% compared to 58% present in the glide. Both had moderately-sized material present while boulders, granules, and fine material were absent from the pebble count.

Water Quality

Control Transect

Between all survey days pre-dredging median values for the control transect ranged from 14.7 °C to 15.8 °C, 16.3 °C to 17.9 °C during dredging and 17.7 °C to 19.4 °C post-dredging (Appendix A). There was a significant increase in temperatures throughout the day at the control transect between timeframes (Kruskal-Wallis, $p < 0.05$). Dissolved oxygen was significantly reduced throughout each day at the control transect with median values ranging from 9.72-10.06 mg/L pre-dredging, 8.91-9.36 mg/L during dredging, and 8.51-8.89mg/L post-dredging (Kruskal-Wallis, $p < 0.05$) (Appendix B). When measured using percent concentration, dissolved oxygen did not show a significant change when all days were combined with medians ranging from 96.0 % to 100.7 % pre-dredging, 96.5 % to 99.4 % during dredging, and 91.7 % to 102.2 % post-dredging (Kruskal-Wallis, $p > 0.05$) (Appendix C). Alterations to specific conductance were insignificant with medians ranging from 38.9 µS/cm to 40.7µS/cm pre-dredging, 40.2 µS/cm to 40.6µS/cm during dredging, and 39.8 µS/cm to 40.7 µS/cm post-dredging (Kruskal-Wallis, $p > 0.05$) (Appendix E). Turbidity readings varied significantly between timeframes with medians ranging from 0.1 to 0.4 NTU pre-dredging, 0.1 NTU to 0.2 NTU during dredging, and 0.15 NTU to 0.46 NTU post-dredging (Kruskal-Wallis, $p < 0.05$) (Appendix G). In contrast, pH was insignificant and medians ranged from 7.3 to 7.5 pre-dredging, 7.4 to 7.7 during dredging, and 7.3-7.4 post-dredging (Kruskal-Wallis, $p > 0.05$).

Temperature

Pre- to Post-Dredging Temporal Comparisons. Temperatures ranged by 5.3°C throughout the day from 14.4 °C to 19.7 °C with a median of 18.1 °C on Day 1, 14.8 °C to 19.8 °C for a range of 5.0 °C with a median of 16.5 °C on Day 2, and 15.6 °C to 17.9 °C for a range of 2.3 °C throughout the day with a median of 16.3 °C on Day 3. In all three survey days temperature was found to be significantly higher as each day progressed with the highest readings after dredging, followed by readings during dredging, and the lowest temperatures before dredging began (Figure 32) (Kruskal-Wallis, $p < 0.05$). Trends were the same for every day at each surveyed transect as well as when all three days were combined (Figure 32). Downstream transects including Dredge 3 through A had median temperature values ranging from 14.5 °C to 15.8 °C before dredging, 16.2 °C to 17.9 °C during dredging, and 17.6 °C to 19.6 °C after dredging (Appendix A). All surveyed transects experienced a significant difference between timeframes, including the control transect. Temperature values for all transects followed the same increasing trend between all three timeframes throughout each day.

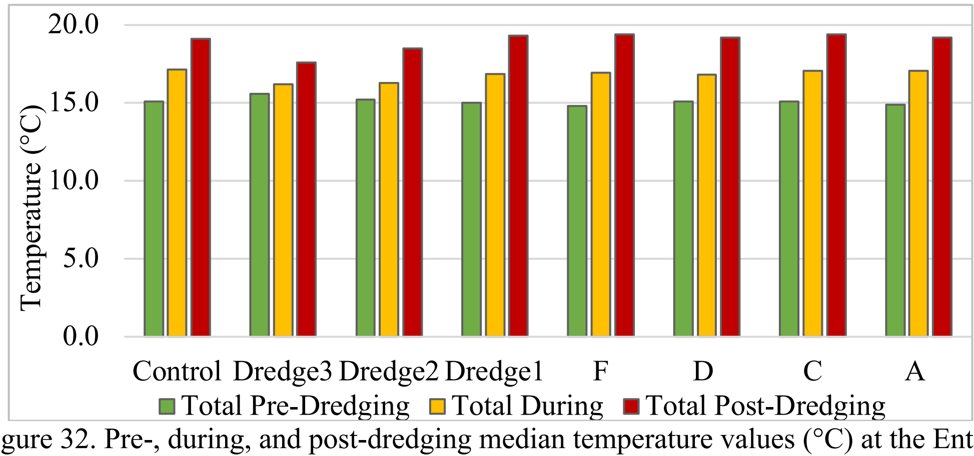


Figure 32. Pre-, during, and post-dredging median temperature values (°C) at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

No significant differences were identified for temperature between each survey timeframe per individual day for the control or far groups when pre-dredging values were compared with values during dredging (Wilcoxon signed ranks, $p > 0.05$). Temperature was slightly higher for the near group on Day 3 during dredging with a median of 16.3 °C compared to the pre-dredge median of 15.6 °C (Wilcoxon signed ranks, $p < 0.05$). When all three survey days were combined, temperature for both the near and far groups were found to be significantly higher during dredging (Table 3).

Table 3. Temperature levels (°C) [median (IQR)] pre-, during, and post-dredging along with associated determinations of significance for the near and far spatial groups (Wilcoxon signed ranks, $p < 0.05$). Data was collected at the Entiat River, Washington between July 30th -August 1st, 2018.

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Near	Day 3	15.6 (0.1)	16.3 (0.1)	17.7 (0.2)	SD	SD	SD
	Combined Days	15 (0.9)	16.9 (0.6)	18.6 (1.7)	SD	SD	SD
Far	Combined Days	15.1 (1.0)	16.9 (1.5)	19.2 (1.6)	SD	SD	SD

*'SD'=Significant difference; 'NSD'= No significant difference

Within the near group, the pre-dredging median value was 15.0 °C, lower than the 16.9 °C median during dredging activity (Table 3). Similarly, the far group had a lower median value of 15.1 °C before dredging when compared to the median value during dredging of 16.9 °C (Table 3).

When pre- and post-dredging values were compared at all groups for each individual day, temperature medians in the near group on Day 3 were higher post-dredging than pre-dredging (Wilcoxon signed ranks, $p < 0.05$). When all three survey days were combined, post-dredging temperatures were observed to be significantly higher at both the near and far groups. The median for the near region was 15.0 °C before dredging while temperatures were slightly higher after dredging at 18.6 °C and had a larger range in measured values of 1.73 °C (Table 3). Temperatures followed the same increasing trend before and after dredging at the far group with the pre-dredging median at 15.1 °C and the post-dredge median at 19.2 °C (Table 3). Temperatures were higher post-dredging than during the activity, showing a continued increase throughout the day.

A significant increase in median values during and after dredging was identified within the near group on the final survey day with 16.3 °C during and 17.7 °C after (Wilcoxon signed ranks, $p < 0.05$). When looking at all three days combined, temperatures were significantly higher after dredging than during dredging for both the near and far groups. Median values continued to show an increasing trend throughout each day for both groups with a slightly higher temperature of 18.6 °C following dredging compared to 16.9 °C during dredging for the near group and 19.2 °C after dredging compared to 16.9 °C during dredging for the far group (Table 3).

Spatial Comparisons. No significant difference was identified between the control and near regions before, during, or after dredging (Table 4) (Mann-Whitney U, $p > 0.017$). In addition, no significant differences were identified when all survey days were combined.

Table 4. Temperature levels (°C) [median (IQR)] between the control, near, and far spatial transect groups along with associated determinations of significance between each spatial group (Mann-Whitney U, $p < 0.017$). Data was collected at the Entiat River, Washington.

Survey Time	Control (C)	Near (N)	Far (F)	C vs. N	C vs. F	N vs. F
Day 3 Pre-Dredging	15.8 (0.1)	15.6 (0.2)	15.8 (0.0)	NSD	NSD	SD
Day 3 Post-dredging	17.7 (0.1)	17.7 (0.2)	19.2 (0.1)	NSD	SD	SD

*'SD'=Significant difference; 'NSD'= No significant difference

Day 3 experienced a slightly larger increase in temperature with distance as the median was 17.7 °C at the control and 19.2 °C at the far region (Table 4) (Mann-Whitney U, $p < 0.017$). All ranges for each group were small indicating minor amounts of spread between measured values in each dataset. No significant spatial differences in temperature readings were identified before or during dredging activity as well as when all survey days were combined (Mann-Whitney U, $p > 0.017$).

Median temperatures before dredging were slightly higher in the far region than the near with 15.6 °C in the near and 15.8 °C for the far on Day 3 (Table 4). Post-dredging medians had slight differences in values between the near and far groups with Day 3 measured a lower value of 17.7 °C in the near group when compared to the far group of 19.2 °C (Table 4). No significant differences were identified during dredging activity as well as when all survey days were combined and compared.

Correlation with Distance to Dredging. Overall, downstream temperatures did not have a strong correlation with distance to dredging activity. Of the significant correlations, values showed mixed results before and during dredging. Temperature showed a strong inverse correlation with distance during dredging on Day 2 with a correlation value of -0.70 (Spearman rank, $p < 0.05$). In contrast, temperature was directly correlated during dredging on Day 1 with a strong correlation value of 0.83, along with a strong pre-dredging correlation value of 0.87 on Day 3. The remaining tests showed no strong positive or negative correlation with distance downstream from dredging activity. Although multiple correlation values were identified within the three survey days as both direct and inverse relationships to dredging, no clear pattern of association was identified.

Dissolved Oxygen (mg/L)

Pre- to Post-Dredging Temporal Comparisons. The Dredge 3 transect immediately downstream of the dredging activity on Day 3 showed significant differences in dissolved oxygen; however, no clear trend was distinguished between all timeframes with median values of 9.78 mg/L before dredging, 9.83 mg/L during dredging, and 9.7 mg/L after dredging was complete (Kruskal-Wallis, $p < 0.05$) (Appendix B). Dredge 2 was surveyed only on Days 2 and 3 and experienced a significant decrease between all sample times for both days with median ranges of 9.77-9.8 mg/L before dredging, 9.62-9.74 mg/L during dredging, and 9.3-9.67 mg/L following dredging (Appendix B). Dredge 1, D, and F downstream transects were surveyed all three days and experienced a significant decrease in timeframes for Days 1 and 2 with medians of 9.83-10.03 mg/L pre-dredging, 8.87-9.62 mg/L during dredging, and 8.43-9.08 mg/L post-dredging (Appendix B). Transects C and A were located furthest downstream and registered significant reductions for Day 2 only with medians of 9.97-10.01 mg/L pre-dredging, 9.44-9.56 mg/L during dredging, and 8.74-8.91 mg/L post-dredging (Appendix

B). Although control transect readings were insignificant for Day 3, slight reductions in dissolved oxygen were measured in the dredged region as far downstream as Dredge 2 with medians between 9.78-9.8 mg/L pre-dredging, 9.74-9.83 mg/L during dredging, and 9.67-9.7 mg/L post dredging. All significantly different measurements followed a similar decreasing trend in dissolved oxygen levels throughout the day. When all days were combined, every surveyed transect had a significant reduction between all three timeframes (Figure 33). Although many downstream transects had differences between timeframes, measurements showed trends similar to the control transect.

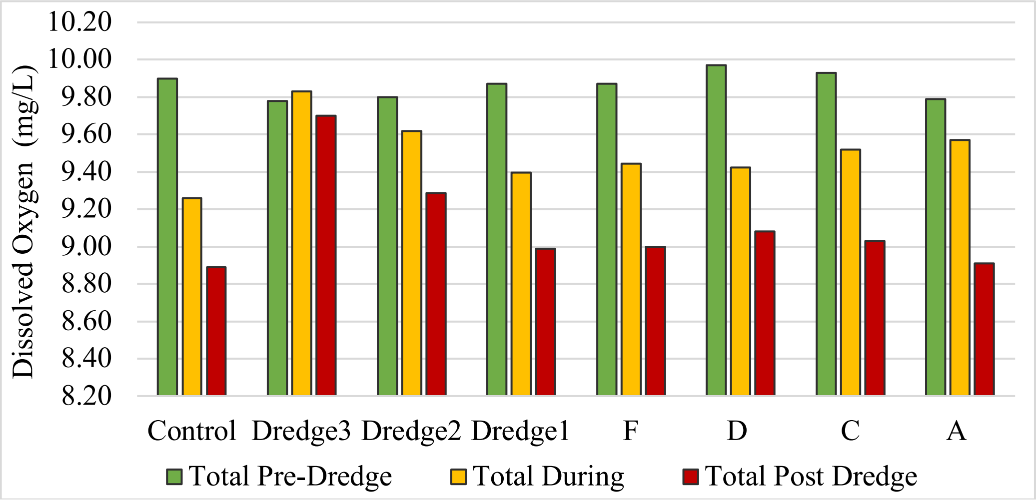


Figure 33. Pre-, during, and post-dredging median dissolved oxygen values (mg/L) at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

When pre-dredging and during dredging values for each group were compared, no significant differences between measurements were observed for any individual day (Wilcoxon signed ranks, $p > 0.05$). When survey days were combined, reductions of dissolved oxygen levels were observed for both the near and far groups (Wilcoxon signed ranks, $p < 0.05$). Median values were slightly lower and experienced a wider range during dredging when compared to pre-dredging levels. Both groups had similar pre-dredge median values of 9.85 mg/L in the near group and 9.86 mg/L in the far group (Table 5). During dredging, the far region had a slightly lower median of 9.47 mg/L compared to the near median of 9.66 mg/L (Table 5).

Table 5. Dissolved oxygen levels (mg/L) [median (IQR)] before, during, and after dredging activity along with associated determinations of significance between each timeframe pair (Wilcoxon signed ranks analysis, p-value < 0.05).

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Near	Day 3	--	9.74 (0.12)	9.64 (0.09)	NSD	SD	SD
	Combined Days	9.85 (0.22)	9.66 (0.28)	9.01 (0.71)	SD	SD	SD
Far	Combined Days	9.86 (0.12)	9.47 (0.69)	8.90 (0.55)	SD	SD	SD

*'SD'=Significant difference; 'NSD'= No SD

A slightly lower median value was observed in the near group on Day 3 when pre- and post-dredging values were compared (Wilcoxon signed ranks, $p < 0.05$). When survey days were combined, reduced dissolved oxygen levels were observed after dredging for both the near and far groups, while the control was insignificant. Values for dissolved oxygen after dredging were lower than before dredging began in both groups with the near median of 9.85 mg/L and the far median of 9.86 mg/L before dredging compared to 9.01 mg/L in the near and 8.90 mg/L in the far group after dredging (Table 5). Post-dredging measurements experienced a larger variance when compared to ranges observed before dredging began.

When values were assessed between during and post-dredging, one difference occurred in the near group on Day 3 that showed a slight decrease in median values from 9.74 mg/L during dredging to 9.64 mg/L after dredging; however, no other significant differences were observed throughout the individual days (Wilcoxon Signed Ranks, $p < 0.05$). When days were combined, similar decreases in median values were observed for both the near and far groups after dredging, while the control was insignificant. The near group had a lower median value of 9.64 mg/L after dredging when compared to the 9.74 mg/L median during dredging (Table 5). Similarly, the far group had a value of 8.90 mg/L after dredging while the median during dredging was 9.47 mg/L (Table 5). When temporally compared, both the near and far groups experienced differences in all analyses with decreasing dissolved oxygen levels throughout the day at both groups. Readings after dredging were observed to be lower than during the activity. All median values for both groups show a decreasing trend throughout survey timeframes for all days with the lowest values occurring during the post dredging measurements.

Spatial Comparisons. No significant differences were observed between the control and near groups on any individual day as well as when combined (Mann-Whitney U) ($p > 0.017$) (Table 6).

Table 6. Dissolved oxygen (mg/L) [median (IQR)] between the control, near, and far spatial transect groups along with associated determinations of significance between each spatial group (Mann-Whitney U, $p < 0.017$). Data was collected at the Entiat River, Washington between July 30th-August 1st, 2018.

Survey Time	Control (C)	Near (N)	Far (F)	C vs. N	C vs. F	N vs. F
Day 3 Post dredging	--	9.61 (0.12)	9.47 (0.30)	NSD	NSD	SD
Combined post dredging	--	9.04 (0.69)	8.96 (0.70)	NSD	NSD	SD

*'SD'=Significant difference; 'NSD'= No SD

When control and far groups were compared, no significant differences in dissolved oxygen were identified throughout each individual survey day as well as when all days were combined and compared (Mann-Whitney U, $p > 0.017$) (Table 6). After dredging was complete on Day 3, medians showed a similar higher value in the near group at 9.61 mg/L than in the far group at 9.47 mg/L (Table 6) (Mann-Whitney U, $p < 0.017$). When all days were combined, post-dredging values showed a similar trend of decreased dissolved oxygen in the far group of 8.96 mg/L when compared to the near group of 9.04 mg/L (Table 6). Although differences were present between the near and far groups, median values were higher in the near group where the dredging was taking place.

Correlation with Distance to Dredging. Overall, there was no significant correlation between dissolved oxygen levels in mg/L and distance downstream from dredging. Of the collected dissolved oxygen measurements, only one significant correlation value was identified at 2PM on Day 1 with a value of -0.86 (Spearman rank, $p < 0.05$). This negative correlation value shows an inverse relationship as distance increased from dredging activity, dissolved oxygen decreased.

Dissolved Oxygen (%)

Pre- to Post-Dredging Temporal Comparisons. Significant differences throughout all timeframes in each day occurred less frequently in percent saturation dissolved oxygen levels than levels in units of mg/L. The control transect showed a significant decrease in median values only on Day 2 throughout the survey day (Kruskal-Wallis, $p < 0.05$). On Day 2 the control had a pre-dredge median of 100.7 %, a median during dredging of 97.8 %, and a post-dredge median of 97 % (Appendix C). Significant increases in dissolved oxygen levels were present at both Dredge 2 and Dredge 3 transects for Day 3. Before dredging the Dredge 2 and Dredge 3 transects had medians of 98.4 % and 98.2 %, 100.2 % and 99.4 % during dredging, and 101.7 % and 101.2 % after dredging, showing a contrasting increase throughout the day compared to dissolved oxygen levels in mg/L (Appendix C). The largest amount of significant difference occurred at the furthest transect away from dredging with a slight decrease post-dredging. Slight reductions in transect A occurred on Days 2 and 3, as well as when all days were combined with median ranges of 98.3-99.6 % before dredging, 98.2-100.6 % during dredging, and 95.8-96.6 % post dredging (Appendix C). When survey days were combined, transect A was the only transect to show a significant reduction throughout the day (Figure 34). Overall variations in percent saturation dissolved oxygen levels were minor throughout the survey days and did not follow a clear trend throughout transects.

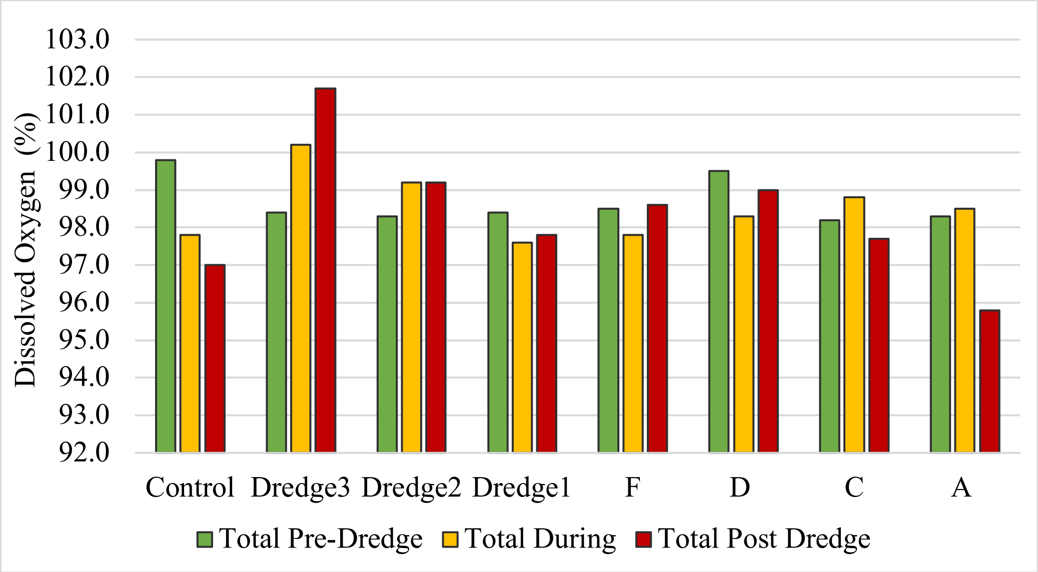


Figure 34. Pre-, during, and post-dredging median dissolved oxygen values (%) at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

No significant differences were identified within any individual days or combined days for dissolved oxygen (%) when pre-dredging and during dredging levels were compared (Wilcoxon signed ranks, $p > 0.05$) (Table 7).

Table 7. Dissolved oxygen levels (%) [median (IQR)] before, during, and after dredging activity along with associated determinations of significance between each timeframe pair (Wilcoxon signed ranks analysis, p-value < 0.05).

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Far	Combined Days	99.1 (2.4)	97.9 (3.7)	96.8 (4.5)	NSD	SD	SD

*'SD'=Significant difference; 'NSD'= No SD

When pre- and post-dredging measurements were compared, no significant differences in dissolved oxygen percent saturation levels were identified in any of the three individual survey days (Wilcoxon signed ranks, $p > 0.05$) (Table 7). Only one significant reduction in dissolved oxygen was identified when all days were combined at the far group showing a decreased median value of 96.8 % after dredging when compared to the pre-dredge median of 99.1 % (Wilcoxon signed ranks, $p < 0.05$) (Table 7). In addition, when all values during and post-dredging were compared, no significant differences were identified in any of the three individual survey days (Wilcoxon signed ranks, $p > 0.05$) (Table 7). When all days were combined the far group had a slightly higher dissolved oxygen level of 97.9 % during dredging compared to the 96.8 % median value after dredging (Wilcoxon signed ranks, $p < 0.05$) (Table 7).

Spatial Comparisons. When all spatial regions were compared, no significant differences in percent dissolved oxygen levels were identified between the control and near, the control and far, or the near and far for any individual survey day or when all three days were combined (Mann-Whitney U, $p > 0.017$). Overall, ranges of values were small between groups and did not show specific impacts to dissolved oxygen following dredging.

Correlation with Distance to Dredging. When measurements were assessed for correlation with dredging only a few significant values were identified (Spearman rank, $p < 0.05$). Of the significant correlations, all were inversely related showing a decrease in dissolved oxygen with increasing distance. Negative correlations were present during dredging at 2pm on Day 1 with a strong value of -0.79 and immediately following the completion of dredging activity at 1pm on day 3 with a value of -0.61. Both show a significant inverse correlation of decreasing dissolved oxygen levels with increased distance from dredging activity. Although these two readings were identified, the majority of readings showed no significant relationship between distance from dredging activity and differences in present dissolved oxygen levels.

Specific Conductance

Pre- to Post-Dredging Temporal Comparisons. The control transect showed slight variances in specific conductance throughout all three timeframes for Days 1 and 2; however, Day 3 was insignificant. (Kruskal-Wallis, $p < 0.05$) (Appendix E). Median ranges for the control transect on Days 1 and 2 were 38.9-40.5 μS/cm before dredging, 40.2-40.5 μS/cm during dredging, and 39.8-40.7 μS/cm after dredging (Figure 35) (Appendix E).

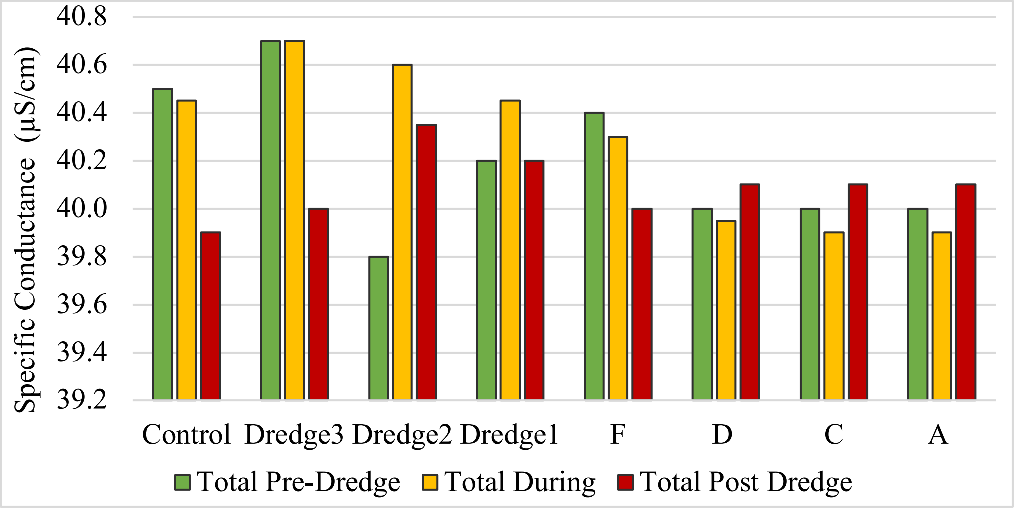


Figure 35. Pre-, during, and post-dredging median specific conductance values (µS/cm) at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

Dredge 3 and Dredge 2 transects showed slight differences throughout Day 3 with median ranges of 38.9-40.7 µS/cm pre-dredging, 40.6-40.7 µS/cm during dredging, and 40.0-40.7 µS/cm post-dredging (Appendix E). Downstream transects did not show any further differences for Day 3 (Kruskal-Wallis, $p > 0.05$). Day 2 medians for Dredge 2 and the downstream transects showed slight increases in values with medians ranging from 38.9-40.0µS/cm before dredging, 39.6-40.6 µS/cm during dredging, and 40.1-40.7 µS/cm after dredging (Kruskal-Wallis, $p < 0.05$) (See Appendix E).

When all spatial groups were assessed for differences in specific conductance levels pre- and during dredging, no significant differences occurred throughout any individual day or when all three survey days were combined (Table 11) (Wilcoxon signed ranks, $p > 0.05$).

Table 8. Specific conductance (μS/cm) [median (IQR)] before, during, and after dredging activity along with associated determinations of significance between each timeframe pair (Wilcoxon signed ranks analysis, p-value < 0.05).

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Near	Day 3	NSD	40.7 (0.1)	40.0 (0.0)	NSD	NSD	SD
	Combined Days	NSD	NSD	NSD	NSD	NSD	NSD
Far	Combined Days	NSD	NSD	NSD	NSD	NSD	NSD

*'SD'=Significant difference; 'NSD'= No SD

In addition, no significant differences in specific conductance measurements pre- and post-dredging occurred throughout any individual day or when all three survey days were combined (Table 11) (Wilcoxon signed ranks, $p > 0.05$). When during and post-dredging values were assessed, the near group showed a slightly higher median value of 40.7 μS/cm during dredging compared to 40.0 μS/cm after dredging on Day 3 (Table 11) (Wilcoxon signed ranks, $p < 0.05$). No significant differences occurred at any other individual survey day or when all days were combined.

Spatial Comparisons. No significant differences occurred between the control and near groups for any survey day or when all days were combined (Mann-Whitney U, $p > 0.017$) (Table 12).

Table 9. Specific conductance levels (µS/cm) [median (IQR)] between the control, near, and far spatial transect groups along with associated determinations of significance between each spatial group (Mann-Whitney U, $p < 0.017$). Data were collected at the Entiat River, Washington between July 30th -August 1st, 2018.

Survey Time	Control (C)	Near (N)	Far (F)	C vs. N	C vs. F	N vs. F
Day 1 Pre-dredging	40.5 (0.3)	40.4 (0.8)	38.7 (0.1)	NSD	SD	NSD
Day 1 During dredging	40.2 (2.1)	--	39.5 (1.1)	NSD	SD	SD
Day 1 Post-dredging	NSD	40.2 (0.8)	38.8 (1.1)	NSD	NSD	NSD
Day 2 Pre-dredging	38.9 (0.2)	38.8 (0.2)	40 (0.1)	NSD	SD	NSD
Day 2 During dredging	NSD	33.8 (2.1)	33.4 (1.6)	NSD	NSD	NSD
Day 2 Post-dredging	40.7 (0.1)	40.6 (0.1)	40.1 (0.1)	NSD	SD	SD
Day 3 Pre-dredging	40.7 (0.2)	40.7 (0.1)	40.1 (0.1)	NSD	SD	SD
Day 3 During dredging	40.6 (0.3)	40.6 (0.1)	40.1 (0)	NSD	SD	SD
Day 3 Post-dredging	39.9 (0.3)	40 (0.0)	40.5 (0.1)	NSD	SD	SD
Combined days during dredging	40.5 (0.6)	40.5 (0.3)	39.9 (0.3)	NSD	SD	SD

*'SD'=Significant difference; 'NSD'= No SD

When the control and far groups were compared, the control experienced a slightly higher median than the far region before dredging at Days 1 and 2 (Mann-Whitney U, $p < 0.05$) (Table 10). Pre-dredging median values for the control ranged from 38.9-40.7 µS/cm while the far region medians ranged from 38.7-40.1 µS/cm (Table 12). In addition, higher readings at the control occurred on Days 1 and 3 during dredging as well as on Days 2 and 3 after dredging was complete. Control median values ranged from 40.2-40.6 µS/cm during dredging on Days 1 and 3, and 39.9-40.7 µS/cm post-dredging on Days 2 and 3 (Table 12). In comparison, far group medians ranged from 33.4-40.0 µS/cm during dredging on Days 1 and 3 as well as 38.8-40.5 µS/cm after dredging was complete on Days 2 and 3 (Table 12). When all three days were combined, slightly higher readings occurred at the control when compared to the far during dredging with median values of 40.5 µS/cm at the control and 39.9 µS/cm and the far group (Table 12).

When the near and far groups were assessed, medians in the near group were slightly higher than the far for Day 3. Pre-dredge medians were 40.7 µS/cm for the near group and 40.1 µS/cm for the far group (Table 12). Higher median values also occurred in the near group during dredging on Day 3 with the near group median of 40.6 µS/cm during dredging and far group median 40.1µS/cm (Table 12). When survey days were combined, near readings were slightly higher during dredging with the near median at 40.5µS/cm and the far median at 39.9 µS/cm (Table 12).

Correlation with Distance to Dredging. When correlation was assessed for specific conductance levels, multiple correlations were present throughout the survey days (Spearman rank, $p < 0.05$). Day 1 showed an inverse correlation during dredging with a strong value of -0.76 at 1pm, while Day 2 also showed an inverse correlation post-dredging with a strong value of -0.71 (Appendix F). Day 3 experienced significant correlations throughout the survey day with strong correlation values of -0.86 before dredging, -0.72 during dredging, and 0.59 after dredging (Appendix F). Significant values were not consistent throughout all hours during dredging.

Turbidity

Pre- to Post-Dredging Temporal Comparisons. Turbidity showed few significant differences at two survey transects when measurements were assessed throughout each survey day. The control transect experienced a slight increase in turbidity on Days 1 and 2 (Kruskal-Wallis, $p < 0.05$). Median control values before dredging ranged from 0.10-0.20, 0.10-0.30 NTU during dredging, and 0.15-0.28 NTU after dredging (Figure 36) (Appendix G).

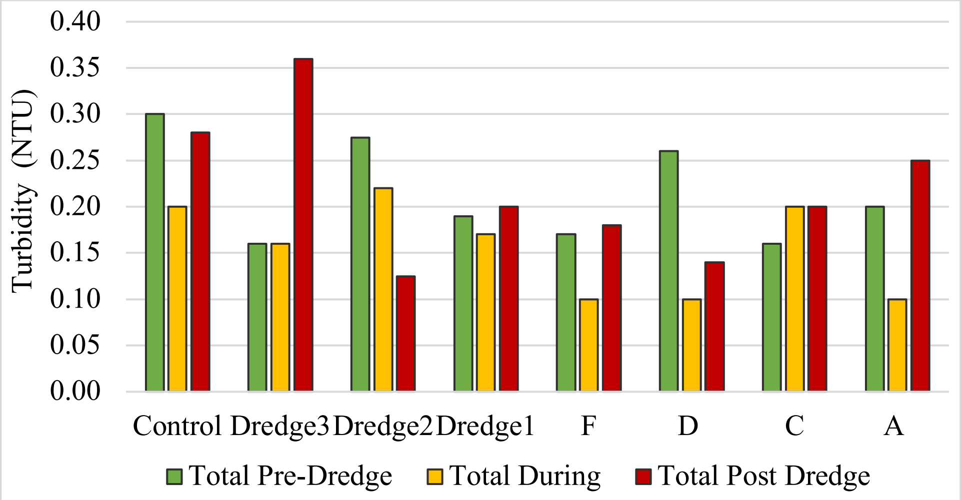


Figure 36. Pre-, during, and post-dredging median turbidity values (NTU) at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

Transect D showed a slight decrease on Days 1 and 2 (Appendix G). Median values for transect D ranged from 0.10-0.30 NTU pre-dredging, 0-0.30 NTU during dredging, and 0-0.24 NTU post-dredging (Appendix G). No other significant differences were identified downstream.

When groups were compared before and during dredging, a higher median was identified in the far group with a value before dredging at 0.24 NTU and a lower median during dredging at 0.18 NTU (Table 13) (Wilcoxon signed ranks, $p < 0.05$). No other differences in turbidity values were significant before and during dredging (Wilcoxon Signed Ranks, $p > 0.05$).

Table 10. Turbidity levels (NTUs) [median (IQR)] before, during, and after dredging activity along with associated determinations of significance between each timeframe pair (Wilcoxon signed ranks analysis, p-value < 0.05).

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Far	Combined Days	0.24 (0.15)	0.18 (0.20)	--	SD	NSD	NSD

*'SD'=Significant difference; 'NSD'= No SD

When all turbidity values for each group were assessed before and after dredging, no significant differences occurred (Wilcoxon signed ranks, $p > 0.05$) (Table 13). Finally, when all turbidity measurements in spatial groups were assessed during and after dredging, no significant differences occurred (Table 13).

Spatial Comparisons. When spatial regions were compared at each time period, no significant difference was observed between the control and near, the control and far, and the near and far groups (Mann-Whitney U, $p > 0.017$).

Correlation with Distance to Dredging. One inverse correlation was identified during dredging at noon on Day 2 with a strong value of -0.85 (Spearman rank, $p < 0.05$). In addition, Day 3 showed a strong positive correlation value of 0.87 before dredging. Overall turbidity levels did not show strong correlations when assessed against their location from dredging activity.

Suspended Sediment

Pre- to Post-Dredging Temporal Comparisons. All collected suspended sediment weights were low, ranging from 0 to 0.09g throughout all three survey days. When measurements throughout each survey day were compared, no significant differences in suspended sediment measurements were identified for any transect (Kruskal-Wallis, $p > 0.05$). No significant differences were found when each spatial group was assessed using suspended sediment weights before and during dredging, before and after dredging, or during and after dredging (Wilcoxon signed ranks, $p > 0.05$).

Spatial Comparisons. No significant differences were found when suspended sediment weights were compared between control and near, control and far, and near and far groups (Mann-Whitney U, $p > 0.017$).

Correlation with Distance to Dredging. No significant correlations were identified when suspended sediment weights were compared against their associated distance downstream from dredging activity (Spearman rank, $p > 0.05$).

pH

Pre- to Post-Dredging Temporal Comparisons. Overall transects did not show significant differences between all timeframes when pH levels were compared throughout each survey day (Figure 37). Significant increases in values were observed during dredging when compared to values before dredging at the Dredge 1 transect on Day 1 (Kruskal-Wallis, $p < 0.05$).

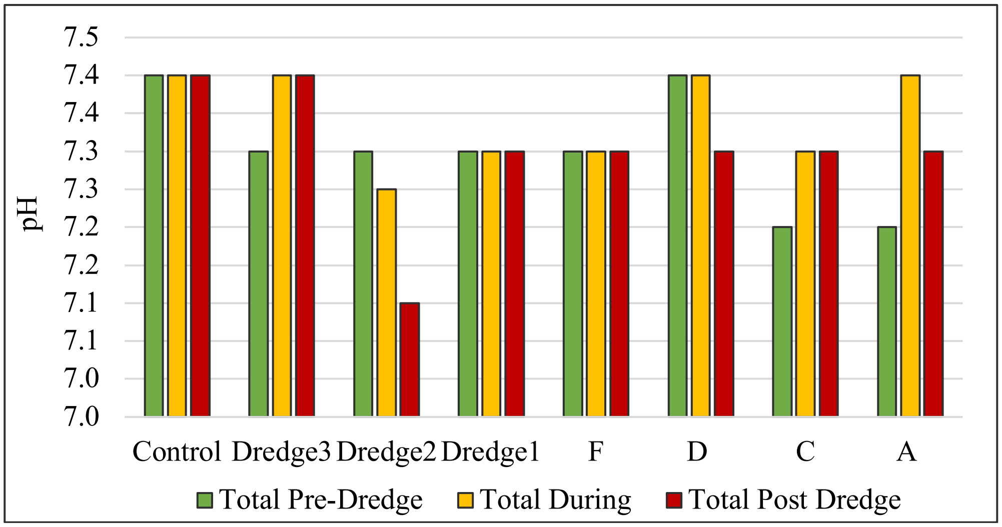


Figure 37. Pre-, during, and post-dredging median pH values at the Entiat River when all survey days were combined. Surveys took place between July 30th through August 1st, 2018.

Dredging took place within the vicinity of Dredge 1 working upstream on Day 1, showing elevated levels during dredging; however, pH returned to baseline levels by transect F located 100 ft downstream. Increased values were also observed at transect C on Day 1 with the pre-dredge median at 6.6, the median during dredging at 7.4, and the post-dredge median at 7.4. Although this transect registered a difference between all timeframes throughout the day, no other transects located further upstream and closer to the dredging had any significant differences in pH levels.

When all groups were analyzed temporally against each individual timeframe, the far group showed a lower median value before dredging at 7.3 and a slightly higher median during dredging at 7.4 (Table 15) (Wilcoxon signed ranks, $p < 0.05$). No other differences in pH values were significant before and during dredging (Wilcoxon signed ranks, $p > 0.05$).

Table 11. pH levels [median (IQR)] before, during, and after dredging activity along with associated determinations of significance between each timeframe pair (Wilcoxon signed ranks analysis, p-value < 0.05).

Spatial Group	Survey Day	Pre-Dredging	During Dredging	Post Dredging	Pre- vs. During	Pre- vs. Post	During vs. Post
Far	Combined Days	7.3 (0.3)	7.4 (0.2)	--	SD	NSD	NSD

*'SD'=Significant difference; 'NSD'= No SD

When pH measurements in all groups were assessed before and after dredging or during and after dredging, no significant differences occurred (Table 15).

Spatial Comparisons. When the control and near spatial groups were compared for pH measurements collected at each time period, no significant differences were observed (Mann-Whitney U, $p > 0.017$).

Table 12. pH [median (IQR)] between the control, near, and far spatial transect groups, along with associated determinations of significance between each spatial group (Mann-Whitney U, $p < 0.017$). Data was collected at the Entiat River, Washington between July 30th -August 1st, 2018.

Survey Time	Control	Near	Far	C vs. N	C vs. F	N vs. F
Day 2 Post-dredging	7.4 (0.3)	7.1 (0.2)	6.7 (0.6)	NSD	SD	NSD

*'SD'=Significant difference; 'NSD'= No SD

When the control and far groups were compared, a higher value was observed in the control on Day 2 after dredging was completed with the control median at 7.4 and the far median at 6.7 (Table 16) (Mann-Whitney U, $p < 0.017$). No other significant differences were detected between the control and far group pH levels throughout the survey days (Mann-Whitney U, $p > 0.017$). Finally, no significant differences were identified between the near and far group pH measurements for any individual day or when all three survey days were combined (Mann-Whitney U, $p > 0.017$).

Correlation with Distance to Dredging. No significant correlations were identified between pH levels and the associated distance downstream of the sample location from dredging activity (Spearman rank, $p > 0.05$).

Grain Size Distributions

Wolman Pebble Counts

Wolman pebble count datasets were collected along the Dredge 1 through 3 transects after dredging and compared against the pre-dredging pebble count taken within the survey area glide to determine significant alterations to grain size proportions (Figure 37). The Dredge 1 transect was located the furthest downstream and dredging on Day 1 began just upstream of this transect. The Dredge 2 transect was located 100 ft upstream of Dredge 1 and was the direct start of dredging for Day 2. Dredge 3 was between the control and Dredge 2 transects and was located downstream of the dredge starting point on Day 3.

Before dredging began, the mean grain size of the dredged area was -6.35Φ with a range of 3.46Φ between present grain size values of -4.32Φ and -7.78Φ, all of which fall within the pebble or cobble categories according to the Wentworth scale for classifying sediment (Wentworth, 1922) (Figure 38).

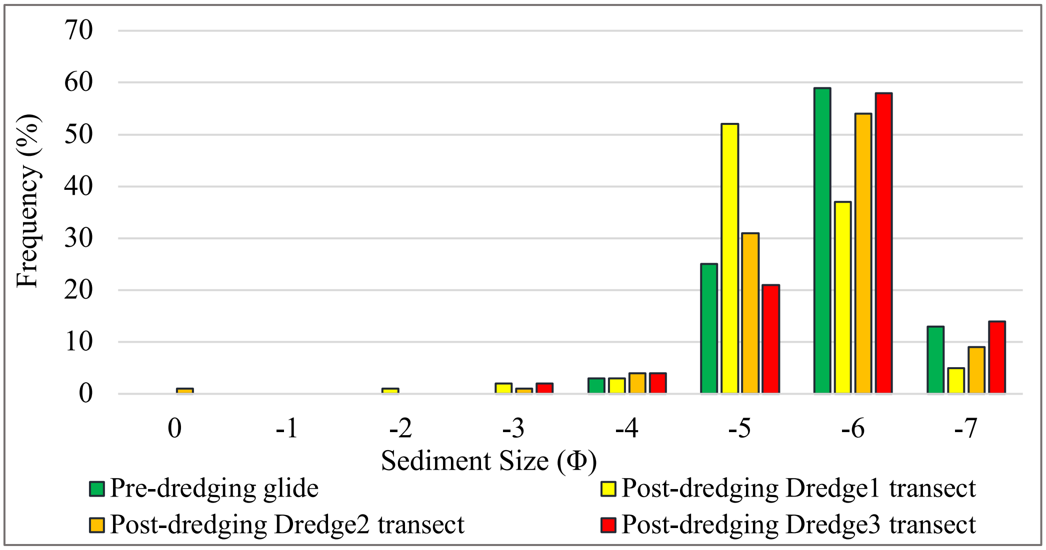


Figure 38. Grain size distribution of Wolman Pebble Count datasets pre- and post-dredging at all three dredged transects. Distributions are presented using the phi scale.

The mean grain size at Dredge 1 after dredging was slightly lower with a value of -5.9Φ and a larger range present of 4.7Φ between -2.8Φ and -7.5Φ (Figure 38). The post-dredging mean was classified within the pebble category on the Wentworth scale and values show a wider distribution of material. When compared against pre-dredging proportions, the Dredge 1 transect had greater amounts of intermediate-sized material present as well as less coarse material (Figure 39).

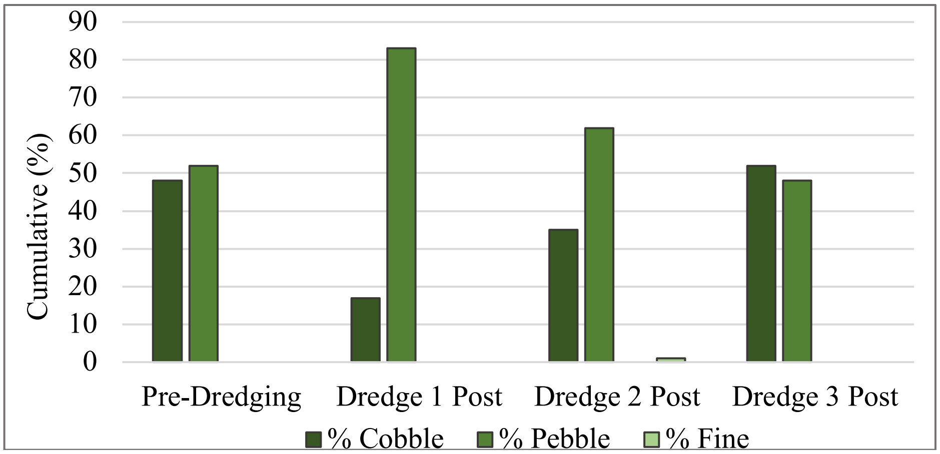


Figure 39. Grain size distributions of collected Wolman pebble count datasets pre- and post-dredging at all three dredged transects in the Entiat River, Washington. Pre-dredge measurements were collected on July 26th, 2019 while post measurements were collected on August 6th, 2019.

The mean value at Dredge 2 after dredging occurred was -6.11Φ and had the largest range of all transects at 7.78Φ with present grain sizes between 0 and -7.78Φ (Figure 38). Grain types ranged from coarse sand to cobble with the average value located within the cobble category. When compared against the pre-dredging distribution, the Dredge 2 transect had a similar trend to Dredge 1, having greater amounts of fine and intermediate-sized material present and less coarse material (Figure 39).

The grain size distribution at Dredge 3 after dredging was most similar to the pre-dredge distribution with the mean value at -6.28Φ and a range of present material being 3.94Φ between -3.91Φ and -7.85Φ (Figure 38). Present material types ranged from pebble to cobble with a mean value classified as cobble. The overall distribution of Dredge 3 closely resembles the pre-dredge distribution (Figure 39).

Sediment Sample Compositions

Control. Overall distributions before and after dredging were similar in the control when sampled under natural conditions with the exception of additional coarser material collected at both the 50% and 75% channel width after dredging (Figure 40).

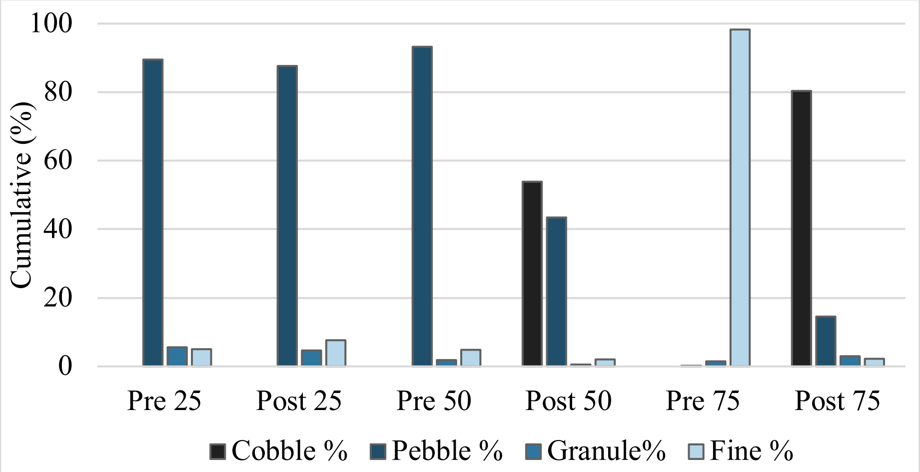


Figure 40. Grain size distributions pre- and post-dredging from sediment samples collected at the control transect in the Entiat River, Washington. Samples were taken at the 25%, 50%, and 75% channel widths. Pre-dredging samples were collected July 26, 2019 while post-dredging samples were collected August 6, 2019.

Dredge 3. Although similar, there was an observed reduction in coarse material as well as an increase in finer particle sizes after dredging when compared to pre-dredging distributions (Figure 41).

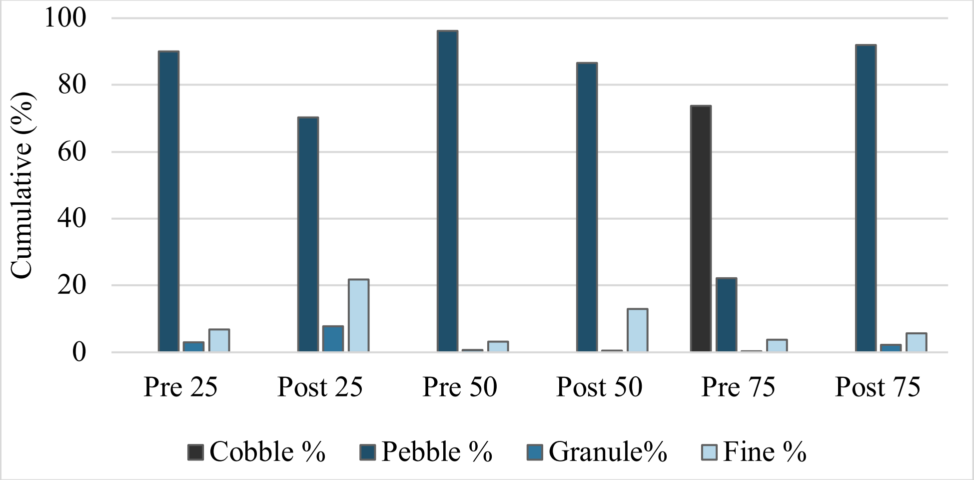


Figure 41. Grain size distributions pre- and post-dredging from sediment samples collected at the Dredge 3 transect in the Entiat River, Washington. Samples were taken at the 25%, 50%, and 75% channel widths. Pre-dredging samples were collected July 26, 2018 while post-dredging samples were collected August 6, 2018.

At the 75 % channel width survey point, there was an approximate 70 % reduction in cobbles as well as a 70 % increase in pebbles and slight increases in granule and fine material. Composition at the 50 % channel width experienced a 10% increase in fine material as well as a 10% reduction in pebble material. Finally, the 25% channel width experienced a 20 % reduction in pebbles, a 5 % increase in granules, and a 15 % increase in fine material.

Dredge 2. Overall, the distribution at Dredge 2 varied differently throughout the sample locations along the channel following dredging (Figure 42).

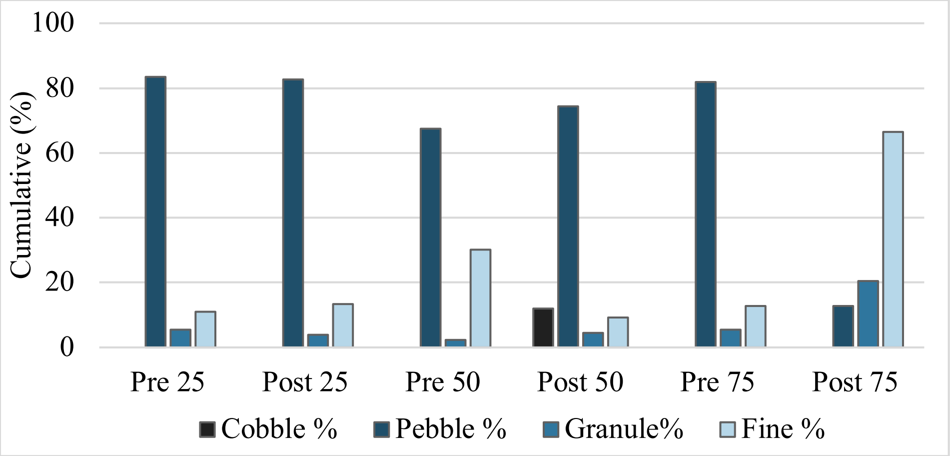


Figure 42. Grain size distributions pre- and post-dredging from sediment samples collected at the Dredge 2 transect in the Entiat River, Washington. Samples were taken at the 25%, 50%, and 75% channel widths. Pre-dredging samples were collected July 26, 2018 while post-dredging samples were collected August 6, 2018.

No change was observed at the 25 % channel width. A 12 % increase in cobble material occurred at the 50 % channel width location along with a 20 % reduction of fine material. In contrast, a 70 % reduction pebble material occurred at the 75 % channel width location, along with a 9 % increase in granule material and a 55 % increase in fine material.

Dredge 1A. Grain size distribution at the Dredge 1A transect exhibited an overall coarsening of material across the transect (Figure 43).

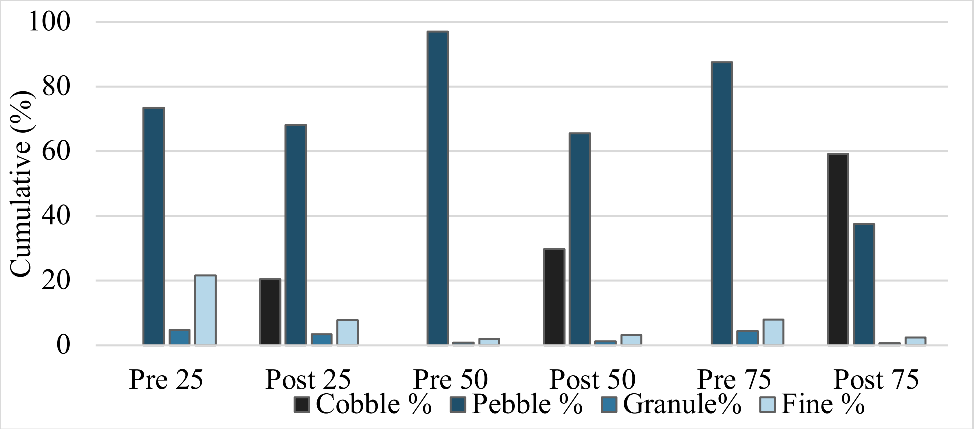


Figure 43. Grain size distributions pre- and post-dredging from sediment samples collected at the Dredge 1A transect in the Entiat River, Washington. Samples were taken at the 25%, 50%, and 75% channel widths. Pre-dredging samples were collected July 26, 2018 while post-dredging samples were collected August 6, 2018.

All points showed an increase in cobble substrate and a reduction in pebble grains. For cobble material, there was a 20 % increase at the 25 % channel width, 30% increase at the 50 % channel width, and a 60 % increase at the 75 % channel width. Pebble material was reduced by 5 % at the 25 % channel width, 32 % at the 50 % channel width, and 50 % reduction at the 75 % channel width. Granule and fine sediment proportions varied between locations with a 13 % reduction following dredging at the 25 % channel width and a 5 % reduction at the 75 % width.

Dredge 1. Grain size distributions at Dredge 1 were similar pre- and post-dredging and showed the same range in material size. Changes were minor following dredging with the sample at 50 % channel width showing a slight 5 % reduction in cobble material while the 75 % channel width sample showed a contrasting 5 % increase. (Figure 44).

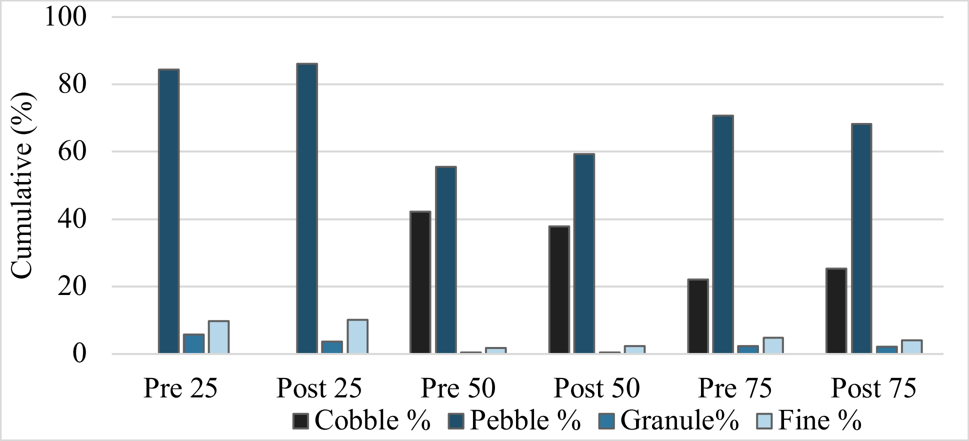


Figure 44. Grain size distributions before and after dredging from sediment samples collected at the Dredge 1 transect. Samples were taken at the 25%, 50%, and 75% channel widths. Pre-dredging samples were collected July 26, 2018 while post-dredging samples were collected August 6, 2018.

Downstream transects. When pre- and post-dredging distributions at transects G through A were compared, proportions between grain sizes were similar with minor variations between categories. No large differences or clear trends resulted between each category.

Alterations to Channel Morphology

Stream Power

Stream power was calculated for the time of survey using the Manning's equation of velocity of water in a uniform open channel:

$$V = \left(\frac{1.49}{N}\right) * R^{0.66} * S^{0.5}$$

Where V is the mean velocity of the flow (in ft/sec), N is the roughness coefficient, R is the hydraulic radius, and S is the channel slope. Using an N value of 0.05, an R value of 0.22, and an S value of 0.003 previously identified in the study reach (BOR, 2009), stream power was calculated to be 23.1 ft/sec. Present stream power was low compared to the stream power present at bankfull determined to be 83.3 ft/sec.

Channel Profiles

Cross-shore channel profiles were overlaid against one another to identify the amount of vertical change that occurred along the channel bed at specific transects before, after, two months, and one year following dredging activity.

Control

The control transect was captured as a baseline of natural variance between channel surveys to compare against observed alterations in the downstream transects and to isolate direct impacts from dredging activity. The control profile was located at the channel transition from a meander bend to a straightaway and captured a sand and gravel bar on the right side of the channel looking downstream (Figure 45). The channel bed sloped into a pool on the outer bank.

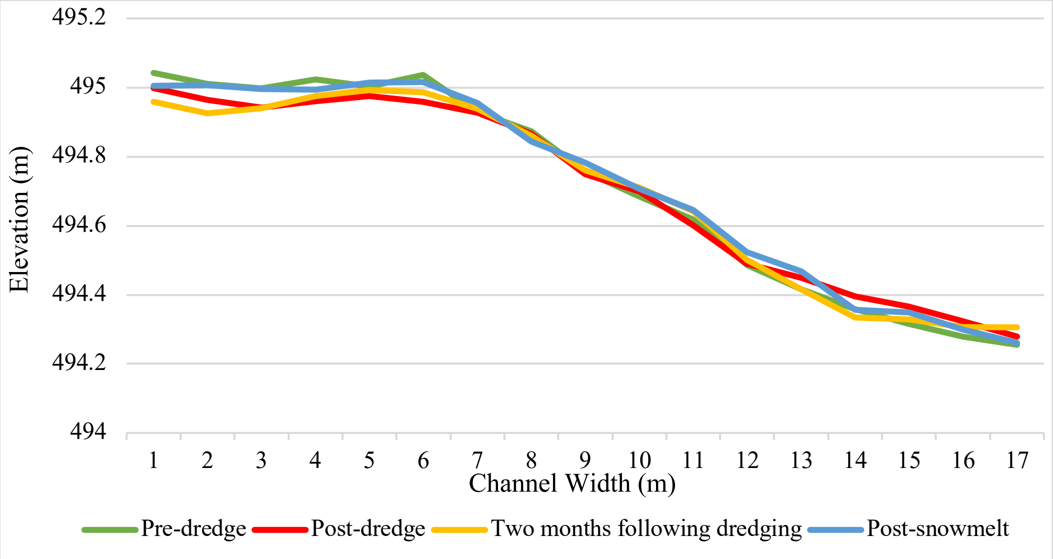


Figure 45. Control transect elevation profiles before, after, and two months following dredging activity at the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles were collected July 13th, 2019.

A slight offset of 0.10 m was observed across the entire channel width between the pre-dredge survey and post-dredge survey profile. This offset is also seen in profiles

Dredge 3 through Dredge 1A in which were collected at the same total station location. The observed offset is due to a slight variance in the total station placement between profile mapping surveys. All pre-dredge profiles were therefore adjusted for transects including the Control, Dredge 3, Dredge 2, Dredge 1A, and Dredge 1 to remove the 0.10 m offset for a direct comparison with post-dredging profiles as well as two months after. The station was required to be moved further down the river channel to collect the Dredge 1 transect furthest downstream. When mapping the Dredge 1 profile following dredging, the total station was reset at the same location showing no offset in the transect. When the control post-dredge profile was compared with pre-dredge profile, natural variation occurred at a maximum of 0.05 m along the transect (Figure 46). Similar negligible differences in elevation occurred both two months after dredging as well as at the start of the next season (Figure 46).

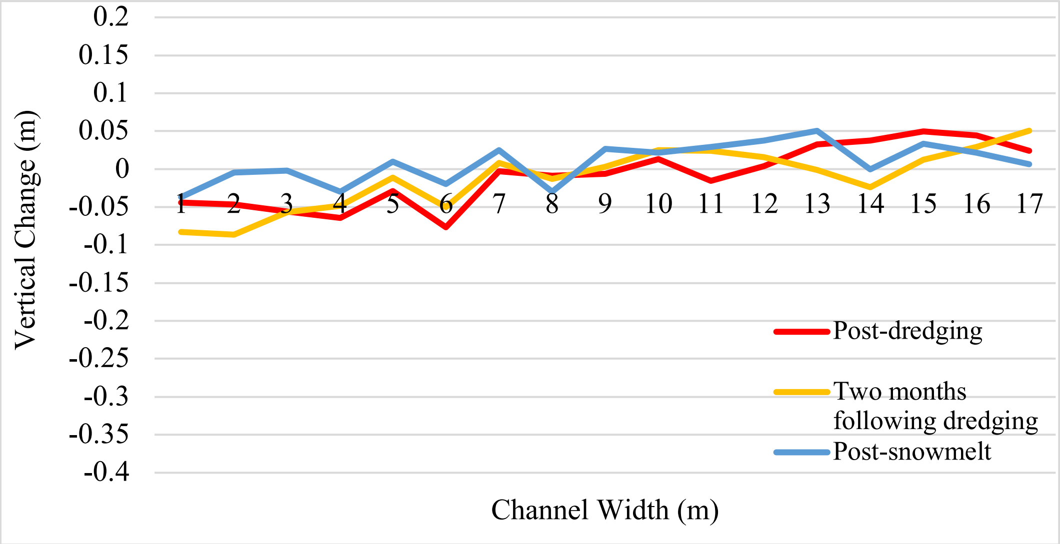


Figure 46. Amount of vertical change observed between pre- and post-dredging (red), pre-dredging and two months later (yellow), and change following snowmelt (blue) at the control transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

Minor changes occurred at the control location along the channel bed between all timeframes and the transect was relatively stable showing a maximum reduction of 0.09m and a maximum aggradation of 0.05m over the 11-month timeframe (Figure 46). Figure 47 represents the amounts of vertical change that occurred at all mapped profiles between the pre- and post-dredge medians as well as between the post-dredging median value and the median two months later.

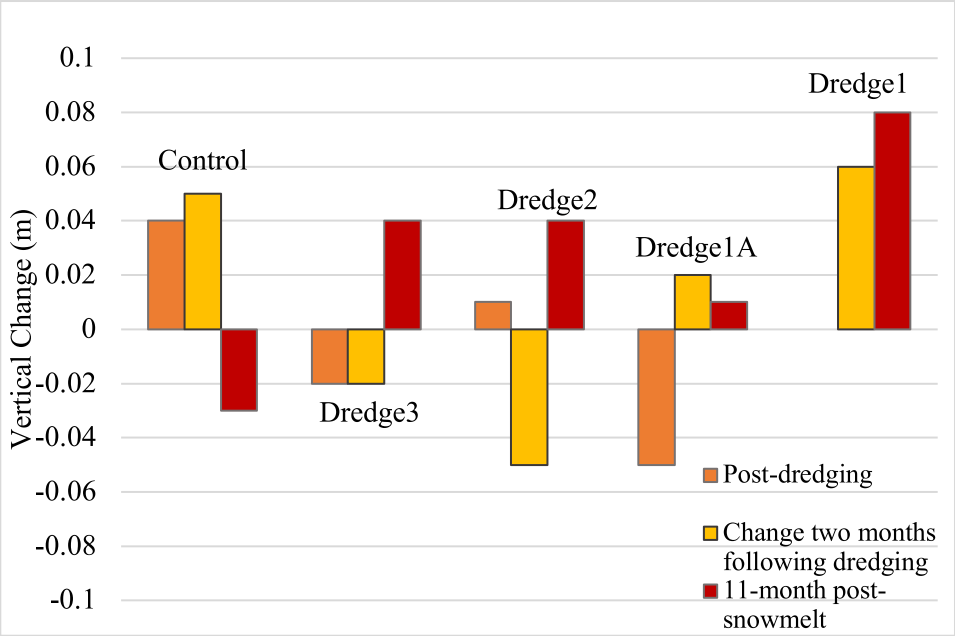


Figure 47. The median vertical change observed between pre- and post-dredging, post-dredging and two months later as well as two months later and 11 months after dredging at all transects in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and 11-month profiles were collected July 13th, 2019.

When depths to bankfull height were identified along 1-m intervals at the control transect and all pre-dredge depths were compared against post-dredging values, the post-dredging median depth was determined to be 1.80 m, showing a significant reduction when compared to the pre-dredging median value of 1.84 m (Wilcoxon signed ranks, $p < 0.05$) (Figure 47). Similarly, when all post-dredge depths were compared against depths two months after dredging was complete, a significant decrease in median depth was observed with the October median depth at 1.75 m, slightly shallower than the post-dredge control of 1.80 m (Wilcoxon signed rank, $p < 0.05$) (Figure 47). Finally, a significant decrease in depth was identified 11 months after dredging with a median of 1.72m (Wilcoxon signed rank, $p < 0.05$)

Dredge 3

The Dredge 3 transect was established approximately 26 m downstream from the control transect along the channel. Deeper pool sections were still present on the left bank looking downstream; however, a more gradual gradient was present, showing the flattening of the channel bed (Figure 48).

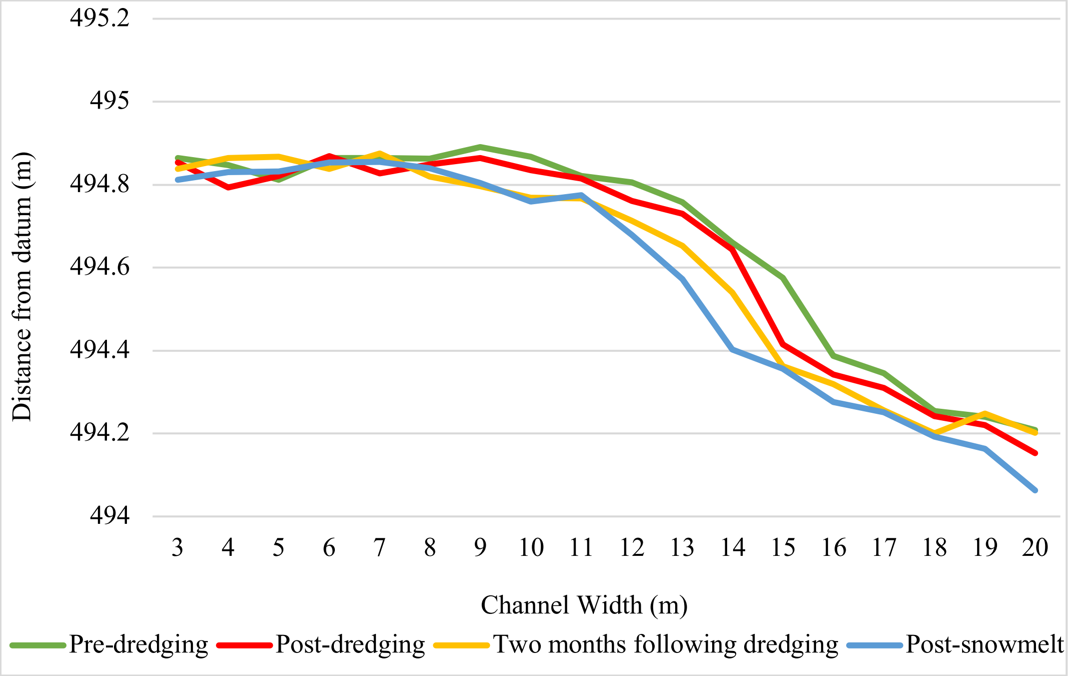


Figure 48. Dredge 3 transect elevation profiles before, after, and two months following dredging activity at the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles were collected July 13th, 2019.

The Dredge 3 profiles showed a slight reduction in material along channel meters 14-17 following dredging activity, however overall no large changes were observed along the transect (Figure 49). Dredging on Day 3 began approximately 15 m further upstream from the transect, leaving the direct profile minimally impacted and more significant alterations were present further upstream.

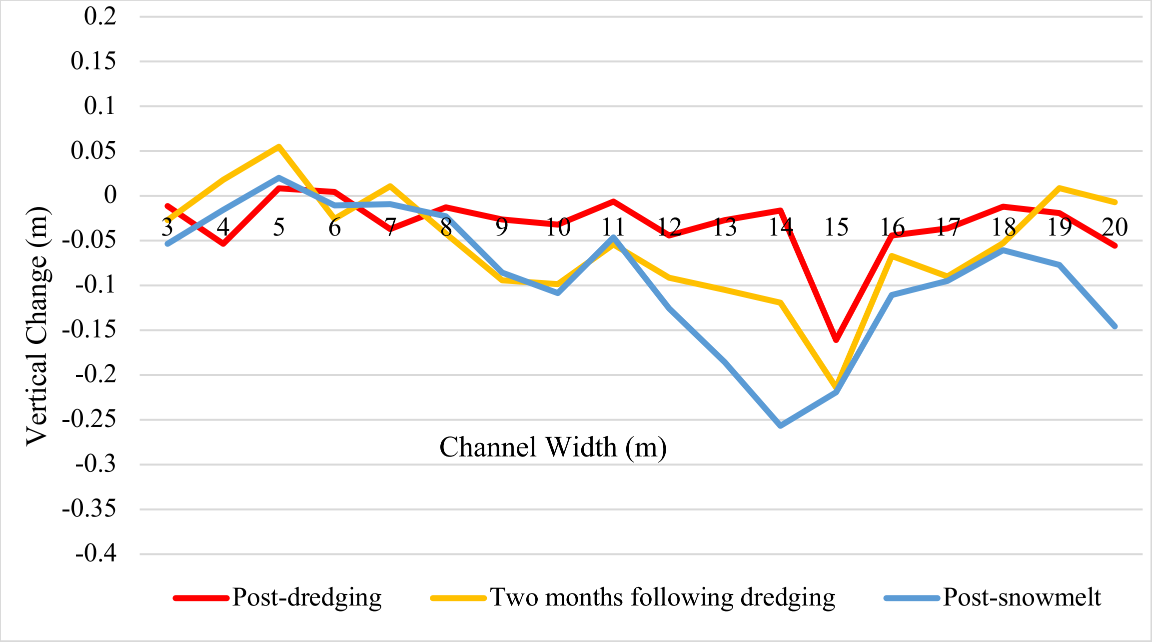


Figure 49. Amount of vertical change observed between pre-dredging, post-dredging, two months later, and following snowmelt at the Dredge 3 transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

Dredge 3 was instead representative of any potential downstream impacts in a deeper water column further downstream from dredging activity. Elevations showed some erosion after two months with a maximum reduction of 0.15 m; however, the overall bed structure remained the same along the channel profile when re-mapped in October (Figure 49). This transect showed similar trends with the control transect of a slight increase in depth. When re-mapped at the beginning of the next season following snowmelt, continued erosion was observed along channel meters 12-17, showing a widening.

When all measurements of pre-dredge depths were compared against post-dredging, a significant increase in median depth was observed for the Dredge 3 transect (Wilcoxon signed ranks, $p < 0.05$). The post-dredging median measured at 1.63 m and was slightly deeper than the pre-dredging median of 1.61 m. When all post-dredge depths were compared against depths two months after dredging was complete, no significant difference was observed for the entire transect (Wilcoxon signed rank, $p > 0.05$). The median depth two months following dredging was 1.65 m, slightly deeper than the post-dredge control of 1.63 m (Figure 45). A similar continued increase in median values of approximately 0.02 m of material occurred two months following dredging activity (Figure 45). Finally, when values from two months following dredging were compared with values collected 11 months after dredging, there was a significant increase with a median value for the 11-month dataset of 1.69 (Wilcoxon signed ranks, $p < 0.05$).

Dredge 2

The Dredge 2 transect was located 30.5 m downstream of Dredge 3 and was present within the channel straightaway (Figure 50). The channel bed continued to flatten with a slight deepening gradient towards the left channel bank.

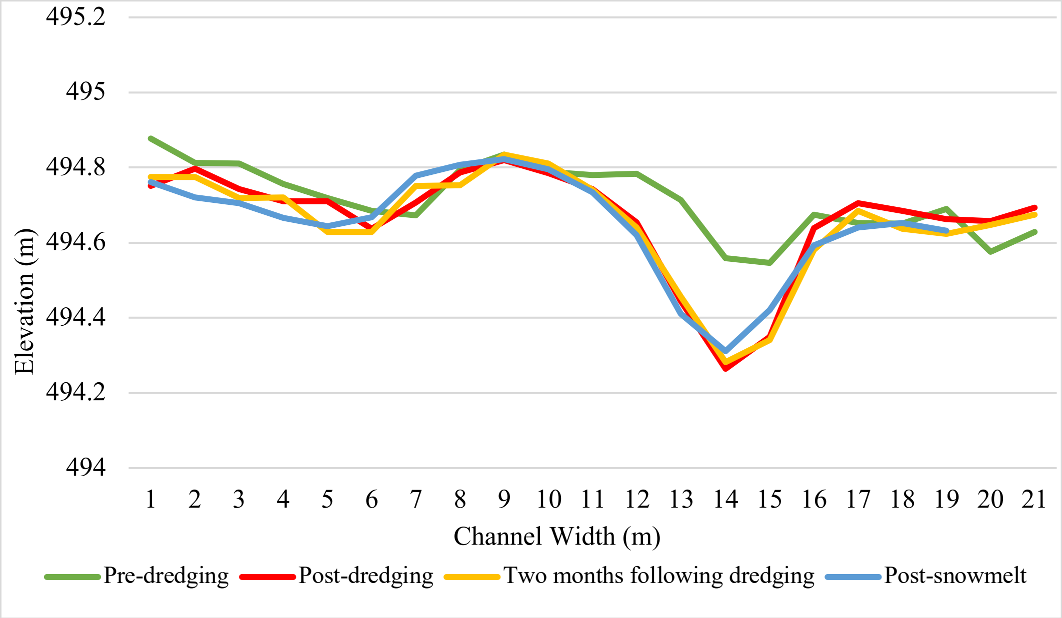


Figure 50. Dredge 2 transect elevation profiles before, after, and two months following dredging activity at the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles were collected July 13th, 2019.

Immediately following dredging activity, a decrease in material was captured throughout the main channel. Variations resulted in the reduction of the channel bed ranging from an aggradation of 0.07 m to a 0.30 m decrease in channel bed material (Figure 51). An approximate 0.30 m reduction along the channel bed at meters 11-16 was captured directly where dredging took place at the start of Day 2 (Figure 51). This transect showed a greater amount of erosion from the channel bed due to dredging when compared with the slight natural reduction seen in the control.

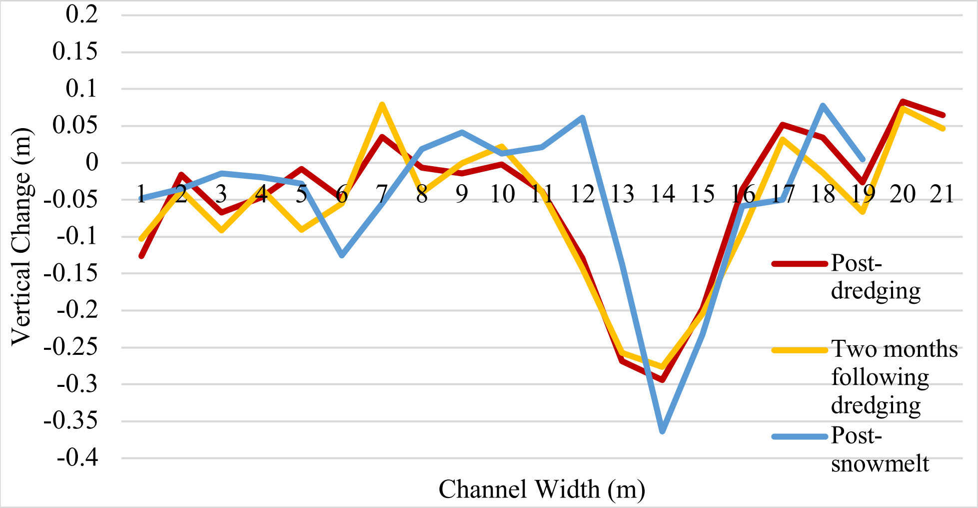


Figure 51, Amount of vertical change observed between pre- and post-dredging (red), pre-dredging and two months later (yellow), and change following snowmelt (blue) at the Dredge 2 transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

The decrease in material is representative of an artificial dredge hole created from dredging activity. When resurveyed two months later, the October profile showed minor elevation changes in comparison to the profile captured immediately following dredging activity, showing negligible restoration along with a contrasting increase in erosion (Figures 51). Minor recovery was also observed following snowmelt at the start of the following season with a slight continued reduction of material in the dredge hole (Figure 51).

When all pre-dredge depth measurements were statistically compared against all post-dredging depths, no statistically significant difference in depth occurred for the entire Dredge 2 transect (Wilcoxon signed ranks, $p > 0.05$). The post-dredging median measured at 1.60 m and was slightly shallower than the pre-dredging median of 1.61m. When all post-dredge depths were compared against depths two months after dredging was complete, a significant increase in depth was observed for the entire transect

(Wilcoxon signed rank, $p < 0.05$). The median depth two months following dredging was 1.65 m, slightly deeper than the post-dredge median of 1.60 m. There was a decrease in depth of 0.01m between median values along the channel bank at Dredge 2 directly after dredging, while the median two months after dredging showed a 0.05 m increase in depth compared to the post-dredging median (Figure 45). Values showed no significant difference in depth between 2 months and 11 months following dredging activity (Wilcoxon signed rank, $p > 0.05$).

Dredge 1A

Dredge 1A was located approximately 15 m downstream from Dredge 2 along the channel straightaway. The channel width was shallowest in the center with a deeper region remaining along the outer left channel bank (Figure 52).

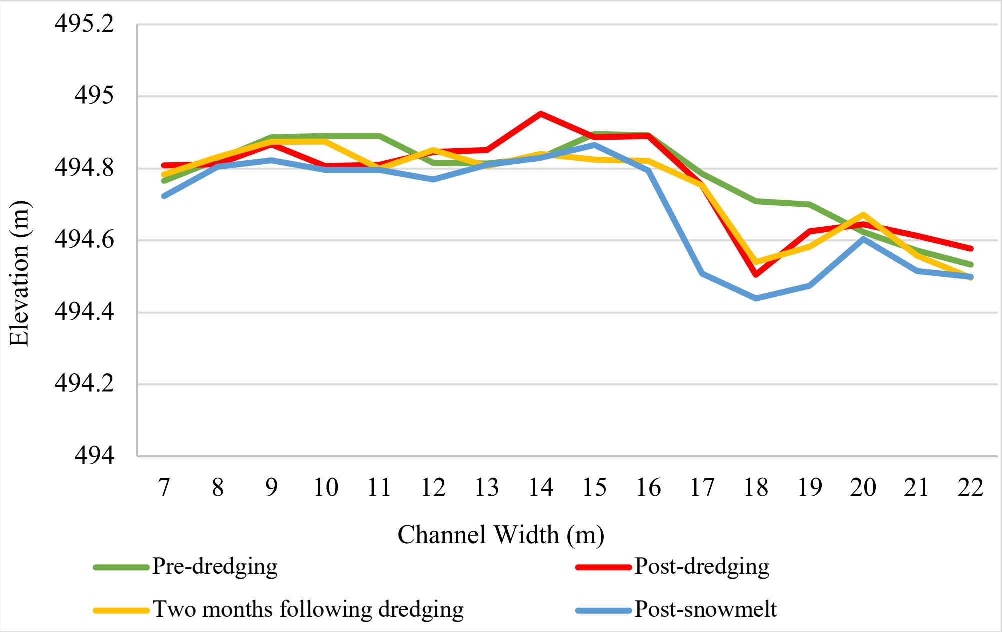


Figure 52. Amount of vertical change observed between pre- and post-dredging (red), pre-dredging and two months later (yellow), and change following snowmelt (blue) at the Dredge 1A transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

When Dredge 1A was resurveyed immediately following dredging activity, alterations in material along the channel profile varied with the largest vertical reduction of approximately 0.20 m and the largest aggradation of approximately 0.11 m of material from upstream dredging (Figure 53). The 0.20 m reduction in material occurred at channel profile meters 17 through 20 in which partially captured the creation of an artificial dredge hole following dredging (Figure 53). Overall the channel experienced increased erosion when compared with the control transect.

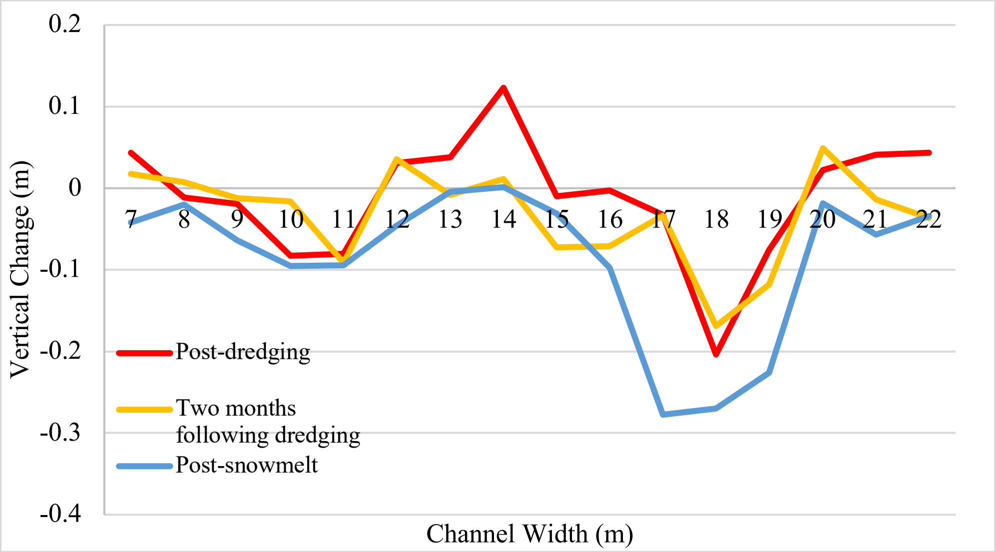


Figure 53. Amount of vertical change observed between pre-dredging, post-dredging, two months later, and following snowmelt at the Dredge 1A transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

When resurveyed two months later, the profile showed similar elevations to the channel profile collected immediately after dredging activity, although variations occurred along the channel width (Figure 53). Continued erosion was observed throughout the profile with further scour occurring at the previously disturbed sites. Overall no recovery to the channel was observed and instead experienced further reduction in material over the two-month time period. Slight aggradations between 0.03-0.07 m of material occurred at isolated points, while further erosion between 0.07-0.11 m occurred at a wider site along the center of the channel. The created dredge hole did not experience considerable recovery of channel material after the two-month timeframe. The transect showed a slow rate of change over two months similar to the control transect. Following snowmelt at the start of the next season the profile showed a continued scouring and widening of the present dredge hole (Figure 53).

When all measurements of pre-dredge depths were compared against post-dredging depths, a significant increase in depth was observed for the entire transect (Wilcoxon signed rank, $p < 0.05$). The post-dredging median measured at 1.55 m and was slightly deeper than the pre-dredging median of 1.50 m. When the post-dredge median depth was compared against the median depth two months after dredging was complete, a significant decrease was observed with a slightly shallower median two months following dredging of 1.53 m, compared to the post-dredge median of 1.55 m (Wilcoxon signed rank, $p < 0.05$). The profile experienced an overall increase in depth of 0.05m between transect medians immediately following dredging, as well as a contrasting decrease of approximately 0.02 m in depth between medians two months following dredging activity (Figure 45). A significant increase in depth was observed at the Dredge 1A transect between two months and 11 months after dredging with a median value of 1.54m 11 months following the activity (Wilcoxon signed rank, $p < 0.05$).

Dredge 1

Dredge 1 was similarly located within the channel straightaway with a flattened bed section that experienced an increased width from the upstream region. The transect was present in the transitional region between the upstream glide and downstream riffle habitat (Figure 54).

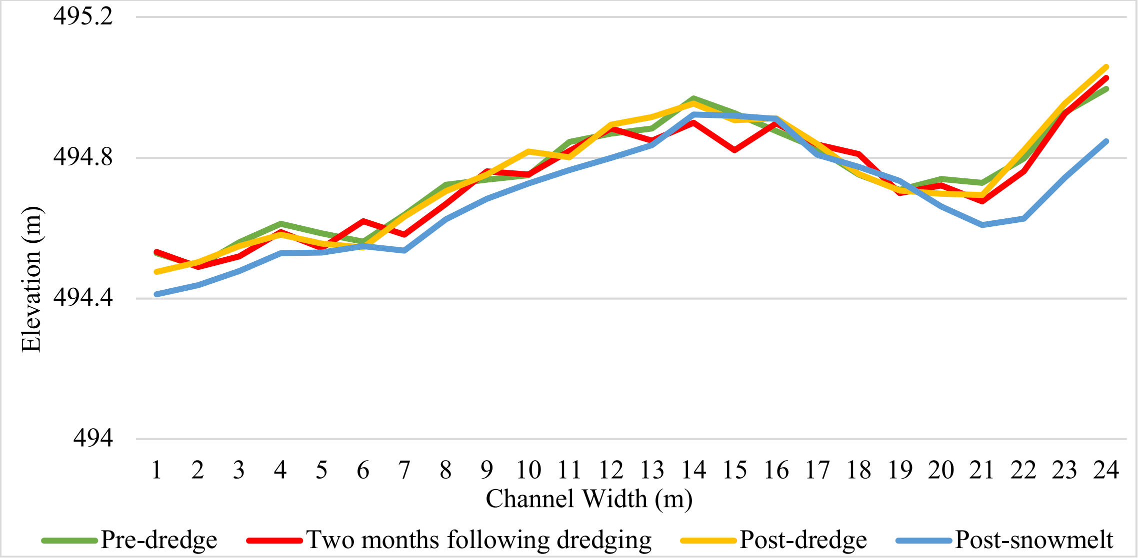


Figure 54. Dredge 1 transect elevation profiles before, after, and two months following dredging activity at the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles were collected July 13th, 2019.

When Dredge 1 was surveyed immediately following the completion of dredging activity, small fluctuations in elevations were identified along the channel width and showed minor changes to the profile (Figure 55). Alterations to the channel following dredging were similar to those seen at the control transect, showing changes in the region were most likely due to natural variation.

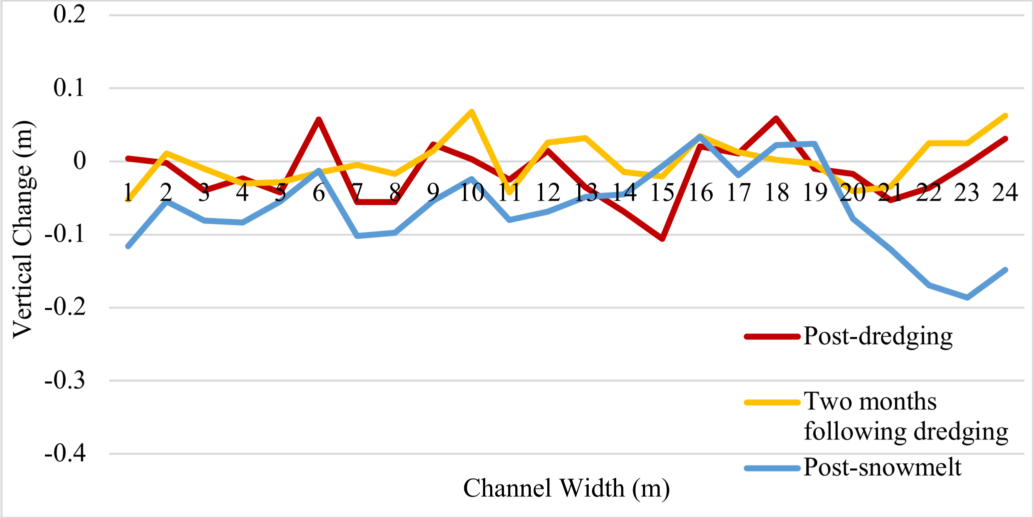


Figure 55. Amount of vertical change observed between pre- and post-dredging (red), pre-dredging and two months later (yellow), and change following snowmelt (blue) at the Dredge 1 transect in the Entiat River, Washington. Pre-dredging profiles were collected July 10th, 2018, post-dredging profiles were collected August 6th, 2018, two-month profiles were collected October 3rd, 2018, and post-snowmelt profiles July 13th, 2019.

On Day 1, dredging began above the Dredge 1 transect and worked directly upstream. Because of the shallow section of channel at the transition from glide to riffle, the dredging started slightly upstream from the surveyed transect to properly function with sufficient water for the dredge intake. Water intake structures vary between dredges with different designs allowing for easier maneuverability. The dredge's intake pump was constructed of hard plastic and required a small hole to be dug at this water depth for sufficient water flow. Due to the restriction of the water pump, the majority of the created tailings piles and holes were located just upstream of the transect and not directly captured in the profile. This profile therefore serves as a representation of potential downstream alterations to the channel in shallow water following upstream dredging starting approximately 5 ft upstream. Similarly, when the channel was resurveyed in October, negligible alterations along the profile were observed with small amounts of aggradation throughout the transect (Figure 55). Finally, negligible alterations to the profile were observed 11-months later at the start of the following season after snowmelt was complete (Figure 55). Overall, channel bed alterations were similar to trends observed in the control transect and represented natural variation.

No significant difference was observed along the transect when post-dredging depths were compared statistically against pre-dredging depths (Wilcoxon signed rank, $p < 0.05$). The post-dredging median was equal to the pre-dredge median at 1.33 m. When all pre-dredge depths were compared against depths two months after dredging was complete, a significant decrease was observed for the entire transect (Wilcoxon signed ranks, $p < 0.05$). The median depth two months following dredging was 1.27 m, slightly shallower than the pre-dredge control of 1.33 m (Figure 47). Finally, a significant increase was also observed at the Dredge 1 transect with a median value 11 months after dredging of 1.35m.

Artificial Features

Tailings Piles

Grainsize Distributions

Sediment samples were collected along each created sediment pile for Days 1 and 2 at the main region and at the transition into the sediment tail (Figure 56). Sediment was not collected at created sediment piles on the final survey day due to the incoming Cougar Creek fire in the watershed.

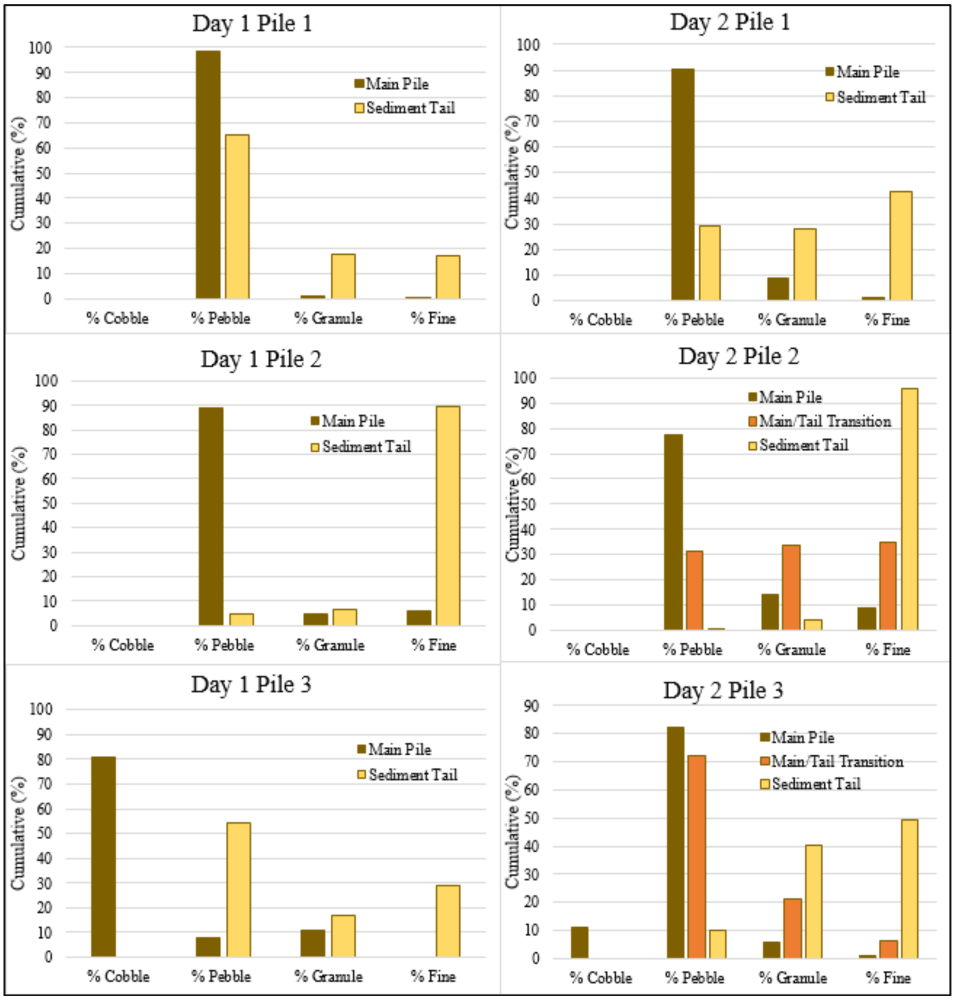


Figure 56. Grainsize distributions of bulk samples collected at tailings piles for Days 1 and 2 following dredging on August 1st, 2018.

Extra samples were taken at two piles on Day 2 that showed a visibly finer section of tail further downstream from the upstream tail (Figure 56). Each tailings pile sample showed a sorting of particle size and weight downstream due to water flow. The main portion of piles showed higher amounts of coarse material with cobble grains ranging from 0-80 % and pebble grains ranging from 9-98 % while downstream tails showed higher amounts of fine grains ranging from 5-40 % granule material and 18-95 % fine material (Figure 56). When distributions of tailings were compared with the pre-dredging Wolman pebble count collected in the experimental reach location where dredging occurred (Figure 39), the majority showed smaller proportions of cobbles present in the pile compared to the 49 % cobble distribution seen pre-dredging. No granules or fine material was present in the pre-dredging Wolman pebble count, showing larger proportions of granule and fine material were present in all of the created piles. Dredging was shown to disturb and expose a large proportion of fine grains, increasing the amount of unstable material and the likelihood of dispersion downstream from dredging activity.

Channel Bed Disturbance

All created tailings piles were measured immediately following dredging activity to determine the approximate amount of disturbed material. Each pile was measured for width, length of the main pile portion as well as the length of the sediment ‘tail’, which was identified from the downstream drift and settling of finer sediment, to determine the total length. Eight total tailings piles were identified with a mean width of 1.75 m, a mean tail length of 5.44 m, and a mean total length of 7.41 m (Table 17).

Table 13. Tailings pile measurements collected at the Entiat River site on the final survey day of August 1, 2018. Measurements were collected in the field and post-processed to determine the total surface are and volume displaced.

Tailings Pile	Length (m)	Width (m)	Length of Substrate Tail (m)	Total Length (m)	Surface Area Disturbed (m^2)	Volume of Material Disturbed (m^3)
1	0.50	0.96	0.00	0.50	0.38	0.01
2	2.90	1.80	2.10	5.00	7.07	0.29
3	2.00	2.10	9.50	11.50	18.97	4.43
4	2.50	2.00	7.60	12.00	7.23	0.88
5	1.60	1.00	9.50	9.20	18.85	4.59
6	3.10	2.70	6.00	9.10	19.30	5.02
7	1.60	1.50	3.60	5.20	6.13	1.09
8	1.60	1.90	5.20	6.80	10.15	2.71
Average	1.98	1.75	5.44	7.41	11.01	2.38
				Total Area Disturbed	88.06	19.01

The average amount of surface area disturbed during dredging was determined to be 11.01 m^2 per pile while the total surface area of material disturbed was 88.06 m^2 (Table 17) (Figure 57).

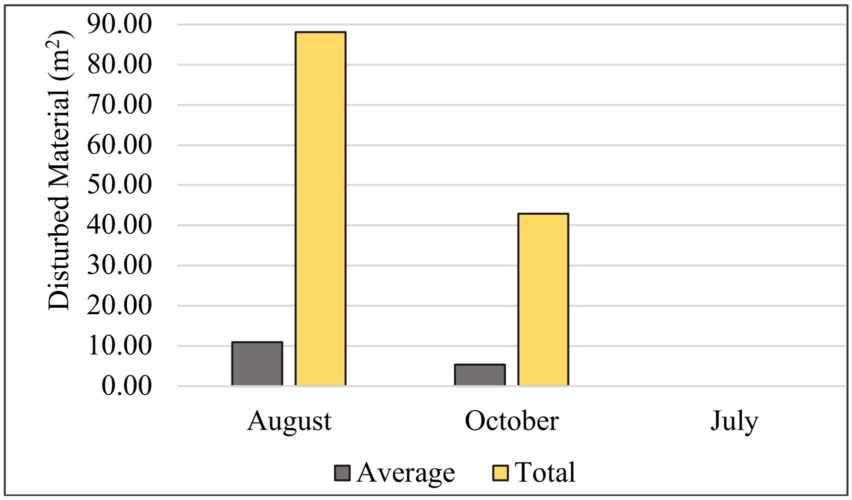


Figure 57. Comparisons of the average and total surface area of disturbed material within created tailings piles when measured immediately after dredging in August as well as two months and 11 months following dredging activity.

Tailings piles were re-measured two months after dredging to determine the amount of remaining material as well as recovery rates that occurred within the two-month timeframe. Of the eight total tailings piles identified, the October mean width was 1.63 m with an average total length of 3.96 m (Table 18). When re-surveyed 11 months after dredging following spring snowmelt, no visible signs of tailings piles remained (Figure 57).

Table 14. Tailings pile measurements collected at the Entiat River site two months following dredging on October 6th, 2018. Measurements were collected in the field and post-processed to determine the total surface are and volume displaced.

Tailings Pile	Length (m)	Width (m)	Length of Substrate Tail (m)	Total Length (m)	Surface Area Disturbed (m^2)	Volume of Material Disturbed (m^3)
1	0.80	1.10	0.00	0.80	0.69	0.05
2	1.40	1.40	1.90	3.30	3.63	0.57
3	2.20	2.00	2.40	4.60	7.23	0.94
4	1.70	1.80	2.20	3.00	2.83	0.45
5	0.80	1.20	2.80	4.50	6.36	1.52
6	2.20	2.10	2.30	4.50	7.42	2.31
7	1.20	1.60	3.40	4.60	5.78	1.18
8	1.80	1.80	4.60	6.40	9.05	1.46
Average	1.51	1.63	2.45	3.96	5.37	1.06
				Total Area Disturbed	42.98	8.48

The average surface area of remaining disturbed material was 5.37 m^2 per pile while the total surface area of material disturbed was 42.98 m^2 (Figure 55). Between August and October there was approximately a 51 % reduction in the total surface area of disturbed material within all measured tailings piles in the two-month timeframe.

The majority of individual tailings piles experienced a reduction in surface area between the August and October surveys with varying rates of erosion (Figure 58).

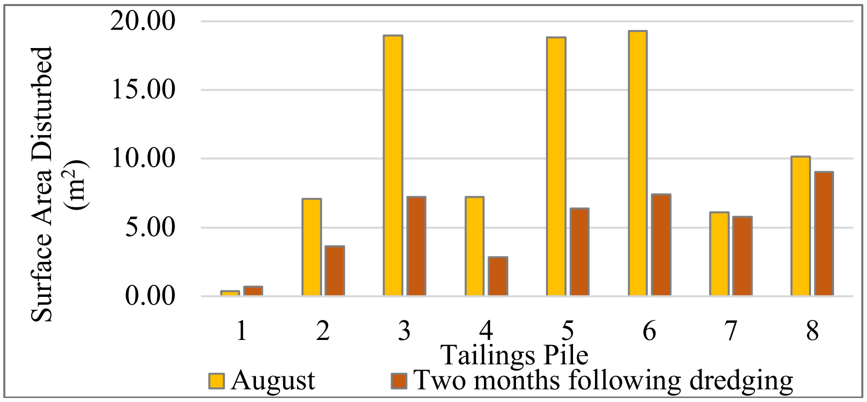


Figure 58. Surface area comparisons between individual tailings piles collected immediately following dredging as well as two months later. Data was collected at the Entiat on August 1st and October 6th, 2018.

Dispersal of tailings downstream was dependent on water flow and depth at each location as well as the composition of sediment present. Day 1 tailings were located in the central region of the channel at a reach where the channel flattens out and is more uniform in depth throughout the entire bed (Figures 50 and 52). Sediment piles showed moderate erosion amounts ranging between 0.00 to 12.00 m^2 and a larger amount of coarse material than other transects. Piles 1 and 2 both had pebble material composing 88-98 % of the main pile region, while pile 3 had 80 % cobble material in the main pile for Day 1 (Figure 56). Day 2 piles were located in the center as well as on the left side of the channel looking downstream in the deeper regions and showed overall larger proportions of fine material (Figure 48) (Figure 56). Pile 1 showed no cobble material was present, pile 2 was composed of 96 % fine material in the 'tail' region, and pile 3 showed 10 % cobble material in the main pile region and 50 % fine material in the tail (Figure 56). Due to the increased depths and finer material, these experienced large reductions ranging from 4.50-13.00 m^2. Day three tailings piles showed low amounts of reduction of less than 1.00-2.00 m^2. These were located on the shallower region of the bed, with the thalweg on the left side looking downstream (Figure 46). Although tailings pile samples were not collected on the third survey day due to the incoming Cougar Creek Fire, sediment distribution in the Dredge 3 region shows high amounts of coarse material with cobbles ranging from 0-74 %, pebbles ranging from 74-98 %, and fine material ranging from 3-8 % (Figure 46). With higher proportions of coarse material and lower flows, less material was dispersed downstream. When all individual piles were analyzed statistically between the August and October datasets, a significant decrease in surface area of material was present over the two-month timeframe (Wilcoxon signed ranks, $p < 0.05$). The median two months later was 6.10 m, significantly smaller than the 8.70 m median in August.

In addition, volumes of each tailings pile were measured to identify the total amount of material displaced immediately following dredging in August. The average volume of disturbed material was determined to be approximately 2.38 m^3 per pile, while the total volume disturbed was 19.01 m^3 (Table 18) (Figure 59). The median volume two months later was 1.1 m, 0.8 m smaller than in August.

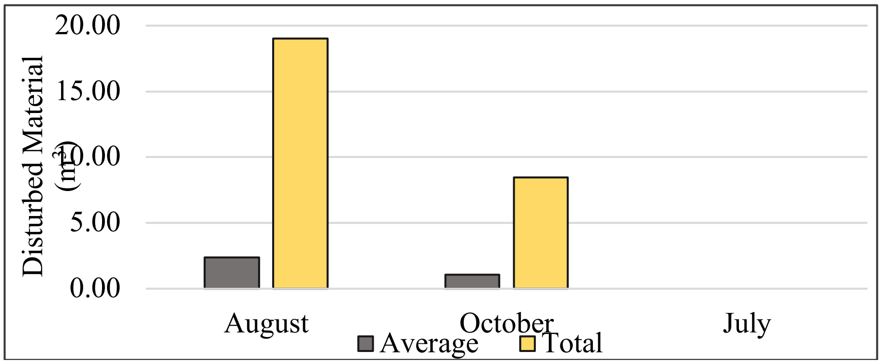


Figure 59. Comparisons of the average and total volume of disturbed material within created tailings piles when measured immediately after dredging in August, two months, and 11 months following dredging.

When the same tailings piles were re-measured in October, the average amount of remaining material was 1.06 m^3 per pile, while the total volume remaining was 8.48m^3 (Figure 59). Overall there was approximately a 55.4 % reduction in the total volume of displaced tailings material over the two-month timeframe. The majority of individual tailings piles did not experience a significant reduction in volume between the August and October surveys ranging from no change to approximately 4.5 m^3 (Figure 60) (Wilcoxon signed ranks, $p > 0.05$). When resurveyed 11 months after dredging following spring snowmelt, no visible signs of tailings remained (Figure 59).

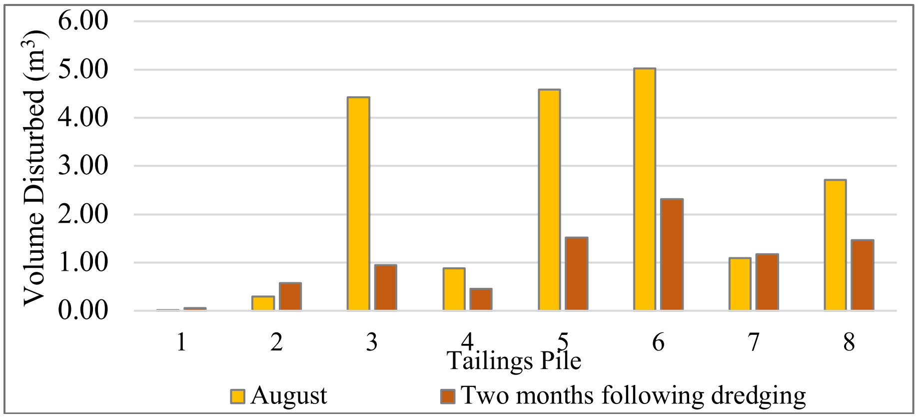


Figure 60. Volume comparisons between individual tailings piles collected immediately following dredging as well as two months later. Data was collected at the Entiat on August 1st and October 6th, 2018.

Dredge Holes

Channel Bed Disturbance

Similar to tailings measurements, all created dredge holes were counted and measured to determine the amount of material initially displaced as well as the recovery that occurred within the two-month timeframe between dredging in August and the following survey in October. Seven total dredge holes were identified in August with a mean width of 4.06 m and a mean length of 3.71 m (Table 19).

Table 15. Dredge hole measurements collected at the Entiat River site on the final survey day of August 1, 2018. Measurements were collected in the field and post-processed to determine the total surface are and volume displaced.

Dredge Hole	Length (m)	Width (m)	Hole Depth (m)	Surface Area Disturbed (m^2)	Volume of Disturbed Material (m^3)
1	1.80	1.70	0.22	2.40	0.34
2	1.80	2.10	0.25	2.97	0.49
3	4.80	2.90	0.36	10.93	2.62
4	9.20	7.60	0.11	54.92	3.94
5	3.10	4.20	0.24	10.23	1.60
6	3.30	2.90	0.36	7.52	1.80
7	20	7.00	0.44	11.00	3.23
Average	3.71	4.06	0.28	14.28	2.00
			Total Area Disturbed	99.96	14.03

The average amount of surface area disturbed following dredging was 14.28 m^2 per hole while the total surface area of material disturbed for all created holes was 99.96 m^2 (Table 19) (Figure 61).

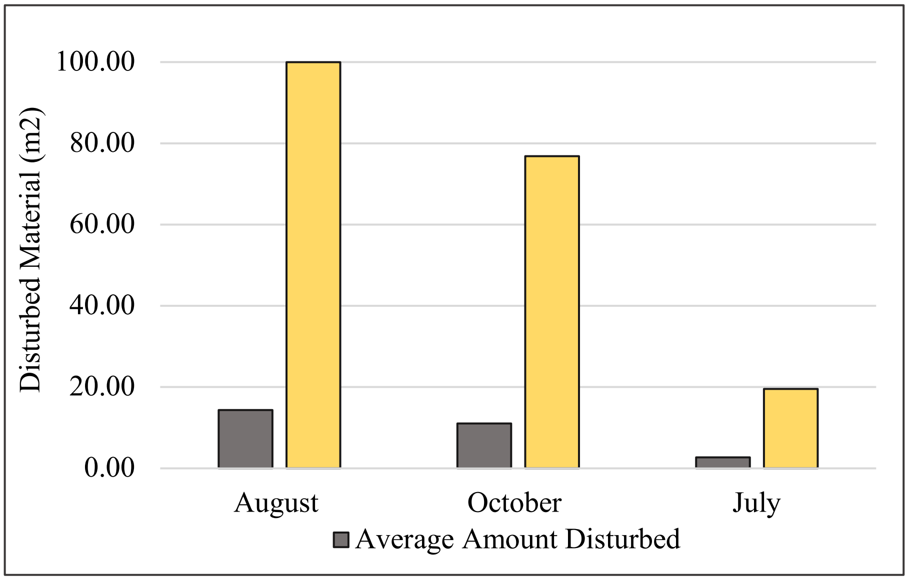


Figure 61. Comparisons of the average and total surface area amounts of disturbed material within created dredge holes when measured immediately after dredging in August and two months following dredging.

All seven dredge holes were re-measured in October and were determined to have an average width of 3.36 m and average length of 3.41 m per hole (Table 20).

Table 16. Dredge hole measurements collected at the Entiat River site two months following dredging on October 6th, 2018. Measurements were collected in the field and post-processed to determine the total surface are and volume displaced.

Dredge Hole	Length (m)	Width (m)	Hole Depth (m)	Surface Area Disturbed (m^2)	Volume of Disturbed Material (m^3)
1	2.80	1.40	0.05	3.08	0.09
2	1.40	1.30	0.13	1.43	0.12
3	4.30	2.50	0.33	8.44	1.83
4	8.30	6.90	0.26	44.98	7.80
5	1.50	2.10	0.13	2.47	0.22
6	4.00	2.50	0.53	7.85	2.79
7	1.60	6.80	0.41	8.55	2.31
Average	3.41	3.36	0.26	10.97	2.17
			Total Area Disturbed	76.80	15.16

The average surface area remaining per hole was 10.97 m^2 while the total disturbed surface area remaining was 76.80 m^2 (Table 20) (Figure 58). Between August and October, there was an overall reduction of 23.2 % in surface area of created dredge holes. The majority of individual dredge holes experienced a reduction in surface area between the August and October surveys with aggradation ranging from 0.00 to approximately 9.00 m^2 (Figure 62).

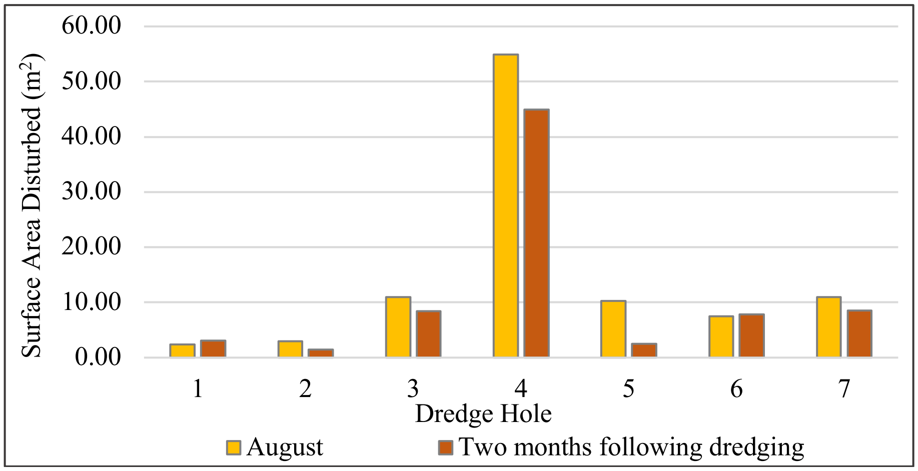


Figure 62. Surface area comparisons between individual dredge holes collected immediately following dredging as well as two months later. Data was collected at the Entiat on August 1st and October 6th, 2018.

When resurveyed 11 months after dredging activity following spring snowmelt, the average depth of each hole remaining was 2.79 m^2 while the total amount remaining was 19.50 m^2 (Figure 61). Of the original total disturbed surface area, 19.5 % remained 11 months after dredging (Figure 61).

Deposition rates downstream into the dredge holes was dependent on water flow and depth at each location as well as the composition of available sediment. Day 1 holes ranged from no change to approximately a 3.00 m^2 reduction in area and all holes were located in the center region of the channel with uniform channels with less depth and coarser material observed in the created tailings piles (Figure 52) (Figure 54). Less water depth and larger grains limit the amount of material able to be transported and deposited to the region. Day 2 holes that were present in the deeper portion of the channel bed experienced the largest amount of aggradation of approximately 9.00 m^2, potentially due to the increased deposition of previously suspended sediment from deeper flows and smaller material (Figure 54) (Figure 60). The dredge hole from Day 3 showed approximately a 2.00 m^2 aggradation and was located in a shallower side of the channel, with less flow energy that would deposit suspended sediment (Figure 56) (Figure 60).

In addition, volumes of each dredge hole were measured to identify the total amount of material removed from the channel bed immediately following dredging in August. The average volume was determined to be 2.00 m^3 per hole, while the approximate total volume removed was 14.00 m^3 (Table 20) (Figure 63).

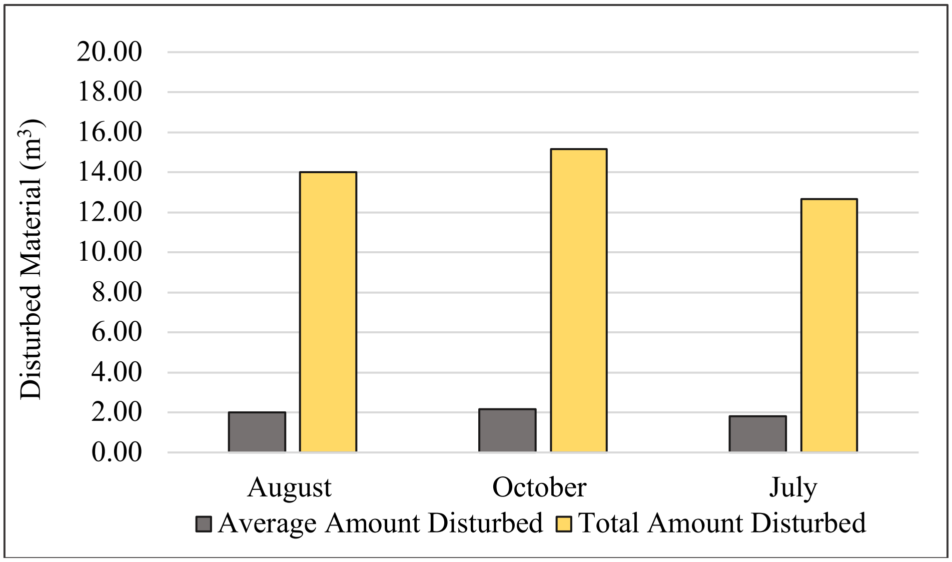


Figure 63. Comparisons of the average and total volume of disturbed material within created dredge holes when measured immediately after dredging in August and two months later.

When the dredge holes were re-measured in October, the average volume remaining was 2.17 m^3 per hole, while the total volume was 15.16 m^3 (Table 20) (Figure 63). Overall, there was approximately an 8.1 % increase in the total volume of created dredge holes over the two-month timeframe. The majority of individual dredge holes experienced a reduction in volume between the August and October surveys with varying rates of aggradation (Figure 63). In contrast, dredge holes 4 and 6 were shown to experience further erosion over the two-month period of low summer flows. No significant difference in either surface area or volume of material was present over the two-month timeframe (Wilcoxon signed ranks, $p > 0.05$).

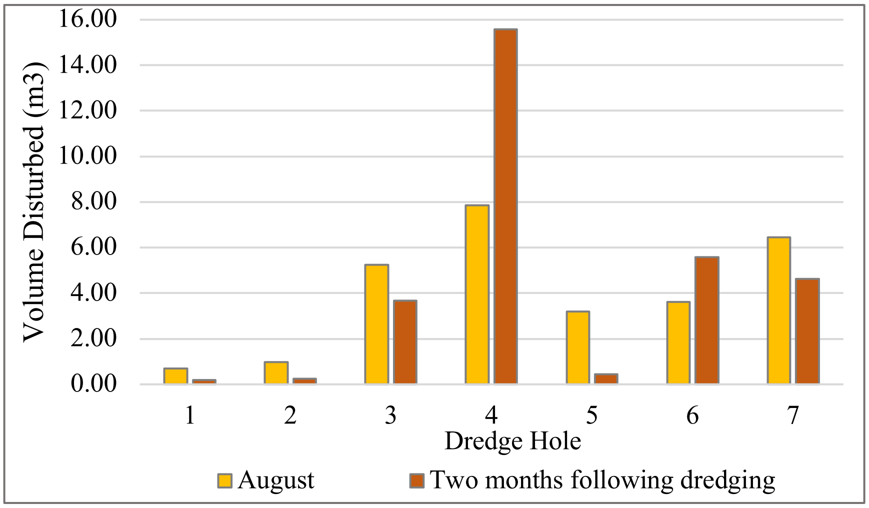


Figure 64. Volume comparisons between individual dredge holes collected immediately following dredging as well as two months later. Data was collected at the Entiat on August 1st and October 6th, 2018.

All created dredge holes were still remaining in the channel one year after dredging occurred when the survey site was revisited on July 13th, 2019. All seven dredge holes were determined to have an average width of 2.18 m and average length of 1.8 m per hole (Table 21).

Table 17. Dredge hole measurements collected at the Entiat River site 11-months following dredging on July 13, 2019. Measurements were collected in the field and post-processed to determine the total surface are and volume displaced.

Dredge Hole	Length (m)	Width (m)	Hole Depth (m)	Surface Area Disturbed (m^2)	Volume of Disturbed Material (m^3)
1	2.49	1	0.44	0.39	0.23
2	1	0.7	0.22	0.19	0.06
3	1.4	2.3	0.54	2.08	1.50
4	2.3	1.48	0.59	0.86	0.68
5	1.5	1.6	0.46	1.01	0.62
6	3	2.6	0.9	2.65	3.19
7	1.4	5.6	0.39	12.32	6.40
Average	1.87	2.18	0.51	2.79	1.81
			Total Area Disturbed	19.50	12.67

Of the original disturbed footprint, 19.5 % remained at the beginning of the next season while 90.4 % of the total volume originally disturbed remained (Figures 61 and 63).

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Average dredging completed in the Entiat River was determined to be 4.5 hours per day, fitting within the range of 4-8 hours previously cited in a 1994 California Department of Fish and Game study on suction dredge mining, yet slightly lower than the average daily duration of 5.6 hours (CDFG, 1994). Dredging occurred at least 5 hours per day for the initial two survey days; however, the Cougar Creek fire was spreading rapidly within the watershed and required work to be completed early on Day 3, significantly reducing the time available for dredging.

Alterations to Water Quality

Initial assumptions were that dredging would increase in temperature, specific conductance, turbidity, and suspended sediment along with a decrease in dissolved oxygen downstream during dredging activity. Assumptions were based on previously collected results from other impact studies focused on suction dredging. With increased dredging, more material is uplifted into the water column with the potential to increase the turbidity, suspended sediment, and specific conductance levels. Suspended sediment more effectively absorbs thermal energy due to incoming solar radiation compared to water with 100 % clarity, transferring heat to the molecules of water and increasing temperature (Fondriest Environmental, Inc. [FEI], 2013). Temperature assesses the speed of molecules and is subsequently a measure of the kinetic energy and heat in an aquatic system. The amount of heat transferred between molecules is dependent on the amount present and is therefore also affected by turbidity levels. Conductivity and temperature are highly correlated and can cause daily fluctuations with varying temperature (FEI, 2013).

Dissolved oxygen was hypothesized to decrease following increased temperatures. Dissolved oxygen is a result of photosynthetic activity and mixing from the atmosphere, and is affected by external impacts including water temperature, the depth at which it is measured, season, temperature, hour of day, and turbulence. Turbidity and suspended sediment were expected to increase following dredging, increasing the temperature in the dredged reach. With increased temperature, dissolved oxygen is less soluble, and the resulting amount present is reduced (FEI, 2013). Finally, an increase in pH was hypothesized to occur during dredging. pH is a measurement of the present hydrogen ions in an aquatic system. With an increase in temperature a reduction of ions is known to occur, subsequently increasing pH levels (FEI, 2013). In addition, with increased photosynthetic activity typically observed with increased sunlight throughout the day, a subsequent increase in pH is hypothesized to occur.

Water quality monitoring during dredging within the Entiat River showed rivers of this size and substrate composition are able to sufficiently flush the system when flows are approximately 200 cfs; therefore regulating temperature, dissolved oxygen, specific conductance, turbidity, pH, and suspended sediment levels in a short distance from one suction dredge. When all measurements were analyzed statistically, dredging activity was not found to have a significant effect on water quality overall throughout the survey region. Few significant differences were present when all measurements were analyzed, showing alterations to habitat were minor and occurred over the short-term. Of the transects that showed altered measurements, similar levels were rarely seen in the following transect directly downstream showing impacts were localized to the sample site.

The majority of resulting levels did not show a clear trend of impact or direct association to dredging activity; all significant correlation values identified were not consistent throughout all hours during dredging, showing correlation was not likely associated with dredging. When the outfall just below the sluice was measured once during dredging on Day 2, no significant effects to water quality were captured from the discharge. Measured parameters directly within the discharge region included water temperature at 15.9 ℃ compared to the Dredge 2 profile temperature of 15.8 ℃, 9.62 mg/L dissolved oxygen compared to 9.59 mg/L at Dredge 2, 97.3 % percent dissolved oxygen saturation compared to 96.9 % at Dredge 2, 40.6 µg/cm for specific conductance compared to 40.6 µg/cm at Dredge 2, pH of 7.3 compared to 7.2 measured at Dredge 2, and a turbidity level of 0.2 NTU equal to Dredge 2. No suspended sediment sample was collected immediately below the dredge outfall. Parameters were similar to readings present at surrounding transects, showing no immediate alteration to water quality at this location.

Over the three survey days the weather was sunny and air temperatures ranged between lows of 70 °F and highs of 100 °F (National Weather Service [NWS], 2019). The control transect also experienced similar readings throughout the day to all other survey transects, confirming values were most likely a result of natural environmental conditions. All temperature readings showed an increasing trend throughout the day in survey transects with the highest measurements taken after the dredge was stopped. The Entiat River is known to have increased temperature throughout the day in late summer months when high insolation, low water flows, and high ambient air temperatures occur (CCCD, 2004). A study completed by the Washington Department of Ecology (WDOE) observed higher water temperatures in the Entiat River during summer and early fall months that typically exceeded designated water quality standards for the state of less than or equal to 17.5 ℃ set for salmonid habitat (Ehinger, 1994) (Table 21).

Table 18. State water quality standards for freshwater habitat including temperature, dissolved oxygen, pH, and turbidity along with the associated measured levels in the survey site within the Entiat River, Washington. Standards are set for salmonid spawning, rearing, and migration requirements.

Parameter	Measured Transect Range	Measured Below Dredge	State Standards
Temperature	14.4-19.8℃	15.9℃	<= 17.5℃
Dissolved Oxygen	7.87-10.22mg/L	9.62mg/L	>= 8.0mg/L
pH	6.2-7.8	7.3	pH within 6.5 to 8.5 with a human-caused variation of less than 0.5 units
Turbidity	0-3.6NTU	0.2NTU	Max 10 NTU over background levels in waters of 50NTU or less

Temperatures measured in the survey region ranged from 16.3-19.5 ℃ and typically exceeded state standards in the evening after dredging was completed. The specific study reach was previously assessed in 2002 by Archibald and Johnson who identified increases to river temperatures at river mile 20 between early August to September (Archibald and Johnson, 2002). Although the Entiat River is known to experience increased channel temperatures in the summer months, a groundwater aquifer was identified between river miles 21 to 16 composed of glacial till which has been shown to be a moderating influence on stream temperatures for the river reach (CCCD, 2004).

Proceedings following the 2008 Pacific Lamprey Conservation Initiative work session stated impacts of altered water temperature to egg development and emergence of larvae are currently unknown (Luzier et al., 2008). Previous studies performing trials in lab settings found water temperatures ranging from 10.0-18.0 °C showed the highest larval survival while temperatures at or above 22.0 °C contributed to higher levels of egg mortality and deformation of early stage ammocoetes (Meeuqig et al., 2005). Temperatures were shown to reach levels of 19.0 °C by the end of the day following dredging showing water temperatures reached slightly above the optimal level; however, dredging did not directly affect temperature.

Dissolved oxygen showed an overall reduction throughout the day with the lowest levels after dredging activity. Median values for all transects ranged between 8.90-9.90mg/L between all three survey days, showing values were still within the approved state standard minimum of 8.00 mg/L for Class A site water quality (CCCD, 2004). When dissolved oxygen was monitored between 1970s to 2000s at the WDOE Keystone site 46A070, located adjacent to the USGS 12452990 flow station located near Entiat, levels were shown to range between 8.50 mg/L to 17.00 mg/L (CCCD, 2004).

Dissolved oxygen within the experimental stretch was similar to the control levels and most likely not negatively impacted by dredging activity. A slight increase in dissolved oxygen actually occurred at sample sites closest to the dredge during dredging, showing short-term and localized effects. The large amount of hydraulic suction created in the dredged region mixed the water in which created turbulent conditions and subsequently increased the aeration, contributing to the localized increase in dissolved oxygen. Dissolved oxygen is known to fluctuate throughout the day and overnight due to external influences such as respiration of aquatic biota, chemical oxidation, air and water temperatures, dilution with other sources of low oxygenated water such as groundwater seeps, and climate (Brown and Hallock, 2009). The present groundwater aquifer identified in the survey area contributes inputs of low oxygenated water, potentially impacting the measured dissolved oxygen readings.

The impacts of low levels of dissolved oxygen and turbidity are unknown on mature lamprey (Luzier, 2011) although minimum dissolved oxygen levels for cold-water species were recommended by the Environmental Protection Agency (EPA) to be 11.0 mg/L as the average within the water column for no production impairment to embryos and larvae (Brown and Hallock, 2009). The lowest median values identified throughout all downstream transects were 9.77 mg/L before dredging, 9.20 mg/L during dredging, and 8.43 mg/L after dredging. These values were similar to the control transect that experienced median values of 9.72 mg/L pre-dredging, 8.90 mg/L during dredging, and 8.51 mg/L post-dredging and are therefore do not show a direct impact from dredging activity. Although measured levels did not reach the federally-set standard for no impairment, the majority of dissolved oxygen readings in the experimental reach measured above the slight production impairment standard of 9.00 mg/L, with the lowest measurements still above the standard for moderate production impairment at 8.00 mg/L

(EPA, 1986). Although minimum required dissolved oxygen levels are unknown, ammocoetes were found in Cedar Creek, Washington where the average percent saturation of dissolved oxygen in channel habitat was 83.0 % (Pirtle et al., 2003). Dissolved oxygen median concentrations ranged between 95.8-100.6 % over the three survey days, showing no direct impact to ammocoetes based on previous findings from Cedar Creek.

According to a 1994 study on the WDOE Keystone site between 1971-2003, pH levels in the Entiat River ranged between 6.5-8.5, and rarely exceeded 8.5 (Ehinger, 1994). Median pH levels in the experimental reach ranged between 7.1-7.4 throughout all three survey days and did not show a clear trend throughout the day. Previous data collected in 1998 by WDOE showed diurnal patterns in resulting pH levels with higher levels late in the afternoon at the time of highest insolation (CCCD, 2004). Although this general trend was not observed throughout the pH measurements, observed levels fell within the range previously observed in the Entiat River.

Specific conductance showed fluctuations with slightly higher medians during dredging that potentially resulted from the activity due to the disturbance of channel material; however, alterations were minor. No specific designated state standards were identified for specific conductance or suspended sediment. Turbidity data collected from the Keystone site showed short-term spikes were created infrequently within the Entiat with the most recorded elevated levels correlating with high flow events (CCCD, 2004). State water quality standards for salmonid spawning, rearing, and migration habitat limit the approved turbidity fluctuation to 10.0 NTU maximum in waters with 50.0 NTU or less (Brown and Hallock, 2009) (Table 21). In the survey reach, turbidity median values ranged from 0.1-0.36 NTU over the three survey days and did not show a clear trend throughout the survey periods. According to state standards, turbidity was not significantly affected by dredging activity during the study. Suspended solids measured at the Keystone sampling site similarly showed increased levels with high flows and natural events including fire (CCCD, 2004). Suspended sediment levels collected in the field downstream from dredging were low to absent with median weights ranging between 0-0.09 g. The Entiat River was able to efficiently dilute created suspension of particles in a short distance downstream from the dredge, showing negligible alterations to background levels of suspended solids and turbidity.

Because the most significant differences observed in parameters relative to pre-dredge measurements were present at the end of each survey day after dredging was completed, measured parameter levels were most likely due to other environmental conditions rather than dredging activity. Potential influences to water quality parameters include the amount of insolation, primary production, and biochemical oxygen demand occurring in the system, as well as effects of groundwater storage within the present aquifer. Overall, no significant, short-term alterations to water quality within the survey site occurred from dredging activity and were rather a result of external environmental conditions throughout the day.

Observed trends did not follow the initial assumption that dredging would have a significant impact to water quality in the Entiat River. Although sufficient dispersion occurred in the Entiat and no significant alterations to water quality were identified from dredging activity, similar-sized rivers with larger proportions of fine sediment have greater potential to significantly increase turbidity and suspended sediment through sediment plumes and should be further monitored for effects to water quality to attain a comprehensive impact of dredging to state-owned aquatic land.

Alterations to Channel Morphology

All transects experienced varying levels of alterations to both the vertical channel profiles and sediment composition following dredging. Natural variation between surveys was captured at the control transect profile and was taken into account when assessing the surveyed profiles.

Large-Scale Morphological Effects to Channel Habitat

Effects to the channel bed captured along the topographic profiles varied based on the amount of dredging that directly occurred along the transect. Within transects that were directly dredged, large amounts of scour and loss of channel substrate were observed to occur over a relatively short amount of time. The Dredge 1A and Dredge 2 transects were representative of large-scale alterations to the channel bed when the site experienced direct dredging activity. Dredge holes with maximum depths of 0.2m for Dredge 1A and 0.3m for Dredge 2 were created directly along the transect, showing large reductions of material from the channel. This observed reduction in channel material can have a significant impact to lamprey habitat. When spawning, adults target low gradient gravel reaches typically present within the tailouts of riffles and pools (Pletcher, 1963; Mattson, 1949; Kan, 1975). When the channel and flow is physically altered through the creation of dredge holes and tailings piles, habitat is directly affected. Although lamprey ammocoetes typically develop in the downstream end of pools (USFWS, 2011; Stone, 2006; Moser et. al., 2007; USDA, 2016), the dredge holes were found to experience a significant increase in unstable coarse material unfavorable to lamprey as seen in the holes created directly along the Dredge 1A and Dredge 2 transects.

Dredge 1 and 3 transects did not experience dredging directly along the established cross-section and therefore did not show large changes to the channel bed. No significant accumulations of discharged sediment occurred along these transects from dredging activity, showing water flow was not sufficient to transport large amounts of coarse tailings this distance downstream in the seven days between dredging and when the profiles were re-mapped (Figures 49 and 55).

When a large amount of material is moved during dredging, it is common for the flows to be altered in the aquatic system. Pacific lamprey prefer reaches with stable water flows that experience changes over days rather than hours (Brostrom et al., 2010). During dredging, flows can be altered in a short time period by the alteration to the channel bed, reducing preferred habitat conditions. In addition, although operators are required to avoid any identified spawning habitat, it is often difficult for an untrained individual to identify lamprey redds when surveying directly in the region to be dredged as well as downstream regions, increasing the likelihood of detrimental impacts. Lamprey redds are smaller and lack the tailspill that is present in salmonid redds created through redd formation, decreasing the ability to distinguish them in a river system (Crandall and Wittenbach, 2015).

In addition to the potential for direct disturbance of redd habitat, impacts can occur through smothering and burial of downstream nests from tailings material. Although profiles did not show large amounts of aggradation from upstream dredging, tailings piles had ‘tails’ of material dispersed by size through stream flow with the potential to cover sensitive habitat immediately downstream. Tails averaged 5.44 m after dredging and significantly increased the potential footprint of dredging activity.

In addition, the piles experienced high rates of erosion and transport post-dredging with the potential to increase lamprey egg mortality downstream. If adult lamprey utilized this material or nearby regions for redd creation, higher rates of eroded redds are likely from loose material or sediment burial. Finally, although ammocoetes prefer fine material for rearing, small larvae have been found in large gravel-cobble streams (Luzier, 2008) and are therefore also at risk of entrainment or burial.

Small-Scale Morphological Effects

Changes to the grainsize distribution were largely dependent on the amount of dredging that occurred directly at or upstream from a survey location. Because dredging did not occur directly along the Dredge 1 and Dredge 3 profiles, alterations to sediment distribution are important to determine any significant settling of fine material or other small-scale alterations from upstream dredging activity. Wolman pebble counts along the Dredge 1 transect showed a 30 % reduction in cobbles as well as a 32 % increase in pebble material at the middle of the channel where multiple tailings piles were located just upstream (Figure 39). This coincides with dredging activity as pebble count datasets were collected at a range of 6 m around the exact transect, likely collecting more tailings pile substrate and therefore a potentially more comprehensive sample of distribution change to the surrounding area. A reduction in cobbles and an increase in pebble material along the transect shows grainsizes similar to preferred spawning habitat; however, the increase in loose tailings material significantly increases the potential for any redds created in the piles by local lamprey populations to be washed downstream.

Coinciding with profile data, the Dredge 3 Wolman pebble count showed the least amount of impact out of all three dredging transects (Figure 39). The same categories of cobble and pebble material were present with slight variances between proportions. The pebble count dataset collected at this transect shows minimal change supporting the fact that dredging did not occur directly along the transect; however, when bulk sediment samples were collected and analyzed alterations to composition were more apparent. The Dredge 3 transect on average experienced a 25 % reduction in cobbles, a 3% reduction in pebbles as well as a 3 % increase in granules and a 9 % increase of fine material present, showing a potential settling of fine sediment from tailings created from upstream dredging on Day 3 (Figure 41). Water depths were deeper at Dredge 3 when compared to the Dredge 1 transect, allowing sediment to travel farther without obstruction from channel features.

In contrast, where transects experienced direct dredging, an overall coarsening of channel substrate was observed. Coinciding with the dredging that occurred along the Dredge 1A transect, grainsize distributions showed an average 37 % increase in cobbles, 26 % increase in pebbles, 1 % increase in granules and a 2% reduction of fine grains after dredging (Figure 43). This pairs with the profile data as more dredging occurred directly on this transect, uplifting large amounts of material, and removing it from the channel bed to create artificial holes. When these areas were dredged, a larger amount of fine and intermediate-sized material was uplifted and removed from the bed using the dredge equipment, while coarser material was either removed by hand due to the limit of the vacuum hose diameter, or remained in the channel. Decreased pebble material and increased cobbles observed along this transect shows the direct reduction of preferred habitat for adult Pacific lamprey to create redds at this location.

Similarly, for Dredge 2 a 12 % increase of cobbles was identified at the 50 % channel width which was directly dredged, along with a 20 % reduction in fine material (Figure 42). In contrast, there was a 70 % reduction in pebble material, a 16 % increase in granules and a 53 % increase in fine material at the 75 % channel width sample location. Observed alterations to grainsize distributions are associated with dredging that was completed on Day 2 directly at the transect near the 50 % channel width sample location as well as a large amount of dredging approximately 15ft upstream of the transect near the 75 % channel width sample location. Dredging occurred directly at the 50 % channel width mark which uplifted and removed the majority of fine material, leaving an increased proportion of cobbles and pebble. A large amount of dredging was present upstream of the 75 % channel mark, coinciding with the large amount of fine material that was transported downstream and observed in the sediment sample. Observed increases in both coarse and fine data coincided with the dredging activity since holes created directly along the profile were likely to experience a coarsening of material due to the removal of fine substrate from the channel bed, while increases in fine sediment were most likely due to created upstream holes on Days 2 and 3. Wolman pebble count data in this region shows a reduction in cobbles as well as an increase in both pebbles and fine material within the 6m buffer along the Dredge 2 transect (Figure 39). When looking at changes to composition at the Dredge 2 location, increases to coarse cobble material at the point of dredging as well as fine material additions downstream of dredging reduces the availability of preferred substrate for spawning as well as increases the probability of burial by fine sediment accumulation.

Pacific lamprey redds were previously identified directly upstream and downstream of the survey region through USFWS surveys, confirming the use of appropriate substrates sizes within the survey area (Grote, A., USFWS; pers. comm., 2018). Although sediment sample distributions before and after dredging were similar, the majority of sediment samples collected in the dredged region increased in either coarse or fine material dependent on the location of the sample collection to dredging activity. This alteration could lead to a reduction in preferred spawning grain size by removing easily transported material utilized by lamprey and instead leaving coarse material difficult to effectively construct redd habitat. In addition, increases in fine sediment proportions can cause detrimental effects to present spawners within the region. Pacific lamprey spawn in the interstitial spaces within gravel material (Crandall and Wittenbach, 2015), increasing the susceptibility of eggs to smothering from increased fine material settlement. Similar to spawn from salmonids, lamprey egg survival is largely dependent on sufficient flows of oxygenated water over sediment without high levels of fine material or organic matter (USDA, 2011). Fish habitat in the Entiat River was identified as having a high susceptibility to suffering an adverse effect from fine sediment deposition through embedding substrate and suffocating redds (Andonaegui, 1999). Although dredging specifically in the experimental reach of the Entiat River did not create large swaths of fine sediment plumes seen in other rivers, even minor changes within each grain size category could have a detrimental effect on Pacific lamprey through the reduction of preferred spawning and rearing habitat, or through burial by discharged substrate.

Channel Bed Recovery Rates

When looking at the amount of recovery that occurred two months following dredging, the October profiles showed low amounts of restoration had occurred since the initial post-dredging mapping in August. The portions of artificially created dredge holes captured along the Dredge 1A and Dredge 2 transects still remained after two months with no significant difference in size, some locations even experiencing further erosion. Water flows continued to decrease throughout the two-month timeframe from approximately 200 cfs in August to 70 cfs in early October with minor variations between timeframes reducing the amount of sediment that could be transported and settled within the pool (USGS, 2018). Alterations were also observed at profiles that did not experience direct dredging. At the Dredge 1 profile, small amounts of aggradation occurred along the transect when resurveyed two months later, potentially as a result from the transport of upstream tailings downriver.

When features were re-measured two-months following dredging, all tailings piles experienced some reduction in material. By October, the total amount of material remaining was reduced in surface area by 51 % and reduced in volume by 55.4 %. Tailings piles are composed of loose, non-compacted substrate material that is easily eroded in water flows and therefore experiences high rates of erosion. All dredge holes also experienced a reduction in surface area, although the identified holes experienced a slower rate of recovery than observed in the tailings with a total surface area reduction of 23.2 %. Total volume increased over the two-month time period, showing additional scour following dredging rather than recovery. Because the created holes are of significant size and the amount of material being transported in the water column from upstream sources is most likely present at a low capacity in summer, the amount of deposition is occurring at a slower rate than the erosion seen at the loose tailings piles. Although some recovery was shown to be occurring within the two-month timeframe for the measured tailings piles, the amount of displaced material was considerable and takes a sufficient amount of time and higher flows to return to natural conditions.

When profiles were re-measured 11 months following dredging activity after spring snowmelts occurred, negligible recovery was observed at dredged transects. Dredge 3, Dredge 2, and the Dredge 1A transects experienced continued erosion along the channel. Although all tailings piles were washed downstream, dredge holes were still remaining following the snowmelt and showed lower amounts of restoration over winter months. Between October 2018-July 2019 flows ranged from 50-1800 cfs with the highest flows occurring between April and June following spring snowmelt. Even with high flows dredge holes still remained the following year, showing storm flows and snowmelts are insufficient to restore the channel bed.

When dredging is allowed to occur immediately before or during lamprey spawning before a complete restoration and dilution of loose material is complete, a large amount of tailings material is still present for redd construction. This loose material has a high probability of being washed downstream, reducing the survival rate of lamprey spawn. Even when rules outlined in the Gold and Fish pamphlet are properly followed and tailings are levelled, a large amount of imbricated material is still present that poses the risk for redd loss.

Other Significant Effects to Preferred Lamprey

Impacts to lamprey can occur through multiple causes when dredging is allowed within critical habitat. Significant impacts to side channel habitat were observed during the transport of equipment by people over multiple trips, contributing a large amount of disturbance to the channel. In addition, although smaller amounts of fine material were present directly in the dredged region of the Entiat River, fine substrate habitat was present along portions of the channel banks, side channels, below boulders and within pool tailout regions. Presence of lamprey larvae have been documented in pockets of low velocity below boulders (Cochnauer et al., 2006). Although fine material is not the primary focus for dredging, it can be present in regions where gold is thought to settle including low-velocity pools, downstream of channel obstructions, and depositional point bars. This habitat is also utilized by juvenile lamprey and shows significant overlap between ammocoete rearing habitat and dredging activity that can occur.

Cumulative Effects

Spatial Effects. When the amount of material displaced from the Entiat River was multiplied to mimic effects from multiple dredges, impacts to the area of channel habitat are greatly increased. The average hours spent dredging per day over the three survey days was determined to be 4.5 hours. By multiplying the average amount of material disturbed per hour in the Entiat River for one 5" suction dredge by 4.5 hours, an average amount of substrate moved per day for one dredge is attained. When this value is multiplied by the amount of dredges present in a system, a much larger amount of material is shown to be potentially displaced in a river system this size per day (Table 22).

Table 19. Estimated regions of disturbance in surface area and volume from created tailings piles (left) and dredge holes (right) using the average daily amount moved for a single 5" suction dredge based on an average dredging day of 4.5 hours as a multiplier of impact. Estimates for a single suction dredge were attained in the Entiat River between July 30th – August 1st, 2019.

Number of Dredges	Potential surface area displaced per day (m^2)	Potential volume displaced per day (m^3)	Potential surface area displaced per day (m^2)	Potential volume displaced per day (m^3)
1	29.35	6.34	33.32	9.35
2	58.71	12.68	66.64	18.70
3	88.06	19.01	99.96	28.05
4	117.41	25.35	133.28	37.40
5	146.76	31.69	166.60	46.75

*Values based on averaged values from all three survey days

Amounts of disturbed material from multiple dredges are more representative of impacts to channel habitat following group dredging activities and is a common occurrence within mining clubs and associations. Variance of disturbed surface area and volume amounts can occur depending on the dredging technique being employed such as if sampling is occurring to find a paystreak, or if one has already been identified and production dredging is occurring. When searching for a paystreak, operators will create multiple small sample holes to identify a productive region (McCracken, 2006). Once a paystreak is located, miners will focus directly on reaching the area most productive between sediment layers, especially at the bedrock. This technique creates larger dredge holes and tailings piles that are worked downward toward bedrock as well as upstream (Harris, 1993; McCracken, 2013). In addition, this is a minimum representation of group dredging based on data collected in the Entiat River, and the area impacted is dependent on the number of dredges being utilized at a time. When this amount of material is disrupted over multiple days with low rates of recovery, alterations to the channel system are likely to be significant.

Temporal Effects. When dredging is allowed to occur directly during or after lamprey spawning, large amounts of critical habitat is at risk of direct destruction from dredging. The Gold and Fish approved dredging window in this section of the Entiat is allowed for two weeks between July 16th and 31st every year. Pacific lamprey are known to spawn in this region of the Columbia River Basin between June and July (Wydoski and Whitney, 1979) and occurs approximately over a two week timeframe depending on environmental conditions. Pacific lamprey redds have been known to create redds in similar locations, often with multiple age classes in the same site. Once eggs hatch, pro-larvae will spend up to 15 days further residing in the redd before they drift downstream to find suitable rearing habitat (Crandall and Wittenbach, 2015). These timeframes leave a significant amount of overlap possible between dredging and sensitive lamprey life stages of eggs and larvae.

Although the Entiat River experiences a more restricted mining timeframe and less dredging activity overall, this system should be used as a proxy for other state-owned aquatic land with longer approved dredging durations and critical lamprey habitat. Many claims are controlled by mining clubs that allow access to members that visit the same general region every year. Sites are commonly dredged over multiple days in one trip and multiple trips occur throughout a mining season. Due to the high intensity of mining activity that occurs within similar locations every year, the likelihood of long-term effects to channel habitat increases. Pacific lamprey spawn throughout the Columbia River and its tributaries between March and July, which overlaps with many allowed mining timeframes. Lamprey are known to use spawning grounds with high ammocoete concentrations due to chemical compounds released by larvae (Crandall and Wittenbach, 2015). Effects to sediment compositions showed slight change in material after just three days of dredging in the Entiat survey site that was previously not dredged. If a reach is permitted to be dredged annually at the same location with multiple dredges, the potential for a larger alteration in sediment composition is greater over time, affecting the preferred habitat previously used by local lamprey populations.

Future Research

Although no significant detrimental effects to water quality were seen during dredging in the Entiat River, it is essential to conduct further primary research in rivers of varying sediment compositions. Sediment plumes created in the Entiat River were small and had less of an impact than initially hypothesized during the dredging experiment; however, practicing with the dredge in the approved timeframe within the Little Naches River created large sediment plumes that were observed to drift a significant distance downstream until dispersed. Due to the large amount of previously studied systems that experienced detrimental impacts from plumes during dredging, it is important to look at rivers of similar size to the Entiat with varying compositions to attain a comprehensive impact review.

In addition, it is important to look further into the effects of multiple dredges within a region. Due to the current regulatory adjustments in Washington state around suction dredging, it was unfeasible to observe multiple dredges and operators from local mining clubs for the study. Although the amount of material moved from one dredge was utilized as a multiplier for cumulative effects, it is important to monitor directly in the field downstream impacts from multiple dredges operating at once to attain direct effects. It would also be pertinent to take findings of footprints of disturbed areas from this analysis and adjust them according to various manuals for different sized dredges according to how much material can be moved in one hour to determine potential area impacted from dredges of multiple sizes. Finally, it is essential to perform further research identifying the amount of reworking of the channel bed that occurs in dredged aquatic systems of varying size following winter storms and snowmelt. The amount of recovery that naturally occurs is important to identify the resulting long-term effects to a system.

Management Recommendations

Based on collected data, it is recommended that agencies responsible for each aquatic system with documented presence of Pacific lamprey perform monthly lamprey spawner surveys within the months of April through July in the Columbia River Basin to attain a more robust dataset which exact reaches are currently or historically used by Pacific lamprey. Information on lamprey populations is less known in comparison to other sensitive cold-water species, although they are vital to the success of at-risk species such as salmonids. In order to provide appropriate protection, a complete and thorough spatial dataset is required.

In addition, it is recommended that dredging be restricted from any previously documented sensitive Pacific Lamprey spawning habitat within the Columbia River Basin between the first and last months observed in surveys and for one month after the last observance. The restriction of one extra month following spawning activity would account for any present eggs or pro-larvae still present in the redds. As novice dredge operators, large amounts of material were still able to be moved within the Entiat River survey site. Even when dredging occurs in the most conservative manner, redd habitat is difficult to identify to the untrained eye and impacts can occur unknowingly. This same template of monthly spawner surveys and increased restrictions can further be applied to all aquatic systems throughout the state with documented Pacific lamprey based on local spawn timeframes.

Finally, it is recommended that dredge operators are required to state exact coordinates of locations to be dredged in order for a more accurate inventory of dredging activity occurring in Washington State. Many current HPA applications state general locations making inventory of mined regions difficult as well as reducing the ability to appropriately enforce dredging activities.

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APPENDIXES

Appendix A. Significant differences in temperature (°C) [median (IQR)] between all three timeframes at each surveyed transect for individual and combined survey days (Kruskal Wallis, $p < 0.05$).

Transect	Survey Day	Total Pre-Dredge	Total During	Total Post Dredge
Control	Day 1	14.7 (0.2)	17.9 (0.8)	19.1 (0.1)
	Day 2	15.1 (0.2)	16.7 (2.6)	19.4 (0.0)
	Day 3	15.8 (0.1)	16.3 (0.1)	17.7 (0.1)
	All Days	15.1 (1.05)	17.15 (1.9)	19.1 (1.7)
D3	Day 3	15.6 (0.1)	16.2 (0.1)	17.6 (0.0)
	All Days	15.6 (0.1)	16.2 (0.1)	17.6 (0.0)
D2	Day 2	14.9 (0.1)	16.2 (2.8)	19.4 (0.0)
	Day 3	15.6 (0.1)	16.2 (0.1)	17.6 (0.0)
	All Days	15.25 (0.7)	16.3 (2.0)	18.55 (1.7)
D1	Day 1	14.5 (0.1)	17.7 (0.9)	19.3 (0.5)
	Day 2	15 (0.2)	16.4 (2.9)	19.5 (0.1)
	Day 3	15.6 (0.1)	16.4 (0.0)	17.7 (0.1)
	All Days	15 (1.1)	16.85 (1.7)	19.3 (1.8)
F	Day 1	14.5 (0.1)	17.85 (0.8)	19.4 (0.2)
	Day 2	14.8 (0.3)	16.6 (3.0)	19.6 (0.3)
	Day 3	15.8 (0.0)	16.3 (0.1)	17.8 (0.2)
	All Days	14.8 (1.3)	16.95 (1.8)	19.4 (1.7)
D	Day 1	14.7 (0.3)	17.75 (1.3)	19.2 (0.1)
	Day 2	15.1 (0.1)	16.3 (2.7)	19.4 (0)
	Day 3	15.8 (0.1)	16.3 (0.1)	19.2 (0.1)
	All Days	15.1 (1.0)	16.8 (2.1)	19.2 (1.7)
C	Day 1	14.7 (1.4)	17.9 (0.6)	19.4 (0.5)
	Day 2	15.1 (0.1)	16.5 (2.7)	19.5 (0.1)
	Day 3	15.8 (0.0)	16.3 (0.1)	19.4 (0.5)
	All Days	15.1 (1.0)	17.07 (2.0)	19.4 (1.7)
A	Day 1	14.6 (0.4)	17.9 (1.1)	19.2 (0.1)
	Day 2	14.8 (0.3)	16.6 (2.6)	19.4 (0)
	Day 3	15.8 (0.1)	16.3 (0.1)	19.2 (0.1)
	All Days	14.9 (1.1)	17.05 (2.2)	19.2 (1.6)

Appendix B. Significant differences in dissolved oxygen (mg/L) [median (IQR)] levels between all timeframes at each surveyed transect for individual and combined survey days (Kruskal Wallis, $p < 0.05$).

Transect	Survey Day	Total Pre-Dredge	Total During	Total Post Dredge
Control	Day 1	9.72 (0.08)	8.91 (0.60)	8.51 (0.13)
	Day 2	10.06 (0.14)	9.36 (0.38)	8.89 (0.26)
	All Days	9.9 (0.33)	9.26 (0.39)	8.89 (1.08)
D3	Day 3	9.78 (0.03)	9.83 (0.1)	9.7 (0.12)
	All Days	9.78 (0.03)	9.83 (0.1)	9.7 (0.12)
D2	Day 2	9.8 (0.27)	9.62 (0.34)	9.285 (0.74)
	Day 3	9.77 (0.03)	9.74 (0.04)	9.67 (0.09)
	All Days	9.8 (0.27)	9.62 (0.34)	9.285 (0.74)
D1	Day 1	9.83 (0.1)	9.195 (0.19)	8.83 (0.38)
	Day 2	10.02 (0.27)	9.62 (0.62)	8.99 (0.14)
	All Days	9.87 (0.19)	9.395 (0.53)	8.99 (0.73)
F	Day 1	9.87 (0.22)	8.88 (1.04)	8.43 (0.41)
	Day 2	9.97 (0.15)	9.49 (0.28)	9 (0.31)
	All Days	9.87 (0.24)	9.445 (0.72)	9 (1.1)
D	Day 1	9.97 (0.53)	8.865 (0.25)	8.46 (0.02)
	Day 2	10.03 (0.35)	9.62 (0.47)	9.08 (0.12)
	All Days	9.97 (0.82)	9.425 (0.82)	9.08 (1.09)
C	Day 2	9.97 (0.28)	9.44 (0.39)	8.74 (0.51)
	All Days	9.93 (0.28)	9.52 (0.61)	9.03 (0.66)
A	Day 2	10.01 (0.22)	9.56 (0.37)	8.91 (0.23)
	All Days	9.79 (0.25)	9.57 (0.55)	8.91 (0.42)

Appendix C. Significant differences in dissolved oxygen (%) [median (IQR)] between all timeframes at each surveyed transect for individual and combined survey days (Kruskal Wallis, $p < 0.05$).

Transect	Survey Day	Total Pre-Dredge	Total During	Total Post Dredge
Control	Day 2	100.7 (2.4)	97.8 (3.1)	97 (2.8)
D3	Day 3	98.4 (0.3)	100.2 (0.7)	101.7 (0.8)
D2	Day 3	98.2 (0.3)	99.4 (0.3)	101.2 (0.9)
F	Day 1	96.4 (2.9)	91.3 (3.6)	91.2 (4.5)
A	Day 2	98.7 (1.4)	98.2 (1.2)	96.6 (2.5)
	Day 3	99.6 (2.0)	100.6 (0.7)	96.1 (2.7)
	All Days	98.3 (3.7)	98.5 (2.9)	95.8 (3.1)

Appendix E. Significant differences in specific conductance (μS) [median (IQR)] between all timeframes at each surveyed transect for individual and combined survey days (Kruskal Wallis, p <0.05).

Transect	Survey Day	Total Pre-Dredge	Total During	Total Post Dredge
Control	Day 1	40.5 (0.3)	40.2 (2.1)	39.8 (0.1)
	Day 2	38.9 (0.2)	40.5 (0.6)	40.7 (0.1)
D3	Day 3	40.7 (0.2)	40.7 (0.1)	40.0 (0.0)
D2	Day 2	38.9 (0.1)	40.6 (0.1)	40.7 (0.0)
	Day 3	40.7 (0)	40.6 (0.1)	40.0 (0.0)
D1	Day 2	38.8 (2.3)	40.5 (1.8)	40.6 (0.1)
F	Day 1	39.8 (0.1)	39.6 (0.1)	39.8 (0.2)
	Day 2	38.8 (0.3)	40.5 (0.2)	40.7 (0.1)
D	Day 3	40.2 (0.1)	40.1 (0)	40.6 (0.1)
C	Day 2	40.0 (0.1)	39.9 (0.1)	40.1 (0.0)
	Day 3	40.1 (0.0)	40.2 (0.1)	40.5 (0.1)
A	Day 3	40.1 (0.1)	40.1 (0.1)	40.5 (0.1)

Appendix F. Significant correlation values between specific conductance (μS) and distance from dredging activity [median (IQR)] (Spearman Rank, p <0.05).

Day 1	
9:30am	NS
1:00pm	-0.76
2:00pm	NS
4:30pm	NS
Day 2	
9:00am	NS
11:00am	NS
12:00pm	NS
2:30pm	NS
4:00pm	-0.71

Day 3	
9:30am	-0.86
11:00am	-0.72
1:00pm	0.59

*'NS' = Not significant

Appendix G. Significant differences in turbidity (NTU) [median (IQR)] between all timeframes at each surveyed transect for individual and combined survey days (Kruskal Wallis, p <0.05).

Transect	Survey Day	Total Pre-Dredge	Total During	Total Post Dredge
Control	Day 1	0.10 (0.10)	0.10 (0.10)	0.28 (0.08)
	Day 2	0.20 (0.10)	0.30 (0.00)	0.15 (0.06)
	All Days	0.30 (0.18)	0.20 (0.11)	0.28 (0.19)
D	Day 1	0.10 (0.30)	0.00 (0.10)	0.24 (0.13)
	Day 2	0.30 (0.10)	0.30 (0.10)	0.00 (0.10)