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Effective Mitigation of Sedimentation on Riparian Riverbeds and Salmonid Populations After Dam Removal

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Effective Mitigation of Sedimentation on Riparian Riverbeds and Salmonid Populations After Dam Removal

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Chapter 1 – Introduction

Humans have altered riparian ecosystems for decades, from river diversion to the deforestation of riparian forests. These alterations are typical and have occurred throughout history, however; in recent years it has been found that altering riparian ecosystems degrades its health. One of the greatest degradation to the health of a riparian ecosystem is from the building of dams (Nilsson and Svedmark 2002).

Dams are detrimental to the health of riparian ecosystems by preventing longitudinal connectivity. Longitudinal connectivity is when a river is able to flow freely from the upper watershed to the lower watershed. Riparian ecosystems rely on longitudinal connectivity of their rivers to maintain a healthy ecosystem. In healthy riparian ecosystems; water, nutrients, sediment, and riverine species are able to move freely within the connectivity. However, dams block downstream flow of water, nutrients, and sediment and blocks the upstream movement of riverine species.

By preventing longitudinal connectivity, dams cause many negative impacts to the riparian ecosystem and native species (Marchetti and Moyle 2001). Dams affect the environment by affecting sediment, energy of water, water flow, water temperature, and blocking the movement of plants and animals up and downstream (Figure 1). Dams cause a buildup of sediment behind the dam that prevents sediment from reaching a river's mouth and increasing land mass. Two dams on the Elwha River in Washington State have caused beach and shoreline erosion, by blocking downstream transfer of sediment to its shoreline (Bednarek 2001).

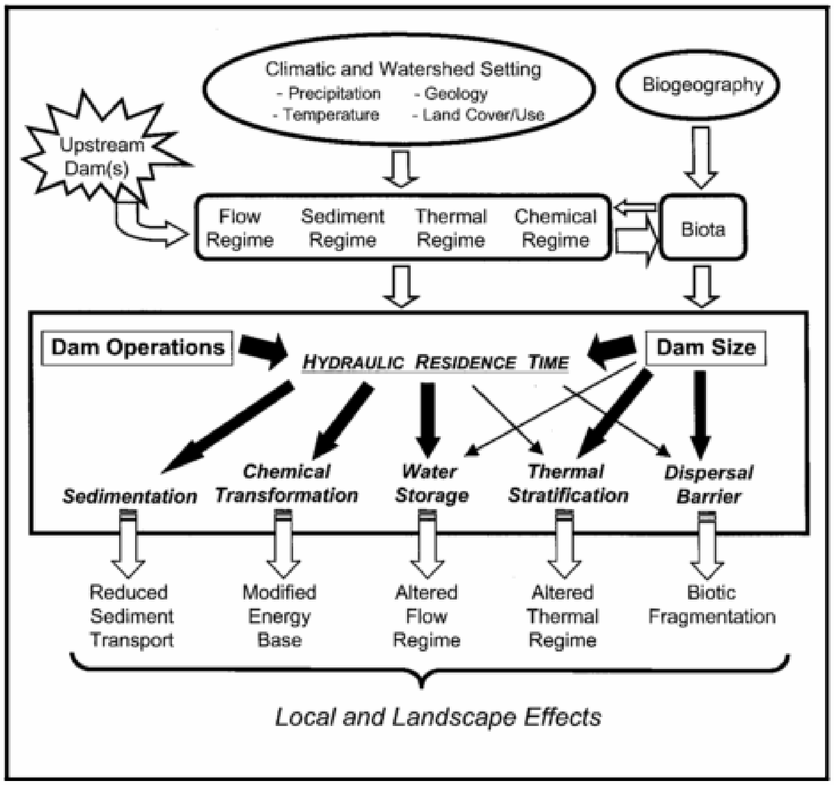

Figure 1. Local and Landscape Effects of Dams. The effects of dam size and dam operations to the riparian ecosystem (Poff and Hart 2002).

Dams block water from flowing downstream, which cause tributaries to experience decreased flows and result in smaller riparian ecosystems and increased water temperatures (Poff and Hart 2002). Plants and animals rely on the longitudinal connectivity of rivers to maintain their populations. Many dams interrupt fish migration by stopping movement up and downstream and prevent anadromous fish species from reaching spawning habitat above dams (Norrgård et al. 2012; Brown et al. 2013). In California alone dams have blocked the passage of salmonids from reaching historical locations by 45% (Quiñones et al. 2014).

Even though dams prevent riparian habitat from maintaining a healthy ecosystem; dams continue to benefit humans by storing potable water and providing hydroelectricity. In fact the majority of the tributaries in the United States contain at least one dam, even though many of these dams are small (less than 5 m) in disarray and are unproductive.

Since most of the dams within the United States are in disarray and are unproductive there are a variety of policies that are promoting dam removals to increase riparian ecosystem health. In 2014 there were 12 dams removed from California alone (American Rivers 2014). Dam removals can increase the survival of anadromous fish species by increasing spawning and rearing habitats that were previously blocked by dams (Lenhart 2003). After removal of the Wollen Mills Dam in Wisconsin, there was a decrease in invasive species that were well suited to slow moving river conditions, and a return of native species (Bednarek 2001). However, the removal of dams may also result in unintended negative effects.

The following sections discuss policies increasing the number of dam removal projects, effects of dam removal on riparian ecosystem, and sedimentation effects on riverbed structure and salmonids.

1.1 Polices Increasing Dam Removal

There has been a variety of policies and programs that contributed to the increasing number of dams being removed within the United States. These policies have focused on the decreasing structural integrity of dams and the potential for increasing endangered species habitat. The three policies that have increased the rate of dam removal are the National Dam Safety Program, the Hydropower Re-licensing Program, and the Endangered Species Act.

1.1.1 National Dam Safety Program

The National Dam Safety Program (NDSP) was created to prevent dam failures throughout the United States. There have been a number of dam failures within the United States that have caused death, environmental damage, and property damage. The NDSP was put into effect to protect life and property from dam failures.

The NDSP allows both the federal government and individual states the right to conduct unannounced dam inspections to ensure the structural safety of dams (Bowmen 2002; Scoones 2012). If a dam is considered unsafe, after inspection, the dam owner must address the issue by either fixing or removing the dam (Bowmen 2002). In many cases; the cost for repairing a dam's structural integrity outweighs the cost for dam removal; therefore, dam owners often opt for dam removal.

1.1.2 Hydropower Dam Relicensing Program

The Hydropower Dam Relicensing Program (HDRP) was created through the Federal Power Act. The Federal Power Act is an act where the federal government assumed authority over hydropower dams that previously were overseen by individual states. The Federal Power Act authorizes the federal government to regulate hydropower projects on navigable streams, United States public lands, and federally owned and operated dams. The Act also created the Federal Energy Regulatory Commission (FERC) to regulate hydropower dams.

Under the FERC, a dam must reapply for a hydropower operating license every 30 to 50 years (Scoones 2012). When a hydropower plant re-applies for a license the FERC will identify if the hydropower plant is within the public interest by comparison of the benefits of power production with river benefits (Scoones 2012). If it is found that the dam is no longer profitable, the dam is slated for decommission and removal.

1.1.3 Endangered Species Act

The federal Endangered Species Act (ESA) is a policy that has the potential to remove dams, but it has yet to be used to require a dam removal (Bowmen 2002). The policy has caused legislatures to consider the removal of dams based on the survival and/or recovery of listed species (either threatened, endangered, or critically endangered species) and has pushed land owners to remove dams because of the ramifications under ESA (Bowmen 2002; Scoones 2012). There are three sections of the ESA that have the potential to remove dams; Section 4, Section 7, and Section 9.

Section 7 and Section 9 of the ESA can force the removal of dams through destruction of a listed species' critical habitat. Section 7 states that a federal entity cannot destroy or modify an endangered species critical habitat or prevent the survival of the species (Salzman and Thompson 2003). Under Section 7 a federally owned dam that is preventing or will prevent the survival and/or recovery of a listed species can be slated for removal based on that fact (Salzman and Thompson 2003). Section 9 is essentially the same as Section 7, although Section 9 considers dams that are privately owned that are preventing or will prevent the survival and/or recovery of a listed species (Salzman and Thompson 2003).

1.2 Effects of Dam Removal on Riparian Ecosystems

There are an increasing number of dams being removed throughout the United States, but with increasing concerns over how dam removal projects are affecting the riparian systems (Sawaske and Freyberg 2012). Dam removal projects are a new science and have only increased in popularity since the 1980's. The current state of research is limited by the number of published studies that monitor the state of the riparian ecosystem before and after dam removals. However; there are an increasing number of studies that are focused on monitoring riparian ecosystems riverine systems after dam removal. Monitoring of dam removal projects is critical in the determination of how dam removals are affecting the riparian ecosystem and ensure that dam removal is not only increasing longitudinal connectivity but having a positive effect on the environment.

Dam removal projects can affect the riparian ecosystem in positive and negative ways by allowing up and downstream movement of plants and animals. Dam removals also reestablish regular water flows that signal salmonids to return to spawning grounds and produce eggs (CA DFG 2003). Along with positive effects from dam removals there also comes negative effects; for example, the redistribution of sediment and contaminants that have been blocked behind the dam for decades. Contaminants and sediment from years of run-off can be re-disturbed into a river in larger quantities than normal and can result in toxicity to species and their habitat (Sloan et al. 2005). The remainder of this section provides an overview of the different effects of dam removals, specifically focusing on the effects of water flow, contaminants, and sedimentation.

1.2.1 Regular Flow of Water

When a dam is built water does not flow in a normal water pattern. Depending on where the dam is, precipitation and snow melt events cause the normal flow of water of rivers. In California there is an increase in river flow during the winter and spring with a decrease in flow during the summer and fall. In extreme cases, a dam stops water from flowing downstream and causes the streams and rivers downstream to decrease in water volume. Below the dam, the decrease in water flow no longer supports a thriving riparian ecosystem that relies on water.

On tributaries that contain endangered salmon there are policies in place that require certain water flows to have enough water to support fish populations (Bradford et al. 2011). When dams are removed water is no longer stored behind a dam and is allowed to flow freely downstream, thus downstream habitat is no longer water deprived and can return to natural conditions over time.

1.2.2 Contaminants

One of the issues with dam removal is the buildup of organic and inorganic contaminants behind a dam. Contaminated natural run-off from terrestrial areas during storm events eventually gets funneled into a river. The presence of a dam blocks contaminants from moving down a river's tributaries. What may be a minimal amount of contaminates during storm events a dam removal can amplify the amount of contaminant load.

Examples of contaminants that negatively affect water quality and aquatic species are polychlorinated biphenyls (PCBs), mercury, phosphorus, and nitrates. Overtime contaminates can build up behind a dam and certain contaminants such as PCBs can sink to the bottom of a reservoir and contaminate sediment at the bottom of the dam.

The removal of the Fort Edward's dam on the Hudson River released sediment that was contaminated with PCBs and released it into the watershed. The release and deposition of contaminated sediment downstream caused sites to require cleaned up by the United States federal government (Sloan et al. 2005). Other contaminates, that can decrease the health of riparian ecosystems include nitrogen and phosphorus from agricultural runoff that can increase eutrophication issues and lead to dead zones after dam removals (Riggsbee et al. 2012).

1.2.3 Sedimentation

Dam removal reestablishes the natural movement of sediment flow from the upper watershed downstream into estuaries, however; the extensive sediment load after dam removal can have detrimental effects on a river or tributary's structure and aquatic species (Naiman et al. 2005). Large sediment releases changes a riverbed's structure in a short period of time and degrades habitat for aquatic species such as macro invertebrates and salmonids. During a dam removal project a removal of a 3 m dam increased the amount of total suspended solids by 30 times more than if the dam remained in place (Ahear and Dahlgren 2005).

Dam removal projects can increase fine sediment load which cause fine sediment to become trapped in the spaces between gravel and create a seal that degrades habitat for aquatic species (Waters 1995). Sediment is stratified in the water column by density and size.

Fine sediment is typically found suspended in the water column and gravel is found along the bottom of the riverbed (Naiman et al. 2005). A large amount of fine sediment present in the water column after dam removal can increase the amount of sediment that is trapped in the spaces between gravel.

The length of time it takes impounded sediment to erode downstream is difficult to predict and it may take a few years to a decade to flow downstream (Gregory et al. 2002). Sediment is naturally moved downstream by a tributary's kinetic energy and the size of the sediment (Morisawa 1968). For example, larger boulders need high kinetic energy in the form of storms for the boulder to move downstream. If sediment left in its reservoir after dam removal is allowed to naturally erode, and depending on whether there are major storms, sediment may take decades to migrate downstream. Sediment left after dam removal also has the potential to harm the riparian ecosystem since it is the least studied aspect of dam removal (Sawaske and Freyberg 2012).

1.3 Effects of Sedimentation on Riparian Ecosystems

Sediment transport is controlled by a river's kinetic energy and the size of sediment a river is able to more (Morisawa 1968). Larger boulders need a high kinetic energy to be transferred downstream, therefore; larger boulders tend to be found in the upper watershed and sediment size decreases downstream (Naiman et al. 2005). This change in sediment size creates a riverbed structure (Naiman et al. 2005). A river's structure consist of large boulders and debris found at the top of the watershed, with medium sized sediment in the middle reach, and fine sediment near the mouth of a river (Naiman et al. 2005). The deposition of sediment downstream may affect riverbed structure negatively but can also create habitat for riparian vegetation and salmonids (Naiman et al. 2005).

1.3.1 Riparian Riverbed Structure

In healthy riparian ecosystems, riverbeds are constantly evolving from the transportation of sediment through a river's flow. A river's flow can transport sediment from the upper watershed to the middle and lower watershed by a river's kinetic energy. When water contains high kinetic energy, such as during a storm, it can transport large sized sediment and large loads of sediment (Naiman et al. 2005). When a river no longer has enough kinetic energy to move sediment, sediment is deposited into the riverbed (Naiman et al. 2005). The transport and deposition of sediment form a riverbed structure of sand bars, pools of water, and riffles that provide critical habitat for riparian species (Naiman et al. 2005). Changes in sedimentation in the riverbed directly affect the riverbed structure needed for spawning salmonids. The natural process of transport and deposition is stopped when a dam is installed.

When a dam is installed, it prevents sediment from being transported further downstream and creates a new riverbed structure. This new riverbed structure is located behind the dam in its reservoir. A dam installation decreases the slope of a river when compared to a natural river and creates a separate riverbed structure (ASCE 1997). With the creation of a new slope, a reservoir structure is created where larger sediment is typically deposited in the back of the reservoir while smaller sediment is located closer to the dam (ASCE 1997).

1.3.1.1 Effects of Sedimentation on Riverbed Structure

Dam removal projects can alter riparian riverbeds quickly. Even though the impounded sediment is naturally occurring sediment, the type and amount of sediment released from a dam removal can change a riverbed's structure in a short period of time. The sediment becomes impounded within the reservoir behind the dam and causes riverbed degradation below the dam (ACE 1997). Dam removal projects allow sediments to redistribute into the tributary. This redistribution is thought to be a positive event for riparian ecosystem restoration and impounded sediment releases can change a hard pan riverbed to a gravel filled riverbed (Kibler et al. 2011).

When a dam is removed the impounded sediment begins to erode by a river's kinetic energy and a new channel begins to form within the impounded sediment (Stanley and Doyle 2003). Channels are thought to decrease in width after dam removal therefore; the impounded sediment located on the lateral edges of the tributary becomes stabilized and forms new riverbanks (Stanley and Doyle 2003).

1.3.2 Anadromous Fish

Anadromous fish species rely on healthy riparian ecosystems and the maintenance of a tributary's longitudinal connectivity for their life cycle. Anadromous fish life cycles are unique in that they spend their adult life in the ocean where salinity levels are high, but return to the fresh water tributaries where they were born to reproduce and spawn (CA DFW 2015). Anadromous fish spawn and lay eggs in redds within the gravel in the middle to upper reaches of a river (CA DFW 2003). When eggs hatch they become alevins and remain in gravel while feeding on the yolk sacs until they become fry. The fry then begin to move out of the protection of gravel to forage for food and become larger. Once they are large enough they become smolts and begin their migration downstream and eventually to the ocean where they mature into adults.

Anadramous salmon, or Salmonids have three 'runs' of populations; Spring, Fall, and Winter run. A salmon run depends on the time of year a salmon begins to migrate from salt water to fresh water habitat to spawn. For example, during the Fall run a salmon begins its migration to spawning grounds in the late summer to spawn in the Fall and produce smolts in the Spring that will migrate to the ocean by the end of Spring (CA DFW 2015).

1.3.2.1 Effects of Sedimentation on Salmonids

The most critical period for a salmon is the early stages of its life cycle, when salmonid eggs, alevin, and smolts require specific conditions in order to survive. Factors that are critical for salmonid survival are the maintenance of specific water temperature, availability of dissolved oxygen (DO), availability of prey, and integrity of spawning habitat. The presence of sediment affects all of these factors and the biggest hindrance to salmon survival is sedimentation.

Sedimentation can affect salmonid's life cycle in many ways. Sediment can decrease the availability of dissolved oxygen (DO) in tributaries, decrease spawning habitat, and decrease the availability of prey (Bogan 1993). Fine sediment in particular decreases the amount of DO available for salmon eggs to survive and also decreases spawning habitat by filling in the spaces between gravel (Sear et al. 2014; Waters 1995). Not only does fine sediment affect salmon eggs but it also affects invertebrate populations used as prey by juvenile salmon (Suttle et al. 2004).

1.4 Research Summary

Dam removal projects undergo a rigorous amount of planning from consideration of how to safely take a dam apart to how sedimentation may affect a riparian ecosystem. There is a lack of scientific research on how dam removal projects are affecting riparian ecosystems. To date there is a limited amount of primary research available that identifies characteristics that are affecting the riparian ecosystem, with many of the published articles identifying the need for further research (Sawaske and Freyberg 2012).

This research assesses whether or not the current mitigation of impounded sediment is effective. This research will identify how sediment is redistributed and how riparian structure and salmonid populations are affected after dams are removed through review of several case studies. The focus of this research is on the effects of dam removals on anadromous fish, in particular salmonid species such as Coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*Oncorhynchus tshawytscha*) which spawn in the Northwestern tributaries of California (CDFG 2003).

Chapter 2 presents information on how sediment can negatively affect salmonid populations. Chapter 3 discusses how dams are currently removed and the sediment mitigation methods. Chapter 4 explains how sediment is eroded from an impoundment and how it alters a riparian riverbed structure. Chapter 5 analyzes the effectiveness of dam removal methods and sediment mitigation for dam removal projects and Chapter 6 presents research conclusions and management recommendations.

Chapter 2 – Sedimentation Effects on Salmonids

The major concern for dam removal projects is the known negative effects of sedimentation on the salmonid life cycle (Downs et al. 2009). Sediment can negatively affect salmonids through increasing turbidity and causing fine sediment infiltration. In particular, fine sediment can negatively affect salmonids by deterring salmonids from potential spawning habitat, decreasing oxygen, and decreasing prey availability. This chapter goes into detail about how sedimentation decreases salmonid populations throughout a salmonid's life cycle.

2.1 Turbidity

Turbidity is the cloudiness of water and increases directly with the amount of suspended material within the water column. The material can consist of anything from algae to organic matter to sediment. The particular type of sediment that increases turbidity is fine sediment. Fine sediment is small and buoyant to be transported downstream by small amounts of kinetic energy. Turbidity greatly impacts salmonid populations.

Turbidity hinders the visual communication between salmonids and impedes migration (Kemp et al. 2011). With a small amount of turbidity there is a clear path for juvenile salmonids to locate a tributary and its rearing habitat. However, with increased turbidity there is no longer a clear path to rearing habitat and deters salmonid from areas with high turbidity. In the cases of upstream migration, spawning salmnids may deter salmon from utilizing a tributary with high turbidity and force salmonids to spawn in another tributary (Kemp et al. 2011).

2.2 Fine Sediment Infiltration

Fine sediment infiltration decreases the amount of space between gravel which reduces the distinction between rifles, bars, and pools and produces a featureless riverbed (Suttle et al. 2004). Fine sediment infiltration occurs when there is a large release of fine sediment from the upper watershed flows downstream. This process may occur during large flow pulses, such as during storms, or when a dam is removed. Fine sediment infiltration is a natural process, but the major concern with fine sediment infiltration is when a dam is removed and a large load of fine sediment is released from an impoundment in a short period of time (Suttle et al. 2004). Fine sediment infiltration can decrease salmonid embryo development by preventing the emergence of salmonids from eggs, decreasing oxygen availability, and causing premature salmonid emergence (Sternecker and Geist 2010; Louhi et al. 2011; Greig et al. 2005a).

2.2.1 Salmonid Embryos

When salmonids lay their eggs, they remove fine sediment from a riverbed's gravel and lay their eggs in pockets within the gravel (Greig et al. 2005a). They then cover the eggs with y loose gravel forming redds (Greig et al. 2005a). Once eggs are deposited, redds need a steady supply of oxygen for proper embryo development (Greig et al. 2005). However, when fine sediment infiltration occurs, the amount of oxygen availability decreases.

Normally, salmonid embryos receive oxygen transferred from water to the embryo via a thin film of water surrounding the egg surface (Greig et al. 2005b). Fine sediment infiltration decreases the amount of space between riverbed gravel, which can decrease oxygen availability for developing embryos (Greg et al. 2005b). With fine sediment intrusion oxygen transfer is blocked. Clay sized sediment creates a thin film of sediment on the egg surface and decreases the amount of available oxygen (Greig et al. 2005b). The mechanism for how sediment decreases an embryo's oxygen availability is unclear, but explanations may be that a film is created with low permeability decreasing the amount of oxygen, or that fine sediment blocks canals within the egg membrane where oxygen consumption occurs (Greig et al. 2005b).

When there is a reduction in a river's flow there is less oxygen that is incorporated into water from the atmosphere. Fine sediment infiltration blocks the space between gravel and reduces interstitial flow velocity (Louhi et al. 2011). When there is less oxygen in water there is less oxygen available for embryos (Louhi et al. 2011). Increases in sedimentation may decrease inter-gravel flow which in turn decreases the removal of embryotic waste and increases the reduction of oxygen availability (Burkhalter and Kaya 1975).

Fine sediment does not only decrease oxygen availability, it also creates a physical barrier. Newly deposited fine sediment can prevent salmonids juveniles from emerging from eggs. A fine sediment layer deposited over redds creates a physical barrier for emerging embryos (Sternecker and Geist 2010; Quiñones et al. 2014). If the fine sediment layer is too deep, emerging embryos may not have the energy to swim through the fine sediment layer into the river. Fine sediment conditions also causes embryos to emerge later than normal (Louhi et al. 2011). The timing between first and last emergence of fish was shorter when exposed to fine sediment rather than coarse sediment, and produced juveniles with a large amount of yolk sac (Sternecker and Geist 2010). Embryos that emerged with high amounts of yolk sac were poor swimmers, lacked energy, and had a higher rate of predation (Louhi et al. 2011).

2.2.2 Juvenile Salmonids

In normal conditions juvenile salmonids stay within the upper watershed to feed on epibentic grazers and predators before they migrate downstream (Suttle et al. 2004). They remain in the upper watershed to grow bigger before they migrate downstream to the ocean. However, when there is a release of fine sediment into a tributary the process of fine sediment infiltration can alter the juvenile stage of a salmonid's life cycle by changing the availability of prey (Suttle et al. 2004).

Fine sediment can directly smother invertebrates, limit oxygen, and decrease the population of lower food chain sources (Kemp et al. 2011). In tributaries that have experienced fine sediment infiltration, the type of invertebrates changes from suspended invertebrates to invertebrates that bury themselves within sediment (Suttle et al. 2004). This shift in prey does not allow salmonids to feed on the species they are used to and decreases salmonid growth linearly with the amount of fine sediment (Suttle et al. 2004). There is no threshold where fine sediment is harm less to salmonid populations and fine sediment infiltration decreases the growth and survival of juvenile salmonid (Suttle et al. 2004).

Fine sediment infiltration can decrease areas where juvenile salmonids are able to escape predators. As mentioned in earlier sections, fine sediment infiltration decreases the space between gravel causing there to be decrease in riverbed features. Since there is no longer space between gravel, juvenile salmonids do not have the space to hide in and escape predators (Suttle et al. 2004). When there is no cover for salmonids to hide in, they expend more energy on continuous swimming rather than conserving energy while resting in the spaces between gravel (Suttle et al. 2004). This lack of cover causes salmonids to be more vulnerable to prey and decreases energy reserves needed to migrate downstream.

2.3 Chapter Summary

The main concern with dam removal projects is the known effects of fine sediment on the salmonid life cycle. In particular fine sediment can negatively affect salmonid survival by increasing turbidity, covering redds, decreasing the amount of available oxygen, causing premature hatching, and decreasing the fitness of juvenile salmonid. Even though it is known that fine sediment negatively affects salmonids there have only been a few dam removal projects that have fully assessed how sediment has affected salmonid populations after a dam is removed.

Chapter 3 – Dam Removal and Sediment Mitigation Methods

This chapter introduces dam removal methods and sediment mitigation methods following dam removal. The determination by dam removal managers of which methods to implement on a dam removal project takes into consideration the amount of sediment behind the dam, sediment composition, and the time frame of dam removal (ASCE 1997). If an environmental assessment uncovers the potential impacts of sediment on the downstream riparian ecosystem, active sediment mitigation is needed during dam removal projects to protect endangered species, such as salmonids (MacBroom and Loehmann 2008).

Many of these techniques were developed 18 years ago and they are still being used today to plan dam removal projects. This chapter provides overviews of dam removal methods, their trade-offs, and current dam removal projects that have used these methods.

3.1 Dam Removal Methods

Dam removal projects either involve partial or complete dam removals. A complete dam removal involves the removal of the entire dam structure whereas a partial dam removal leaves a portion of the dam in place. Complete dam removal projects are recommended to restore a tributary, however; a dam may be of historical importance and cannot be fully removed. If a dam is of historical importance the dam structures are protected under the National Historic Preservation Act (Randle and Helpler 2006). A partial dam removal will not completely restore a tributary to its function, but will return some tributary function and complete dam removal has the potential to restore a tributary's longitudinal function. The remainder of this chapter focuses on both complete and partial dam removal projects.

3.1.1 Complete Dam Removals

There are two approaches for complete dam removal projects. These methods include the rapid release approach and the notch/release approach. Both methods do not allow reservoir to be dewatered before dam removal. The rapid release approach removes a dam all at one and the notch/release approach takes apart a dam in sections.

3.1.1.1 Rapid Release Approach

A dam can simply be removed through mechanical excavation and allowing a reservoir to flow through the initial opening. This method involves the use of an excavator or bulldozer that can take a part a dam by sections until the dam is completely removed (Ahearn and Dahlgren 2005). Since mechanical machinery is used, there must be easy access into the dam site so an excavator and/or bulldozer to easily enter the area and remove the dam. This method is usually used during small dam removals of earthen or rock dams that contain similar material as the riverbed so, the dam material can erode over time and be deposited into the tributary (G & G Associates 2003).

3.1.1.2 Notch/Release Approach at the Elahwa Dam, Washington State

A form of river erosion method for concrete dams is called the notch/release approach. This method was used during the Elahwa Dam removal on the Elahwa River in Washington State. This method of dam removal involves the removal of horizontal sections in stages from the top to the bottom of the dam (Mussman et al. 2008). At the start of the removal a notch is created at the top of the dam to allow water from the reservoir to flow out of the notch into the tributary (G & G Associates 2003) (Figure 2). Once the water stopped flowing through the notch the remainder of the horizontal section could be removed (G & G Associates 2003). This process was repeated with the remaining dam sections until the dam was completely removed.

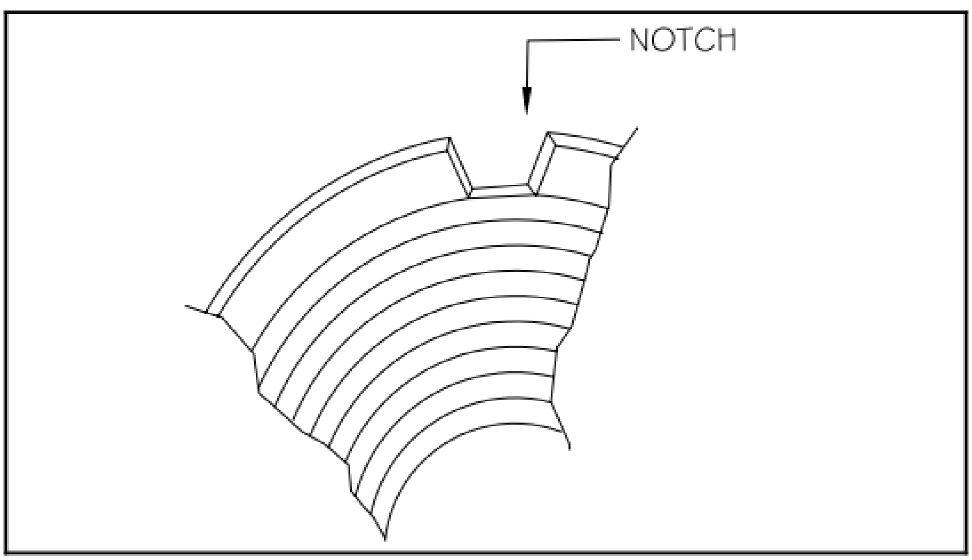

Figure 2. Notch/Release Approach. An image representing how a notch would be cut into a dam to allow the reservoir to be dewatered (G & G Associates 2003).

3.1.2 Partial Dam Removal

Partial dam removal projects involve taking portions of a dam that are not preventing impounded sediment from erosion. Once the portions are removed the remainder of the dam remains in place and prevents impounded sediment from eroding (MacBroom and Loehmann 2008). This method can be implemented when impounded sediment has not yet filled an entire reservoir; the portion of the dam that is higher than the impounded sediment can be removed without the release of impounded sediment (MacBroom and Loehmann 2008).

Partial dam removals can also consist of a full depth removal instead of horizontal removal. The removal of vertical section of the dam allows the middle portion of the impounded sediment to be eroded away and a channel is created and leaves the edges of the impounded sediment to remain trapped (MacBroom and Loehmann 2008).

3.2 Sediment Mitigation Methods

There are four types of sediment mitigation methods that were developed by the American Society of Civil Engineers (ASCE) in 1997 to mitigate the effects of sedimentation to the riparian ecosystems after dam removal. These methods include no action, river erosion, mechanical removal, and stabilization (ASCE 1997). Any of these four methods can be used for a dam removal project, however; there are trade-offs between costs and riparian ecosystem effects that are associated with each method.

The four sediment mitigation methods involve passive and active sediment management. Passive mitigation provides a cheaper option for dam removal projects that allows a river's kinetic energy erode impounded sediment. The no action method and the river erosion method are both passive sediment mitigation methods. Active sediment mitigation includes mechanical removal and stabilization and is effective in preventing sediment from having detrimental impacts to the riparian ecosystem but is very cost intensive.

3.2.1 No Action

The no action sediment mitigation method involves leaving a portion of the dam in place to prevent impounded sediment from eroding downstream (ASCE 1997). Since this dam removal method requires a portion of the dam to remain in place, this method cannot be used for a complete dam removal project. The method does not allow impounded sediment from eroding therefore, no active sediment management is necessary (ASCE 1997).

3.2.2 River Erosion

The river erosion method of dam removal allows a river to naturally erode impounded sediment downstream after a dam is completely removed (MacBroom and Loehmann 2008). This method is the cheapest method, as sediment does not have to be transported elsewhere through trucking and allows a river's kinetic energy to transport sediment downstream (MacBroom and Loehmann 2008). The method also allows the river to naturally self-adjust by creating a natural channel alignment and configuration with minimal effort (Wildman and MacBroom 2005).

This method is an option for all sizes of dams and allows sediment to be redistributed downstream, but may negatively affect the riparian ecosystem (ASCE 1997). The main environmental issue with this method is the release of high loads of impounded sediment. As explained in Chapter 2, fine sediment negatively effects salmonid populations. The prevention of large sediment releases can occur by taking apart a dam in stages, if a river's flow is low and its kinetic energy is not capable of eroding large amounts of impounded sediment, or if there are other dams located on the same tributary that can regulate water flow (ASCE 1997). The river erosion method is also an option for dam removal projects that have a low amount of fine sediment trapped behind the dam, as there would not be a significant amount of impounded sediment available to erode (MacBroom and Loehmann 2008). Even though, this method allows impounded sediment to naturally erode downstream the increase in sediment load can detrimentally affect salmonid populations (MacBroom and Loehmann 2008).

The river erosion method has the highest potential to impact the salmonid life cycle, however; it allows the incorporation of impounded sediment back into the riparian ecosystem (Downs et al. 2009). It is beneficial for sediment to be transferred downstream and be redistributed through the once sediment deprived channel. Sediment deposition can create new habitat through the formation of sand bars and deposition at the mouth of the river (Naimen et al. 2005). Even though the river erosion method can negatively affect salmonid populations, the method should still be used for future dam removal projects, however; it is critical to improve the methods and is the focus of this research analysis.

3.2.3 Mechanical Removal

The mechanical removal method involves the physical removal of impounded sediment from a reservoir and the transportation of the sediment elsewhere for deposition. This method is the most expensive option, but leaves a minimal amount of impounded sediment after dam removal. This method is often the most expensive method because it requires the relocation of sediment through a trucking process or a pipe in order to be transported and deposited elsewhere (Wildmand and MacBroom 2005). The removal methods for impounded sediment includes excavation, mechanical or hydraulic dredging and/or pipeline removal. The removal of impounded sediment limits the potential effects of sediment on the riparian ecosystem; however, it also prevents sediment from naturally being incorporated back into downstream riparian habitat (Downs et al. 2009).

3.2.3.1 Excavation

During the excavation method the river must be re-routed around the reservoir to let the impounded sediment dry before it can be excavated. Once the impounded sediment has dried, excavation can occur through the use of bulldozers and front-end loaders (ASCE 1997). Impounded sediment is then loaded into trucks and transported from the dam removal sites to a disposal site (ASCE 1997).

3.2.3.2 Mechanical Dredging

Mechanical dredging involves the use of a crane-mounted bucket placed at the riverbanks of a river to excavate impounded sediment (MacBroom and Loehmann 2008; ASCE 1997). The material is then placed into dump trucks to be transferred to a disposal site (ASCE 1997). This removal method does not require a reservoir to be dewatered; however the sediment must be dewatered prior to truck transportation (ASCE 1997).

3.2.3.3 Hydraulic Dredging

Hydraulic dredging is the method of choice when removing large amounts of impounded fine sediment (ASCE 1997). The process involves the excavation of large amount of impounded sediment through hydraulic dredges that are barge-mounted and stations within a reservoir (MacBroom and Loehmann 2008). This process involves a barge that can be placed in a water filled reservoir, therefore the reservoir does not have to be dewatered before impounded sediment is removed (ASCE 1997).

Even though, hydraulic dredging is fast and does not require dewatering, the process is unrealistic in woody debris areas or if the majority of impounded sediment consists of gravel (MacBroom and Loehmann 2008).

3.2.3.4 Pipeline Removal

During a pipeline removal, the impounded sediment is transported through a sediment slurry pipeline to its deposit site (ASCE 1997). This process is expensive, but decreases trucking and labor expenses.

3.2.4 Stabilization

The stabilization method involves re-routing the river from the top of the reservoir around the reservoir foot print and reconnects the river at the base of a dam (ASCE 1997). The use of this method decreases all amount of sediment that is eroded by river processes (Wildman and MacBroom 2005). However, as with the mechanical method, this method further deprives downstream riparian ecosystem from the redistribution of impounded sediment (Downs et al. 2009).

This method is very costly as it requires the creation of a new channel in order to bypass a reservoir. This method typically considered when there is a significant amount of impounded sediment that is not cost effective to mechanically remove or when there is too much sediment to be naturally eroded and not impact the riparian ecosystem. The San Clemente Dam removal project is found that the impounded sediment would detrimentally effect the downstream riparian ecosystem is planning to use this method for sediment mitigation (Rogers 2013).

3.3 Chapter Summary

There are four types of sediment management options used to mitigate the effects of sedimentation, downstream of dam removal projects. The four types of sediment mitigation method include no action, river erosion, mechanical removal, and the stabilization method (ASCE 1997). For the no action method, there is no sediment management plan other than allowing sediment to remain in place, by leaving a portion of the dam in place to prevent impounded sediment from eroding downstream (ASCE 1997). The mechanical removal method physically moves impounded sediment from the reservoir to a disposal site, and is very costly. The stabilization method limits the amount of impounded sediment from affecting downstream riparian habitat by re-routing the channel around the impounded sediment. The river erosion method allows impounded sediment to be naturally eroded downstream into the channel.

The potential impacts on the riparian ecosystem depend on whether or not impounded sediment is allowed to naturally erode by a river's kinetic energy after dam removal (Sawaske and Freyberg 2012). Any sedimentation release can alter salmonid populations through the alteration of the tributary's riverbed. These dam removal methods have been used for 18 years, but the effectiveness of these dam removal and sediment mitigation methods have yet to be fully understood. The highest potential to negatively impact salmonid populations occurs when the river erosion dam removal method is used and is the focus of this research (Downs et al. 2009).

Chapter 4 – Sediments after Dam Removal

The biggest concern with dam removal projects is the potential for large amounts of sediment transported downstream (Downs et al. 2009). Large releases of sediment can negatively impact the riparian ecosystem through decreasing oxygen availability, burring of riparian species and vegetation, and increasing turbidity. These impacts are especially relevant for protecting salmonid populations throughout the United States. As Chapter 2 explained large releases of fine sediment are detrimental to each stage of the salmonid life cycle and the prevention of fine sediment releases is a major concern for maintaining salmonid spawning habitat (Downs et al. 2009).

As Chapter 3 explains, there are four dam sediment mitigation methods in order to prevent the downstream transportation of sediment after dam removal. These methods have been developed to prevent large impounded sediment releases after dam removal. For example, the stabilization method eliminates the potential for negative effects of sediment releases through sediment stabilization and channel re-routing (Wildman and MacBroom 2005). The highest potential to impact the riparian ecosystem and salmonid populations is when the river erosion method is used (Sawaske and Freyberg 2012; Downs et al. 2009).

The negative effects of sediment to the riparian ecosystem occur only if large loads of sediment are allowed to erode downstream. Sediment erosion is dependent on a variety of factors and this chapter identifies three sedimentary characteristics that may influence impoundment sediment erosion; sediment composition, sediment properties, and sediment load.

4.1 Sediment Composition

For the purposes of this research, sediment composition can be put into two categories either fine sediment or coarse sediment (Figure 3). Fine sediment is categorized as sediment that is less than 2 mm in diameter and coarse sediment is categorized as sediment that is greater than 2 mm in diameter. Fine sediment is typically found suspended in the water column for a time and then deposited into the riverbed when a river's kinetic energy is too low to carry the sediment any longer. Gravel is usually found on the bottom of the riverbed and takes a higher amount of kinetic energy to transport downstream. Sediment trapped behind a dam is usually fine silt and sand because coarser rock usually settles to the bottom of the reservoir (Kondolf 1997).

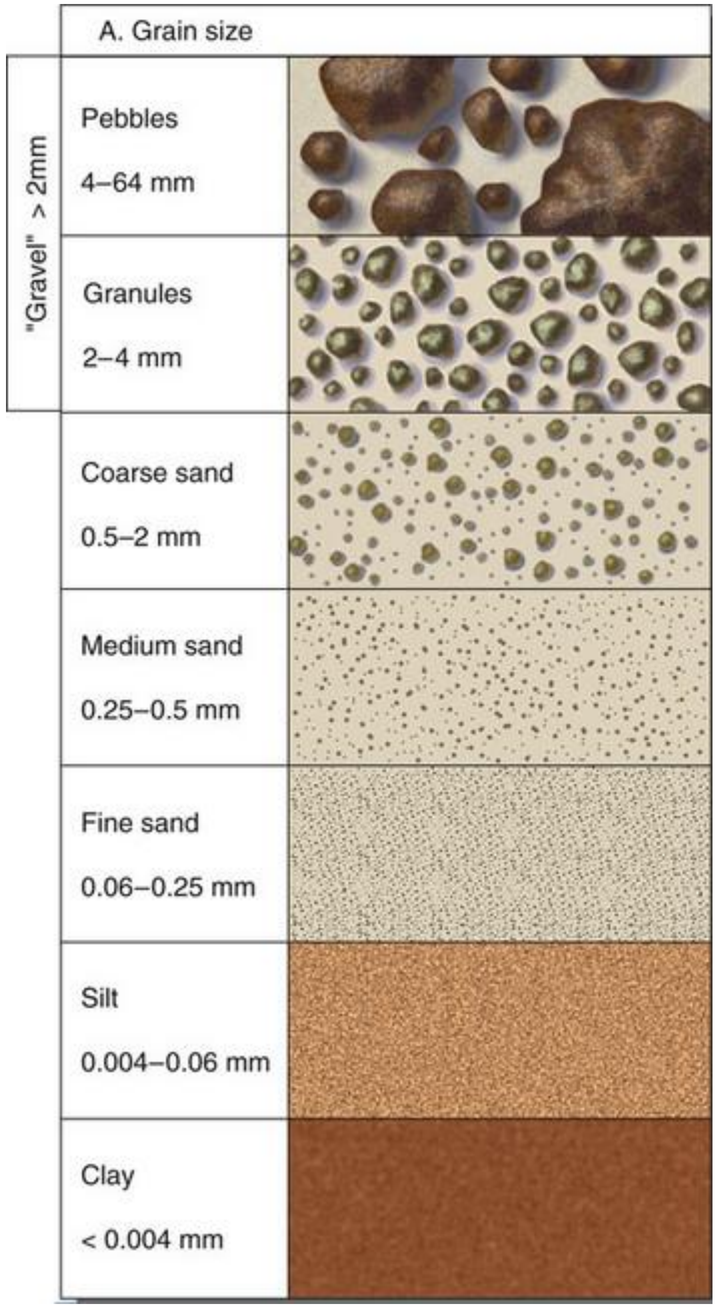

Figure 3. Riverbed Sediment Grain Size. The figure categorizes the difference size requirements for gravel and fine sediment. For the purposes of this research all sediment type less than 2 mm is considered fine sediment. Diagram modified from http://core.ecu.edu.

4.2 Sediment Properties

The potential for impounded sediment to naturally erode from the reservoir downstream depends on its cohesive property. Cohesion otherwise known as “mud,” is sediment that has characteristics of both clay and silt which causes sediment particles to bind together (Grabowski et al. 2011). Non-cohesive sediment is sediment that does not contain clay and does not bind well to other sediment particles. The process of erosion for non-cohesive sediment depends on sediment size, shape, and density (Kothyari et al. 2014). However, the ability for erosion to occur for cohesive sediment is based on electrochemical bonds between similar sediment types (Kothyari et al. 2014; Grabowski et al. 2011). The ability for impounded sediment to erode downstream after dam removal may be due to whether or not the impounded sediment possesses cohesive properties.

4.2.1 Cohesive vs. Non-Cohesive Sediment

Cohesion is a factor to identify whether or not impounded sediment will erode and affect the downstream riparian ecosystem. The amount of cohesion is directly connected to the potential for the material to erode naturally from the impounded reservoir to the riverbed (Sawaske and Freyberg 2012). The more cohesive sediment is, the more likely it is to retain its original volume than non-cohesive sediment (Sawaske and Freyberg 2012). If impounded sediment contains a high percentage of cohesive sediment there is a decrease in the percent of erosion of impounded sediment (Sawaske and Freyberg 2012). A dam removal project in Wisconsin that had impounded sediment with high cohesive characteristics eroded at a lower rate than an impoundment with low cohesive characteristics (Doyle et al. 2003).

Sediment cohesion is not related to sediment composition as cohesive characteristics are found in impounded sediment of varying sediment composition (Sawake and Freyberg 2010). However, gravel tends to have more cohesive properties than sand (Sawaske and Freyberg 2012).

4.3 Sediment Load

The mitigation of effects for sediment is dependent on whether or not the impounded sediment load is large or small. The effects of dam removal projects on the riparian ecosystem depends on the amount of sediment impounded (MacBroom and Loehmann 2008).It is thought that small impoundment amounts affect the riparian ecosystem differently than large quantities of impoundment; since, small sediment loads will have a limited impact on the riparian ecosystem (Cheng and Granata 2007; MacBroom and Loehmann 2008).

4.3.1 Relatively Small Amount of Impounded Sediment

St. Johns Dam, Ohio

A small dam in Ohio was removed using the notch/release method, and then the impounded sediment was allowed to erode downstream (Granata et al. 2008). The dam removal released 0.2 x 10^6 m^3 impounded sediment a relatively small amount of impounded sediment (Granata et al. 2008). After dam removal, natural river flow carried impounded sediment downstream; however, instead of causing a large increase in suspended solids the amount of suspended solids was not higher than the tributaries natural flow (Granata et al. 2008). Even though suspended solids were never higher than the tributaries natural flow, the highest concentration of suspended solids occurred in a short period of time. During dam removal the peak suspended sediment concentration occurred within 8 hours after dam removal (Granata et al. 2008). Since there is only 8 hours of peak sediment transport, small amounts of impounded sediment may not affect the riparian ecosystem.

4.3.2 Relatively Large Amount of Impounded Sediment

Rockdale Dam and La Valle Dam, WI

The Rockdale and La Valle Dam had a relatively large amount of impounded sediment and allowed the erosion of 140,100 m^3 impounded sediment (Doyle et al. 2003). After dam removal, peak suspended solids was between 2,000 and 3,000 mg/L when background suspended solids was at 200 mg/L after the dams were removed (Doyle et al. 2003). Dam removal projects that release large amounts of impounded sediment experience an increase in sediment load 10 times greater than normal channel sediment load (Doyle et al. 2003). Downstream sediment concentrations immediately following dam removal had a high sediment release, by a factor of 10 for the Rockdale Dam and a factor of 4 for the LaValle Dam (Doyle et al. 2003). The amount of sediment released from the dam increased the amount of sediment located within the tributary and may negatively affect riparian ecosystems.

4.4 Sedimentation on Riparian Riverbed

A dam removal project may negatively impact the riparian ecosystem permanently; therefore, it is critical to identify how dam removal projects affect the riparian ecosystem (Doyle et al. 2005; Stanley and Doyle 2003). A riparian ecosystem is variable and many riparian species have adapted to this variability. For example, cottonwood trees produce seed when a river is flooded in order to propagate downstream (Naiman et al. 2005). This chapter identifies the alterations dam removal project create on riparian riverbed structure.

4.4.1 Dam Removal Effects on Riverbed Structure

After dam removal, a channel readjusts to the newly opened free flowing tributary and can alter the downstream riverbed in different ways. There is first an alteration in riverbed structure with the impounded sediment and there is also an alteration downstream of the dam removal site. These two areas receive different alterations in riverbed structure. The reservoir experiences sediment removal while the riverbed downstream of a dam removal site experiences sediment deposition.

Alterations of the riverbed structure depend on a river's kinetic energy to erode impounded sediment, the amount of sediment present, on the dam removal method, and sediment mitigation methods used (Bednarek 2001; Doyle et al. 2005). For small dam removals, erosion of impoundment sediment and alterations in the riverbed structure occur within a year of the dam removal (Sawaske and Freyberg 2012; Kibler et al. 2011).

4.4.2 Impoundment Area

During dam removal, water is drained from the reservoir and allows a new channel to form within the impoundment. After dam removal a new channel is created naturally by a river carving out a path in to the impounded sediment. The resulting channel created is usually smaller than the reservoir, thus leaving the edges of the impounded sediment in place (Figure 4). These edges dry and create new riverbanks where vegetation can propagate (Doyle et al. 2003). In the process of creating a new channel sediment is eroded downstream.

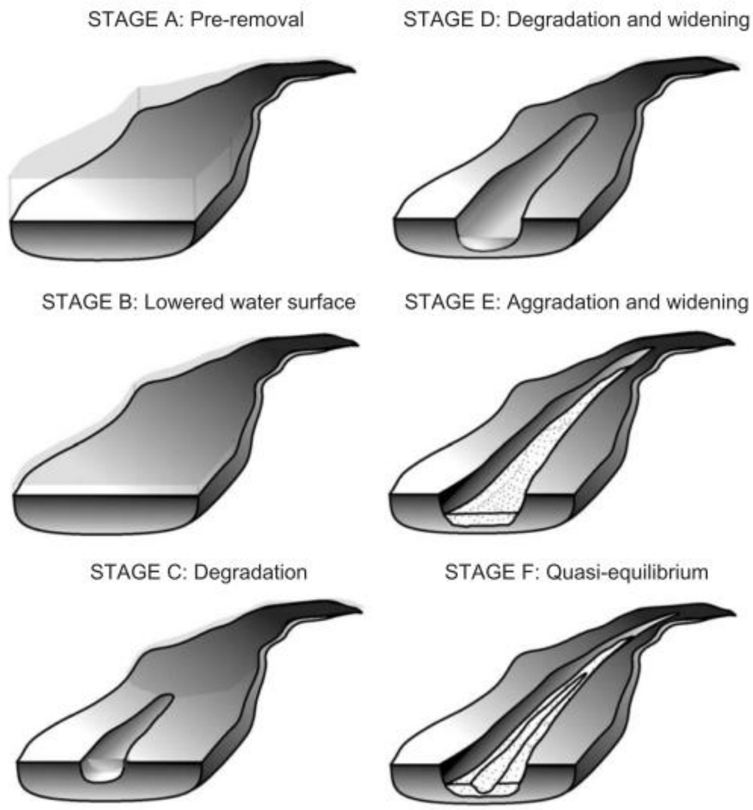

Figure 4. Channel Formation After Dam Removal. Graphic representation of how impounded sediment within a reservoir will be altered after dam removal (Doyle et al. 2005).

Within the reservoir, impounded sediment begins to erode while upstream material is transported into the reservoir. The highest amount of erosion occurs within pools of the reservoir and sand is more likely to be eroded than gravel (Ahern and Dahlgren 2005; Cheng and Granata 2007). Pools also acted as sinks for sand deposits from newly deposited upstream material (Cheng and Granata 2007). Gravel beds within the impoundment also experienced deposition by upstream material (Cheng and Granata 2007).

Exact alterations of channel width at the dam removal sites are unknown. The channel width at a dam removal site is thought to decrease after dam removal; however, this does not seem to be a general characteristic for all dam removals (Doyle et al. 2003). During a low-head dam removal in Ohio there was no change in channel width, while the removal of the Union City Dam in Connecticut altered the channel by making it narrower and deeper (Cheng and Granata 2007; Wildman and MacBroom 2005).

4.4.3 Downstream of Dam Removal Site

Before a dam is removed, the area directly downstream of a dam removal site is typically deprived of sediment. As mentioned, dams prevent sediment form flowing downstream of a dam. The deprivation of sediment creates hardpan riverbed that has little to no riverbed features (Kibler et al. 2011). Once a dam is removed, longitudinal connectivity is regained and sediment can flow freely downstream.

After a dam removal project, longitudinal connectivity is regained and upstream material begins to move freely from the dam removal site downstream. This material includes impounded sediment left behind to erode naturally by the river's kinetic energy and from sediment the upper watershed. The sediment deprived downstream riverbed receives an increase of sediment flux after a dam removal project and receives the majority of eroded sediment.

Downstream riverbed structure can be altered in different ways depending on the impounded sediment composition. In a gravel filled impoundment, a dam removal allowed gravel to migrate downstream and create new bars, riffles, and pools that were previously hard pan (Kibler et al. 2011). In general, impounded sediment erodes and travels downstream and is deposited in pools or areas with low elevation first (Kibler et al. 2011). However, an impoundment filled with fine sediment can detrimentally affect the riparian ecosystem and salmonid populations.

4.5 Chapter Summary

In order for impounded sediment to impact the downstream riparian habitat, impounded sediment must first erode from the impoundment downstream through a river's kinetic energy. The potential for impounded sediment erosion may depend on sediment properties; these include the sediment composition, cohesive properties, and sediment load. These characteristics directly affect how impounded sediment will impact riparian ecosystem by increasing the potential for impounded sediment erosion. Impoundment sediment erosion may decrease due to an increase in cohesive properties, whether or not the impoundment consists of fine sediment, and the load of impoundment sediment eroded. If sediment is able to transfer downstream then sediment will be deposited within the riparian riverbed and impact the riparian ecosystem.

A dam removal project restores a tributary's longitudinal connectivity; however, the tributary needs time to readjust to an equilibrium state after dam removal. Before a dam removal the reservoir contains a sediment storage while there is a deprivation of sediment below the dam. After a dam removal project a channel allows the transfer of sediment downstream, while allowing riparian species to migrate again. A newly opened dam allows a channel to create a new path through the impounded sediment and downstream. In the process impounded sediment is eroded and deposited below the dam. The upstream width of the channel is thought to decrease in width.

The width of the newly created channel at a dam removal site may either be narrower, wider, or stay the same; however, there has not been generalization made because different dam removal project have experienced different results. Once the channel readjusts in the impoundment then the sides of the dam dry up and become stabilized; creating riverbanks.

Water is a transport mechanism for upstream sediment to be transported from the impoundment downstream. The amount of sediment transferred depends on a river's kinetic energy. If there is enough kinetic energy, the impoundment sediment is able to erode and is deposited downstream of the dam removal site. As sediment moves downstream there can be an increase in sediment load to the riverbed that was previously deprived of sediment. Before dam removal, the riverbed below the dam is typically eroded to become a hard pan, with dam removal sediment replenishing the riverbed with newly deposited sediment and subsequently can create habitat.

Chapter 5 – Effective Mitigation of Sediment

It is critical to identify if current river erosion dam removals and sediment mitigation methods are effective in preventing negative effects of sediment during dam removal projects. As Chapter 2 mention, salmonid species are detrimentally impacted by fine sediment loads but how are current river erosion dam removal projects affecting salmonid populations. The cases presented in this chapter consist of primary literature that has measured attributes that would greatly affect salmonid populations. The later section of this chapter assesses the effectiveness of the river erosion dam removal method and sediment mitigation methods through the case studies presented.

5.1 Dam Removal Case Studies

This section introduces six river erosion dam removal project case studies. Case studies consist of small, medium, and large. For this research, small dam removals are defined as projects that removed a dam 5 meters (m) in height or smaller. Large dam removal projects consisted of the removal of a dam higher than 30 meters. A medium sized dam was considered to be between small and large sized dams (higher than 5 m and lower than 30 m). These case studies are presented in order of smallest to largest dam height and all implement variations of the river erosion method.

5.1.1 Brownsville Dam, Calapooia River, Oregon (2007)

The Brownsville Dam is located near Brownsville, Oregon on the Calapooia River (Zunka et al. 2015). The Brownsville Dam was a small dam at 1.8 m tall, which contained a gravel impoundment of 14,000 m^3 (Zunka et al. 2015). The dam was removed by an excavator in August of 2007 (Zunka et al. 2015).

After dam removal, the downstream riverbed experienced an increase in sediment deposition of gravel sized 6-23mm within 720 m downstream from the dam removal site (Zunka et al. 2015). After the removal of this small dam no negative effects were found and created potential salmnid spawning habitat (Kibler et al. 2011). Before dam removal the downstream riverbed was hard-pan and after dam removal the gravel impoundment eroded and changed the hard-pan channel to a gravel filled channel. The Brownsville Dam removal created new sand bars and increased the size and volume of existing sand bars (Kibler et al. 2011).

5.1.2 La Valle Dam, Baraboo River, Wisconsin (2000-2001)

The La Valle Dam is a small dam (2 m high) located on the Baraboo River in Wisconsin that impounded 140,100 m^3 of fine sediment (Doyle et al. 2003; Greene et al. 2013). The dam was removed through a staged method, after dam removal a 3 m high riffle structure made of riprap was created at the dam removal site (Doyle et al. 2003; Greene et al. 2013). A year after removal, 7.8% of the impounded sediment was transferred 160 m downstream and the rip-rap structure continue to act as an impoundment (Greene et al. 2013).

5.1.3 Sparrowk Dam, Murphy Creek, California (2003)

Murphy Creek is located on the Mokelumne River, southeast of Sacramento, CA with three dams located on the tributary (Ahearn and Dahlgren 2005). The Murphy Creek Dam was the lowest dam, closest to the mouth of the tributary, was removed in the summer of 2003 to create salmonid passage (Ahearn and Dahlgren 2005).

The method for dam removal was dewatering of the reservoir by pumping water over the dam and then excavation of the dam (Ahearn and Dahlgren 2005). 15,000 m^3 impounded sediment was allowed to erode naturally other than a gravel control structure was placed in a section of the impounded sediment to prevent sediment from eroding downstream (Ahearn and Dahlgren 2005).

Baseline data was collected for two years prior to dam removal and post-dam removal data was collected a year after the removal (Ahearn and Dahlgren 2005). The years between base line data collection had similar precipitation levels; however, the following year after dam removal there was a large storm that may have been a factor in the amount of suspended sediment observed (Ahearn and Dahlgren 2005).

During prior impounded sediment investigation, the impounded sediment was gravel and fine sediment filled (Ahearn and Dahlgren 2005). The dam removal caused an increase in sediment erosion for the first year after dam removal, as high as 2,000 mg/L of sediment was measured after the removal (Ahearn and Dahlgren 2005).

5.1.4 Marmot Dam, Sandy River, Oregon (2007)

The Marmot Dam is located on the Sandy River, a tributary of the Columbia River, near Portland, Oregon (Cui et al. 2014). The sediment impoundment contained 750,000 m^3 of sediment with 40% fine sediment (Cui et al. 2014). The dam was originally operated by Portland General Electric Company and the 15 m dam was used for the production of hydropower (Cui et al. 2014; Zunka et al. 2015). The dam was set for decommission after its FERC license was set to expire, economic, and ecological factors were determine and studies found that the removal of the dam would increase in fish passage and habitat (Cui et al. 2014). PGE monitored the passage of salmonids during the dam removal process and provided aid if salmonids were impeded by dam removal and continued monitoring four years after removal (Cui et al. 2014).

5.1.5 Condit Dam, White Salmon River, Washington State (2011)

The Condit Dam was a 38 m tall hydroelectric facility located on the White Salmon River in Washington State to increase fish passage and riparian processes (Magirl et al. 2014; Wilcox et al. 2014). It was breached in October in 2011 in a rapid release approach method through an explosion at the base of the dam which allowed sediment and water to be rapidly released through a 6 m wide hole in the dam (Randle et al. 2015; Wilcox et al. 2014; Draut and Ritchie 2015). The rapid release method also increased the amount of kinetic energy that was able to transfer large amounts of impounded sediment was quickly transferred downstream (Draut and Ritchie 2015).

The flow from the breaching reached a peak of 400 m^3/s flow and released 1.8 million m^3 of fine sediment downstream (Wilcox et al. 2014; Draut and Ritchie 2015). After dam removal most of the sediment deposited in an 18 m thick deposit and reached 2 km downstream (Wilcox et al. 2014). The rapid release method allowed for quick dewatering and impounded sediment excavation. After initial sediment transfer, the portions of the dam that remained were excavated (Wilcox et al. 2014).

5.1.6 Elwha and Glines Canyon Dam, Elwha River, Washington State (2011-2014)

The Elwha and Glines canyon Dam removal project is one of the largest dam removal projects that has occurred within the United States to date (East et al. 2015). The Elwha and Glines Canyon Dam Removal Project contained two hydroelectric dam removals (Magirl et al. 2014). The Elwha was a 32 m tall dam located 7.9 km from the river mouth while the Glines Canyon Dam was a 64 m tall dam located 21.6 km upstream from the mouth of the river (Magirl et al. 2014). For the purposes of this research, the two dam removals will be looked at as a whole as both dams were removed at the same time and impact the same tributary.

The dams were removed because they were built without the incorporation of andromous fish passages and blocked the passage of anadromous fish populations from reaching spawning habitat (Magirl et al. 2014). The dams impounded 21 +/- 3 million m^3 of sediment from being transferred downstream (East et al. 2015; Magirl et al. 2014). The method for removal was the river erosion method with a notch/release approach to prevent large loads of sediment from eroding at one time (Magirl et al. 2014). The dam removal project had known salmonid populations that used the tributary therefore, dam removal was put on hold when salmonid species heavily used the tributary (Randle et al. 2015). Drawdown increments were 4.6 m with 14 days in between drawdown and 4-6 week hold periods when fish were known to use the Elwha River (Randle et al. 2015).

The removal of both dams caused an increase of deposition of fine sediment into the downstream riverbed (East et al. 2015). There was an increase in deposition of sediment in pools where the lower elevation was easily filled by the sediment release (East et al. 2015). Downstream transport of sediment resulted in about 1 m deposition of sediment (East et al. 2015). The deposition consisted of finer material than pre-dam removal riverbed and formed new sand bars covering the original pool-riffle morphology (East et al. 2015).

5.2 Effective Mitigation of Sediment after Dam Removal

The methods used to mitigate sediment impacts to the riparian ecosystem involve dam removal techniques and stabilization of impounded sediment. This research uses metrics to evaluate whether or not river erosion dam removal projects are effective in mitigating sedimentation. This research specifically looks at how sedimentation after river erosion dam removal using the river erosion method affects salmonid populations. This research chose case studies that contain metrics that would impact salmonid species via impounded sediment erosion, sediment composition, turbidity, and deposition. The metrics used to identify the effectiveness of the river erosion dam removal method and its sediment mitigation methods are amount of sediment deposition, percent of fine sediment, peak amount of suspended solids, and length of downstream deposition. The focus of this research was on the downstream habitat of the riparian ecosystem where sediment will likely affect the riverbed structure and salmonid populations.

5.2.1 Erosion of Impounded Sediment

The amount of impounded sediment erosion depends on a river's kinetic energy. This research correlates a river's kinetic energy to peak flow that occurred after a river erosion dam removal project. The highest peak flow occurred during the Condit Dam removal and had the highest percentage of impounded sediment erosion (Table 1). The La Valle Dam had the lowest peak flow and the smallest percentage of impounded sediment erosion (Table 1). Even though the Condit Dam had the largest percentage of erosion dam size does not seem to correlate with amount of impounded sediment erosion. The largest river erosion dam removal project was the Elwha and Glines Canyon Dam removal project that had a peak flow of 292 m^3/s and experienced only 11.9% impoundment sediment erosion (Table 1). The Elwha and Glines Canyon Dam peak flow was similar to peak flows observed at the medium sized Marmot Dam, river erosion dam removal (Table 1). However, the Marmot Dam experienced 50% impounded sediment erosion. It seems that dam size does not correlate with peak flow or the amount of impounded sediment eroded, so other factors most likely influence impounded sediment erosion.

Table 1. Dam Removal Case Studies. A list of river erosion method dam removal projects and their corresponding sediment properties. Note: (–) signifies data that could not be found within current literature.

Size	Dam Name	Sediment Composition	% Fine Sediment	Sediment Load Eroded	Downstream Deposition	Sediment Reach	Peak Total Suspended Solids	Peak Flow	Source
Small	Brownsville Dam	Gravel	—	6,630 m^3	~ 0.3 m	720 m	700,000 mg/L	68 m^3/s	Zunka et al. 2015; Tullos et al. 2014
	La Valle Dam	Fine Sediment	—	10,928 m^3	—	160 m	—	10.36 m^3/s	Greene et al. 2013; Catalano et al. 2007; Doyle et al. 2003b; Provencher et al. 2008
	Sparrowk Dam	Fine Sediment	65%	—	—	—	2,000 mg/L	—	Ahearn and Dahlgren 2005
Medium	Marmot Dam	Gravel	50%	365,000 m^3	4 m	1.3 km	49,000 mg/L	38 m^3/s	Draut and Ritchie 2015; Cui and Wooster 2014; Zunka et al. 2015; Sawaske et al. 2012
Large	Condit Dam	Fine Sediment	95%	1,600,000 m^3	18 m	2 km	850,000 mg/L	400 m^3/s	Randle et al. 2015; Wilcox et al. 2014
	Elwha & Glines Canyon Dam	Gravel	23%	3,100,000 m^3	1 m	21.6 km	7,890 mg/L	42 m^3/s	Warrick et al. 2015; Draut and Ritchie 2015; Magirl et al. 2014; Randle et al. 2015

When taking into consideration the sediment mitigation methods with the percentage of impounded sediment, the river erosion dam removal projects that had sediment mitigation methods in place experienced less impounded sediment erosion (Figure 5). The dam removals that had sediment mitigation methods in place were the La Valle Dam and the Elwha and Glines Canyon Dam that incorporated a notch/release method to stabilize impounded sediment. The Condit Dam had the highest percentage of erosion out of all of the river erosion method case studies (Figure 5). This high erosion may be due to the way the dam was removed in a rapid release approach, which allowed the majority of the impounded sediment to be transported downstream all at one time.

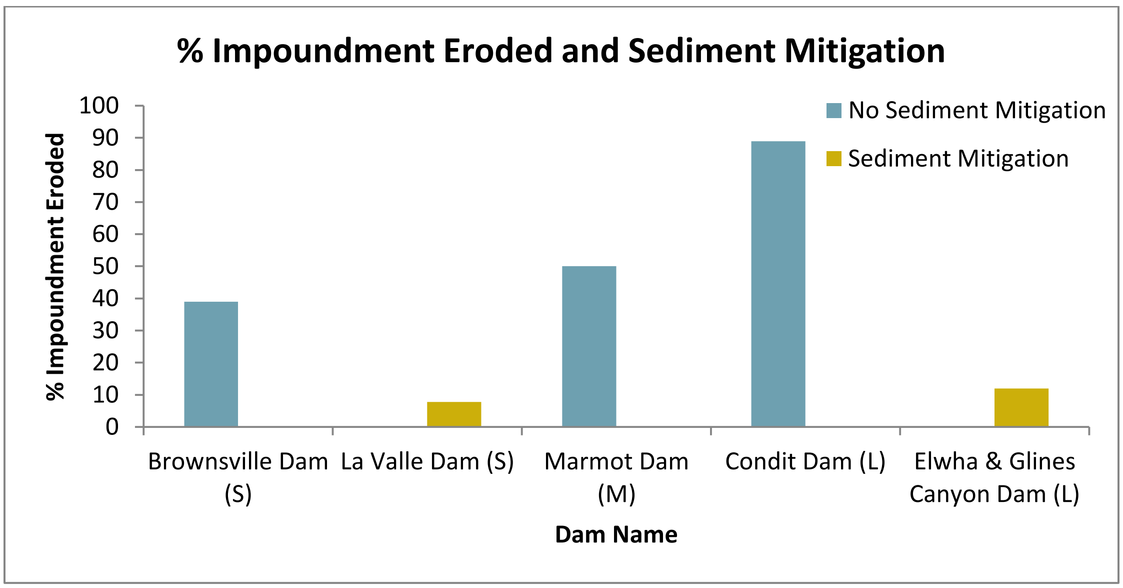

Figure 5. Percentage Impounded Sediment Eroded and Sediment Mitigation. The percentage of impounded sediment eroded downstream compared to dam removal projects that had no sediment mitigation in place. Dam size abbreviations are S = small, M = medium, L = large. Note: Sparrowk Dam excluded from this figure because no data was available.

The percentage of impounded sediment eroded seems to be depedent on whether or not there is a dam removal method that incorporates sediment mitigation methods, such as the draw down dam removal method that allows portions of the impounded sediment to be stabilized through drying before they are able to erode downstream. Dam size does not seem to influence the percentage of impounded sediemnt erosion the La Valle Dam was a small dam while the Elwha and Glines Canyon Dam was a large dam and both experienced a smaller percentage of impounded sediment erosion than the other dams in this study (Figure 5).

5.2.2 Sediment Composition

Depending on impounded sediment composition, there is a potential for eroded sediment to improve or temporarily decrease salmonid habitat. These case studies contained river erosion dam removal projects that consist of either gravel or fine sediment impoundments. The Brownsville, Elwha, Glines Canyon, and the Marmot dams all contained gravel impoundments; while the Condit, La Valle, and the Sparrowk dams all contained fine sediment impoundments (Table 1).

The largest percent of impounded sediment erosion occurred during the Condit Dam removal, while the smallest percentage of impounded sediment erosion occurred in the La Valle Dam (Figure 6). Both of these dam removals had the potential to greatly impact salmonid populations because the impoundments were composed of fine sediment (Figure 6).

The Marmot and Condit dams both experienced 50% and higher impoundment sediment erosion (Figure 6). Even though there was a large amount of sediment eroded in both the Marmot and Condit dams; the Condit Dam has a higher potential to impact salmonid populations due to the release of fine sediment. The Marmot Dam may positively impact salmonid populations through the creation of spawning habitat through the erosion of gravel sediment.

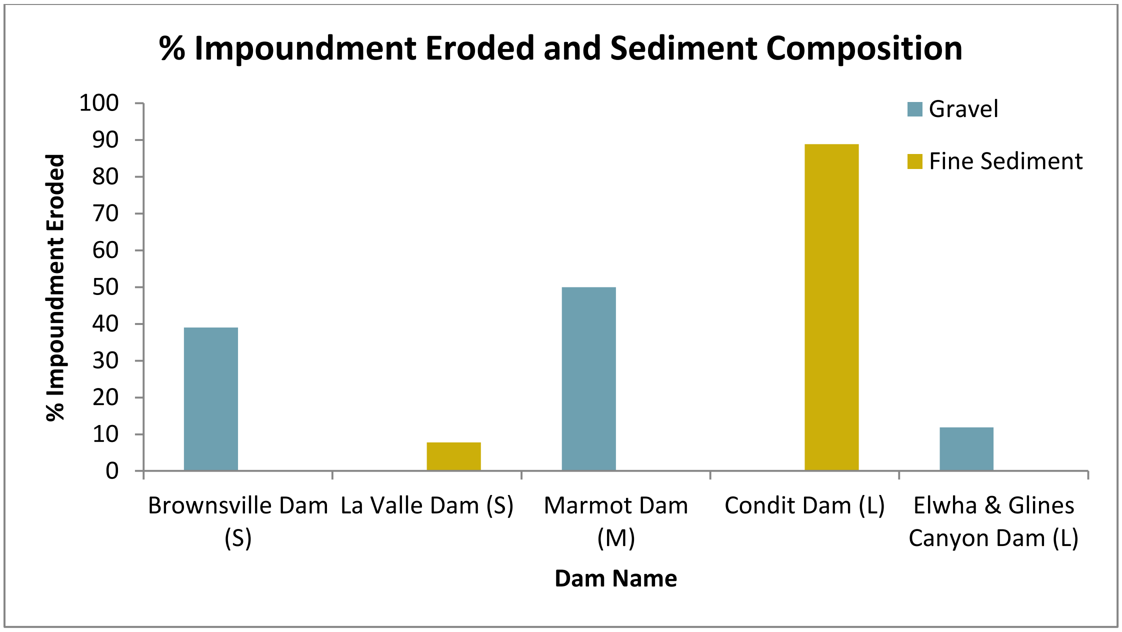

Figure 6. Percent Impoundment Eroded and Sediment Composition. The percentage of impounded sediment eroded downstream. Dam size abbreviations are S = small, M = medium, L = large. Note: Sparrowk Dam was excluded from this figure because no data was available.

5.2.2.1 Turbidity

As mentioned in Chapter 2, an increase in turbidity negatively affects salmonid populations due to a decrease in oxygen availability. Turbidity increases with the amount of suspended solids. Fine sediment will increase suspended solids during high flow events through the erosion of impounded fine sediment. River erosion dam removal projects that have high suspended solids would negatively impact salmonid populations rather than dam removal projects that have low suspended solids.

The largest peak total suspended solids value was highest in the Condit Dam removal (Figure 7). The smallest peak total suspended solids occurred during the Sparrowk Dam removal (Figure 7). The largest peak total suspended solids happened to occur during a large dam removal project and the smallest peak total suspended solid was observed in a small dam removal project. However, generalizations cannot be drawn between peak total suspended solids and dam size. Even though the largest and smallest peak total suspended solid occurred during large and small dam removals, respectively, the Elwha and Glines Canyon Dam was a large dam and had a small amount of peak total suspended solid (Figure 7).

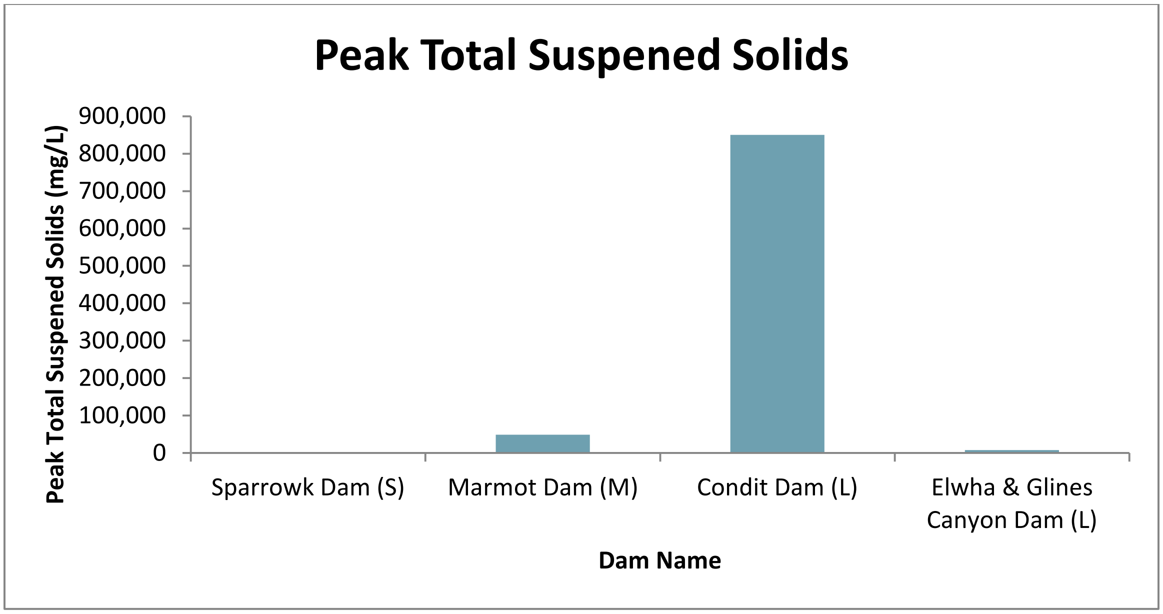

Figure 7. Peak Total Suspended Solids. The peak total suspended solids for each dam removal project and dam size. Dam size abbreviations are S = small, M = medium, L = large. Note: The La Valle Dam and the Brownsville Dam was excluded from this figure because no data was available.

5.2.2.2 Downstream Deposition

The Conduit Dam removal had the highest deposition of out of all cases at 18 m of sediment while the lowest amount of deposition occurred at the Brownsville Dam removal at 0.3 m (Figure 8).

The Conduit Dam contained impounded fine sediment which can negatively affect salmonid populations by creating a layer of sediment over salmonid redds and preventing juveniles from emerging from eggs. However, the Brownsville Dam contained impounded gravel sediment and could positively affect salmonid population by creating salmonid spawning habitat.

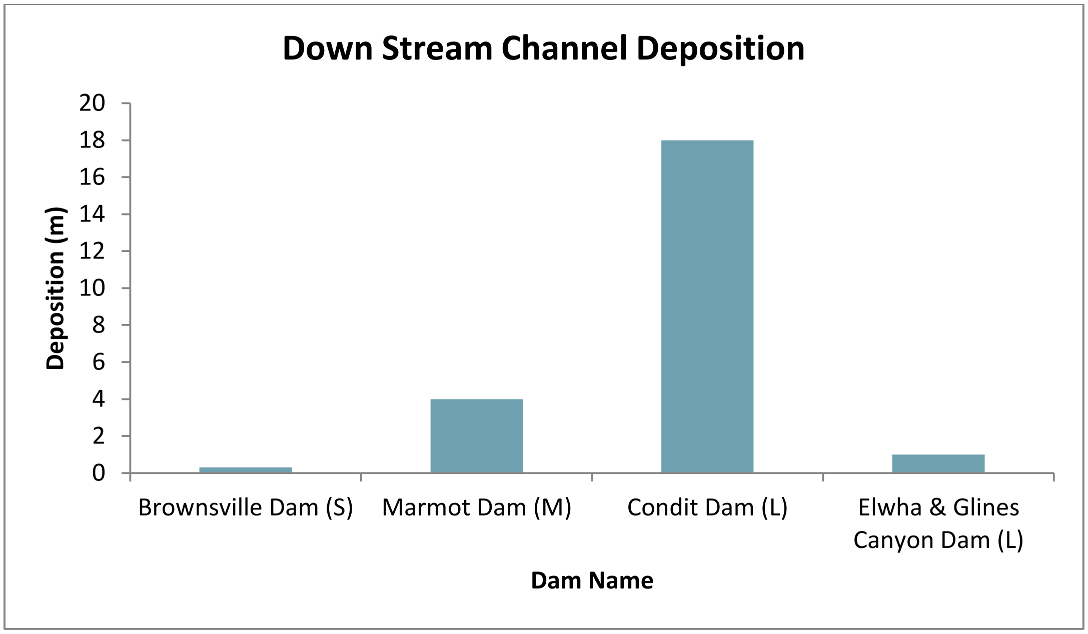

Figure 8. Downstream Channel Deposition. The average amount of sediment deposited within the channel downstream of the dam removal site. Dam size abbreviations are S = small, M = medium, L = large. Note: Sparrowk and La Valle Dam were excluded from this figure because no data was available.

The length of downstream transfer of eroded impounded sediment increases the area of the effects of sedimentation on the riparian ecosystem and salmonid populations. The Elwha and Glines Canyon Dam had the furthest sediment transfer downstream (Figure 9). All other dam removal projects did not experience nearly as high of a transfer downstream than the Elwha and Glines Canyon Dam removal (Figure 9).

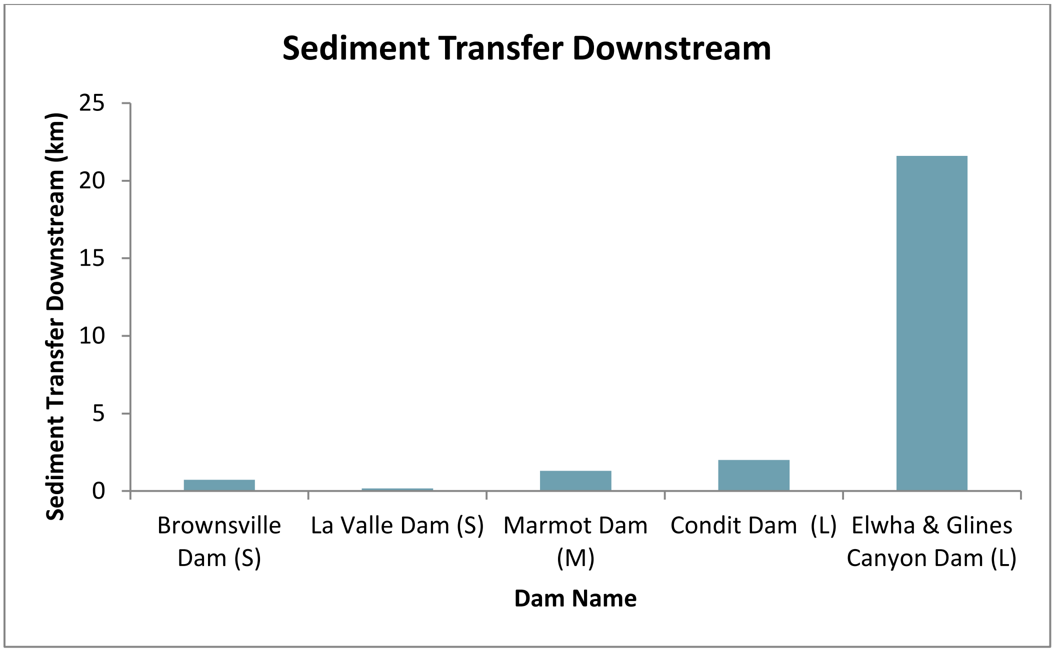

Figure 9. Sediment Transfer Downstream. The length in kilometers of the downstream transfer of sediment deposited. Dam size abbreviations are S = small, M = medium, L = large. Note: The Sparrowk Dam was excluded from this figure because no data was available.

5.3 Effects of Dam Removal on Salmonids

Even though it is known that sediment negatively affects salmonids, there is a lack of studies that assess sediment effects on salmonid populations following dam removal. Among the case studies presented in this research there was only one study, the Marmot Dam removal, which reported whether or not salmonids were utilizing the newly open habitat; even though, the purpose of four out of six river erosion dam removal projects in this research were to increase salmonid passage (Cui et al. 2014). The Elwha and Glines Canyon Dam removal is set to conduct salmonid population surveys post dam removal, however the data has yet to be published.

It remains unclear whether or not dam removals specifically decrease salmonid populations. As mentioned in Chapter 2, fine sediment negatively impacts salmonid population and the prevention of fine sediment has been the focus of mitigation for dam removal projects. However, there have been dam removal projects where impounded sediment consisted of gravel and produced positive effects. The Brownsville Dam removal in Oregon, contained a gravel impoundment had no negative effects on the riparian ecosystem after dam removal

(Kibler et al. 2011). Instead of producing negative impacts to salmonid species the Brownsville Dam positively changed the features of the downstream habitat by changing a hard pan riverbed to potential spawning habitat (Kibler et al. 2011). After dam removal, sediment transport created new sand bars, and increased the size and volume of existing sandbars and created a gravel riverbed (Kibler et al. 2011). The deposition of gravel sediment over a hard pan channel created potential habitat for spawning salmonids (Kibler et al. 2011).

It is predicted that a dam removal project on the Klamath River in Oregon will cause a one-third reduction in a fall-run salmonid population (Quiñones et al. 2014). On the North Fork Poudre River fine sediment eroding from the Halligan reservoir filled pools and interstitial pore spaces within the channels cobble and boulder bed impairing spawning and holding habitats for trout (Wohl & Cenderelli 2000). Other projects have observed salmonid spawning in newly deposited gravel just months after dam removal (Quiñones et al. 2014).

This research focused on sediment metrics that would negatively impact salmonid populations from known negative effects of fine sediment to the salmonid life cycle. From this small set of case studies the dam removal project that has the highest potential to impact the salmonid life cycle is the Condit Dam removal project. The river erosion dam removal eroded 88.9% of fine sediment into the downstream riverbed. Fine sediment is most likely to impact the downstream environment through turbidity and fine sediment infiltration into downstream gravel beds.

5.4 Chapter Summary

A total of six river erosion method dam removal case studies were examined during this research. The cases consisted of dam removal projects for small, medium, and large dams. The Brownsville, La Valle, and the Sparrowk Dams were all small dams under 5 m tall. The Marmot Dam removal was a medium size dam. The Condit and the Elwha, and Glines Canyon Dam removal were large dam removal projects.

Specific metrics were used to identify potential sediment effects on salmonid populations. The metrics used were peak flow, percentage impounded sediment eroded, sediment mitigation methods, sediment composition, total peak suspended solids, downstream channel deposition, and sediment transfer downstream. Each of these metrics was used to identify the potential for the erosion of impounded sediment, turbidity, and fine sediment infiltration.

Upon analyzing whether or not dam size produces detrimental effects towards salmonid populations; it seems like there is no connection to dam size and sediment negative effects. However, sediment composition and whether or not sediment mitigation methods were implemented seems to have an effect, decreasing sediment negative effects. For example, if a dam removal project did not use a sediment mitigation method there was higher percentage of impounded sediment eroded.

The largest percentage of eroded impounded sediment occurred during a large dam removal project, the Condit Dam, which consisted of fine sediment. The percentage of erosion of impoundment is not related to dam size, but whether sediment mitigation methods were used and sediment composition. The highest amount of turbidity and deposition also occurred during the Condit Dam removal. It seems the rapid release approach used on the Condit Dam had the highest potential to negatively impact salmonid populations. Other dam removal projects may depend on sediment composition and whether or not sediment mitigation methods were used.

Chapter 6 – Research Conclusions and Recommendations

The major concern with dam removal projects are how an increase in fine sediment loads will decrease salmonid populations (Downs et al. 2009). The majority of dam removal projects has focused on the prevention of impounded sediment effects on riverbed structure, as well as negative effects on salmonids. The majority of dam removal projects prevents or limits the amount of sediment transported downstream after a dam removal project.

6.1 Research Conclusions

This section presents conclusions from each prior chapter of this research. The section begins with conclusions from Chapter 2 regarding sedimentation and dam removal effects on salmonids and ends with Chapter 5 and the effective mitigation of sediment.

6.1.1 Sedimentation and Dam Removal Effects on Salmonids

The main concern with dam removal projects is the known effects of fine sediment on the salmonid life cycle. In particular fine sediment can negatively affect salmonid population by increasing water's turbidity and causing fine sediment infiltration. Fine sediment can decrease salmonid survival by increasing turbidity, covering redds, decreasing the amount of available oxygen, causing premature hatching, and causing a decrease in juvenile salmonid fitness. Even though it is known that fine sediment negatively affects salmonids, there have only been a few dam removal projects that have fully assessed how sediment has actually affected salmonid populations after a dam removal.

6.1.2 Dam Removal and Sediment Mitigation Methods

There are four types of sediment mitigation methods to limit the effects of sedimentation on the riparian ecosystem. The four types of sediment management options prior to dam removal are no action, river erosion, mechanical removal, and stabilization (ASCE 1997). Each method minimizes the effects of sedimentation on the riparian ecosystem after dam removal. Out of the four methods of dam removal, the river erosion method has the highest potential for impacts to the riparian ecosystem and salmonid populations (Sawaske and Freyberg 2012). The potential impacts for removal are the impacts that impounded sediment is allowed to naturally erode by a river's flow after dam removal (Sawaske and Freyberg 2012). Even though the river erosion method may be determined to be the best dam removal method, any sedimentation release may alter salmonid populations through the alteration of the riverbed structure.

With the river erosion method fish are expected to decline initially because of dam removal projects disturbance of the tributary (Doyle et al. 2005). The disturbance of spawning habitat is due to increasing areas where fine sediment infiltration may occur. This decline may be due to dam removals and the resulting increase in sediment load, increase turbidity, and riverbed deposition (Doyle et al. 2005).

6.1.3 Sediments after Dam Removal

A dam removal project restores a river's longitudinal connectivity; however, the river needs to readjust to an equilibrium state after dam removal. Before a dam removal the impoundment has storage of sediment while there is a lack of sediment below the dam. After a river erosion dam removal project, a channel allows sediment, water, and nutrients to migrate downstream, while allowing riparian species to migrate again. A newly opened dam allows for the reservoir to release water and leaves the channel to create a new path through the impounded sediment and areas downstream. While a new channel is created through natural processes the impoundment area and the downstream habitat is altered by the new flux of water and sediment.

The width of the newly created channel at the dam removal site may either be narrower, wider or stay the same; however, there has not been generalization made because different dam removal projects have experienced different results. The upstream width of the channel is thought to decrease. Once the channel readjusts in the impoundment then the sides of the dam dry up and become stabilized; creating channel banks.

Water is a transport mechanism for upstream sediment to move from the impoundment downstream. The amount of sediment transferred depends on the amount of kinetic energy a channel has. If there is enough kinetic energy, the impounded sediment is able to erode and is deposited downstream of the dam removal site. As sediment moves downstream there can be an increase in sediment load in a riparian habitat that was previously deprived of sediment. The riverbed below the dam is typically eroded to become a hard pan, with dam removal sediment replenishing the riverbed with newly deposited sediment and subsequently creating habitat.

In order for impounded sediment to impact the downstream riparian habitat, impounded sediment must first erode from the impoundment downstream through a river's kinetic energy. The potential for impounded sediment erosion may depend on sediment properties; these include sediment composition, cohesive property, and sediment load of the impounded sediment. These characteristics directly affect how impounded sediment will impact riparian habitat by increasing the potential for impounded sediment erosion. Impoundment sediment erosion may decrease due to an increase in cohesive properties, whether or not the impoundment consists of fine sediment, and the load of impoundment sediment eroded. If sediment is able to transfer downstream then sediment will be deposited within the riparian riverbed and impact the riverbed structure and salmonid populations.

6.1.4 Effective Mitigation of Sediments

The Brownsville Dam removal was beneficial as that it turned a barren incised hardpan channel 400 m downstream of the dam into a channel filled with gravel and cobble (Kibler et al. 2011). This new gravel and cobble habitat may be potential habitat for spawning salmon. The gravel size in the riffle immediately downstream of the dam increased to a size greater than preferred by Chinook salmon for 1 year (Kibler et al. 2011). The channel remains to be potential habitat for future spawning as sediment deposition makes the area more favorable to spawning, rather than a hard-pan where spawning is unlikely.

However, other dam removal projects may be detrimental to a salmonid life cycle. During a dam removal on the Mokelumne River in California a sampling point lacked drainage which caused sediment to remain saturated and decreased oxygen levels at that location (Ahearn and Dahlgren 2005). However, as this research explains, the detrimental effects of sediment to the salmonid life cycle are focused on how fine sediment decreases salmonid populations. The prevention of sediment associated with dam removal projects is how fine sediment will cover gravel and impair salmon spawning grounds. However, with predominantly cobble and gravel behind a dam there may be an increase in spawning habitat by dam removal (Kibler et al. 2011).

The main concern with dam removal projects is the known effects of fine sediment on the salmonid life cycle. In particular fine sediment can negatively affect the salmonid life cycle by increasing water's turbidity and causing fine sediment infiltration. Fine sediment infiltration alters the riverbed structure into a featureless riverbed and decreases the area that salmonids are able to spawn in. Fine sediment can decrease salmonid survival by increasing turbidity, covering redds, decreasing the amount of available oxygen, premature hatching, and causing a decrease in juvenile salmonid fitness. Even though it is known that fine sediment negatively affects salmonid life cycle there have only been a hand full of dam removal projects that have fully assessed how sediment has influenced salmonid populations after a dam removal.

A total of six river erosion dam removal case studies were examined during this research. The cases consisted of dam removal projects that were small, medium, and large in size. The Brownsville, La Valle, and the Sparrowk Dams were all small dams under 5 m tall. The Marmot Dam removal is a medium size dam at a height of 14 m. The Condit and the Elwha, and Glines Canyon Dam removal are large dam removal projects higher than 30 m.

Specific metrics were used to identify potential sediment effects on salmonid populations. The metrics used were sediment composition, percentage of fine sediment, sediment load eroded, deposition, sediment reach, peak total suspended solids, and peak flow. Each of these metrics was used to identify the potential for the erosion of impounded sediment, turbidity, and fine sediment infiltration.

Upon analyzing whether or not dam size produces detrimental effects towards salmonid populations; it seems like there is no connection between dam size and negative effects of sediment s. However, sediment composition and whether or not sediment mitigation methods were implemented seems to decrease sediment negative effects. For example, if a dam removal project did not use a sediment mitigation method, there was higher percentage of impounded sediment eroded.

The largest percentage of eroded impounded sediment occurred during a large dam removal project, the Condit Dam, which consisted of fine sediment. The percentage of erosion of impoundment is not related to dam size or sediment composition of fine or gravel sediment composition. The highest amount of turbidity and deposition also occurred during the Condit

Dam removal. It seems that the rapid release approach the Condit Dam had the highest potential to negatively impact salmonid populations. Other dam removal projects may depend on whether or not sediment mitigation methods were used and sediment composition. This research is a comparison of a small sample of river erosion dam removal projects; even though this is a start to identify how dam removal projects are potentially impacting salmonid populations, more in depth studies must be conducted to make more informed conclusions.

6.2 Future of Dam Removal

Proper mitigation of sedimentation from impacting the riparian ecosystem has yet to be identified. The riparian ecosystem is constantly altered through natural and human influences which make it difficult to attribute riparian alterations to effects of a dam removal. Kibler et al. (2012) found it difficult to evaluate changes in riparian riverbed structure after a dam removal due to local river effects.

In depth studies of how the river erosion method is impacting the riparian ecosystem are critical to improve the method to minimize its impact on salmonid populations as well as understand the impacts of dam removals to the riparian ecosystem. Identification of methods would depend on increasing the number of studies of dam removal projects that use the river erosion method and creating standardized methods to properly analyze variables using the river erosion method.

Such considerations of the salmonid life cycle may be a better estimate of the effects of eroded impounded sediment. As this research suggests, identification of primary gravel impoundment may have more beneficial effects than negative (Kibler et al. 2011). Prior impoundment sedimentation characteristics are critical to identify how the impoundment will affect the riverbed structure and salmonid habitat. Salmonid habitat degrades if there is an increase of fine sediment, but salmonid habitat may also increase if impounded sediment is composed of gravel (Kibler et al. 2011). Fine sediment infiltration may not occur if sediment impoundment does not have a large load of fine sediment.

The need for more documented research is key to identify links between multiple dam removal projects. Current research is focused on researching at single dam removal projects instead of looking at multiple dam removal projects. Currently no individual dam removal effects can be universally understood, however; the use of similar metrics will allow better understanding of dam removal methods than is currently known (Kibler et al. 2011).

Many dam removal projects also identify the impacts to the riparian ecosystem through different parameters of the changes within dam removal projects. Perhaps there needs to be a collective method to measure the alterations of a dam removal project to be able to make comparisons across all dam removal projects. At least this could be possible in terms of sedimentation and may not be beneficial for other riparian ecosystem processes. Identifying if there are any connections and conclusions that can be made would be useful for land manager that may be thinking about a dam removal on their property, instead of being intimidating.

6.2.1 Need for Further Research

There are known negative impacts of fine sediment to salmonid populations however, there is still little primary research on identifying if dam removal projects are directly negatively or positively affecting salmonid populations. For the negative effects of fine sediment to occur, impounded sediment must erode downstream. There are certain factors and the particular characteristics that decrease or increase impounded sediment erosion (Sawaske and Freyberg 2012). The river erosion method is used to allow for the passive transfer from an impoundment downstream to replenish the sediment deprived downstream riparian ecosystem. However, the river erosion method can use improvements to limit the potential effects on salmonid populations.

The ecological effects of dam removal need to be documented and quantified (Bednarek 2001). There needs to be more primary research on the effects of dam removal on channel structure and location and how sediment of dam removals is affecting riparian ecosystems. The lack of research may be difficult as Kibler et al. (2012) found it difficult to identify if changes in riverbed were due to dam removal or due to natural river flow.

Primary literature has been largely case study based, if found at all. The majority of dam removal projects have been reviews of grey literature documents, instead of a review of primary literature. Seawaske and Freybeg (2012) was the only primary literature review that synthesized multiple dam removal projects.

The original focus of this research was to identify how salmonid populations are suffering or rebounding after dam removals. Through this research it remains to be seen if this is occurring. As in both case studies, the focus was to provide rearing habitat for salmonid species, however, neither study identified whether this occurred after dam removal occurred. Additional information might still become available through the process of monitoring for the Elawha Dam, but could not be incorporated into this research as no such data was available to date. There has not been determination of whether these mitigation efforts have been studied.

6.2.2 Recommendations for Further Research

Since there is not a current metric to identify how dam removal projects are affecting the riparian ecosystem, there are particular metrics that should be included to assess the impacts of fine sediments on salmonid populations. These metrics include the parameters included in this research, as they would most likely detrimentally affect salmonid populations. Many of the figures and comparisons used in this research had to leave out particular dam removal projects, as current literature did not measure the metrics used for this research. Consistency of dam removal metrics is key to make possible generalizations across multiple dam removal projects. Metrics to include are percentage of fine sediment, amount of impounded sediment eroded, amount of downstream deposition, how far downstream sediment was deposited, peak total suspended solids, and highest peak flow observed after dam removal.

Another metric to identify is whether or not fine sediment infiltration is occurring within the riverbed. Since fine sediment infiltration is known to decrease salmonid populations then it should be identified whether or not it is occurring after a dam is removed.

In order to identify whether or not an increase in sediment load is attributed to a dam removal or not, there needs to be a better way to compare and contrast sedimentation before and after dam removal. Dam removal projects currently compare and contrast results to baseline data that are taken during the years prior to dam removal. However, collecting baseline data allows for inconsistencies of precipitation effects. It may be necessary to identify how much sediment is eroded from the watershed to properly identify how much sediment erosion is attributed to a dam removal.

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