Minimizing The Ecological Impacts of Dam Removal

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Executive Summary

Over the past decade, as the number of dams in the United States reach the end of their useful lives, proponents of river restoration have seized this opportunity to support the removal of dams for which the benefits of removal outweigh existing economic benefits. The frequency of dam removals have increased substantially in the past ten years contributing to improved river connectivity and restored ecological communities. Managers have struggled, however, with the challenge of determining the magnitude, timing and scale of physical and biological responses following a dam removal, which is critical in deciding if and how dams removals should be performed.

American Rivers, the nation's leading advocate for protecting and restoring rivers, has a keen interest in identifying the best methodologies that dam removal project managers can use to minimize ecological impacts when removing a dam. In support of American Rivers' interest in identifying specific best management practices (BMPs) of dam removals, we analyzed the results of peer-reviewed studies of dam removal sites in conjunction with the respective removal design plans to discern if any consistent ecological outcomes can be associated with particular removal methods.

We found that the primary concern for project managers when designing a dam removal is ensuring that sediment caught behind the impoundment is managed in such a way that does not compromise downstream benthic and fish communities. As such, most of our identified BMPs relate to managing the mobilization and erosion of the sediment that has accumulated behind the dam structure. Standard BMPs primarily include dewatering portions of the reservoir before removing the dam structure, using silt fences to manage sediment and water quality in the short term, and stabilizing banks to reduce erosion over the long term.

There is a suite of BMPs that can be recommended depending on how optimal a stream's geomorphological characteristics are for removal. For example, dams located in low gradient rivers with large quantities of fine sediment accumulated behind the dam impoundment are non optimal and will likely require a phased dewatering process in conjunction with measures to prevent sediment erosion. Contrasted to this, dams in high gradient systems with coarse sediment are typically optimal environments for dam removal. The BMP's for these systems typically include instantaneous dewatering and natural sediment release because the system would have enough energy to flush the coarse sediment rapidly through the downstream system, which is less likely to damage fish habitat and bury benthic organisms. Further, removing dams situated in optimal settings do not need as much management and the process is less costly. Of course, these findings do not discourage the removal of dams in non-optimal settings, it just highlights that their removals will require more planning, logistics and funds.

In addition, our findings suggest that more systematic and consistent monitoring is needed to make a robust meta-analysis of dam removal impacts on stream ecology possible. A meta analysis would require consistency in the type of data collected and frequency and duration of data collection, neither of which has been practiced at large. Specifically, collecting both abiotic and biotic data for each dam removal site would improve the ability to conduct a meta-analysis of BMP impacts on ecological outcomes. Using the

Maine Coastal Council monitoring framework of 2007 as a starting point, we propose key variables to monitor following a dam removal.

Introduction

The number of dam removals throughout the United States has been increasing over the past ten to fifteen years, nearing almost a total of 1,150 dams removed to date (American Rivers). Managers have struggled, however, with the challenge of determining the magnitude, timing and range of physical and biological responses that can occur after a dam removal (Babbitt, 2002). The sudden release of sediment and organic matter following a dam removal can compromise downstream ecological habitat, sometimes permanently (Stanley and Doyle, 2003; Doyle et al., 2003a; Riggsbee et al., 2012). Understanding the response of a river system to dam removal and the potential for ecological disturbance is critical in deciding if and how dam removals should be performed given a project's specific restoration objectives (Hart et al., 2002).

In attempt to fill this knowledge gap, there have been a growing number of scientific studies investigating dam removal impacts on river geomorphological and ecological recovery. Yet in spite of this progress, scientists, environmental managers, state, and federal agencies are still looking to better understand the implications of dam removal on river ecosystems (Tullos et al., 2014). There is broad consensus among the dam removal community that there is a lack of basic data, and what data does exist is highly variable (Palmer et al., 2010). To aid this need, in 2015, the USGS Powell Center Dam Removal Working Group published the Dam Removal Database containing monitoring information associated with all published peer-reviewed scientific studies of dam removals in the United States and abroad (Bellmore, 2015). Generally speaking, studies in this database evaluate either biotic or abiotic response, especially following sediment release. This body of work is a testament to the initial progress the dam removal research community has made in better understanding general best management practices based on the amassing number of experiences across the country.

American Rivers, the nation's leading advocate for protecting and restoring rivers, has played a key role in facilitating a large portion of the nation's dam removals. They have a keen interest in identifying the best methodologies project managers and project designers can employ to minimize ecological harm from the removal process. In support of American Rivers, we analyzed peer-reviewed studies from the USGS Dam Removal database that could be paired with the respective dam removal design plans to identify specific best management practices (BMPs) of dam removals that are least detrimental for aquatic systems. This report contains guidelines for future dam removal projects.

Based on the studies we reviewed, our findings confirmed the consensus among dam removal practitioners that designing a dam removal is river system dependent, but there are specific BMPs that can be recommended for low gradient systems with fine sediment that will minimize the ecological impact downstream. Further, we found that while there has been a growing body of literature, dam removal science is still limited by the differences in quality and type of information collected among different studies (Kibler et al., 2011). This data variability prevents a statistically robust meta analysis, which has been a call from the dam removal community. Having initially tried to meet this call in our analysis for American rivers and been unable to on account of variable data, we recommend a standardized monitoring framework to create uniform data collection across dam removal projects and allow for more large-scale analyses to be done.

Background

Key to understanding the potential impacts of dam removal is recognizing the significance that sediment release can have on downstream water quality and habitat (Pizzuto, 2002). Sediment management is the most important variable to consider when prioritizing the protection of ecological integrity. Sediment response to dam removal, however, is variable, complex, and often times difficult to predict (Katopodis, 2010). How sediment moves downstream depends on four main factors:

- Volume of sediment stored behind the impoundment
- Type of sediment present (fine vs. coarse grained)
- Hydrologic flow regime
- River gradient

Ecological Impact of Dam Removal

While sediment is being released during and after dam removal, water turbidity typically increases downstream, especially for releases of finer sediments (<0.02 mm). Additionally, deposition of released sediment can modify riverbed forms and features (Poff et al., 2002). These physical disturbances to water quality and habitat, be it temporary or permanent, will impact organism functioning and can result in the death or displacement of the river's existing organisms. That being said, sediment pulses do not always compromise river systems. In such cases, concerns for sediment management during dam removal can be unwarranted for those systems (Tullos, 2014). For other dams, however, where the structure's removal clearly generates significant physical and ecological change to the system, managing sediment is paramount for a successful ecological restoration (Tullos, 2014).

The grain size distribution of sediments impounded behind the dam is another crucial factor in determining the extent of ecosystem response. The finer the sediment, the more likely the sediment is to stay suspended in the water column increasing the severity of water turbidity. Finer sediments can also fill the interstitial spaces in downstream riverbed gravels, thereby reducing benthic aquatic habitat (Randle et al., 2015).

Ecological communities most directly affected by sediment deposition are benthic organisms and macroinvertebrates, which lack the mobility of fish and whose abundance is closely linked with particle size (Cummings & Lauff, 1969). Impacts on these communities include dislodgement, interference with gathering food, larval respiratory dysfunction, exterior abrasion, and smothering (Richards and Bacon, 1994; Stewart, 2006). In spite of their sensitivity to immediate disturbances, macroinvertebrates are known to rebound in a short period of time due in part to their high fecundity (Muehlbauer et al., 2011). A dramatic reduction in the number of benthic organisms has implications for fish since these organisms can be a key food source. If food supply is compromised, fish could abandon the river reach in search of areas with more plentiful food resources. The increase in turbidity associated with sediment release also contributes to a disruption of fish food webs as it decreases fish visibility for hunting. Another impact of increased fine sediment deposition on fish includes reduced availability of spawning habitat, given that many fish prefer clean, coarser substrate to lay eggs on (Wood & Armitage, 1997).

Dam Removal Process

There are four main processes that occur during a dam removal process: Dewatering, sediment management, erosion control, and species management (*Figure 1*).

There are various approaches to each of these processes dependent on the project and system characteristics. These approaches may vary based on a dam's height, the type and volume of sediment trapped behind the dam impoundment, the type of system and accessibility to dam structure, and compliance requirements. How each approach is conducted is the best management practice for that system. The following are brief explanations of each approach.

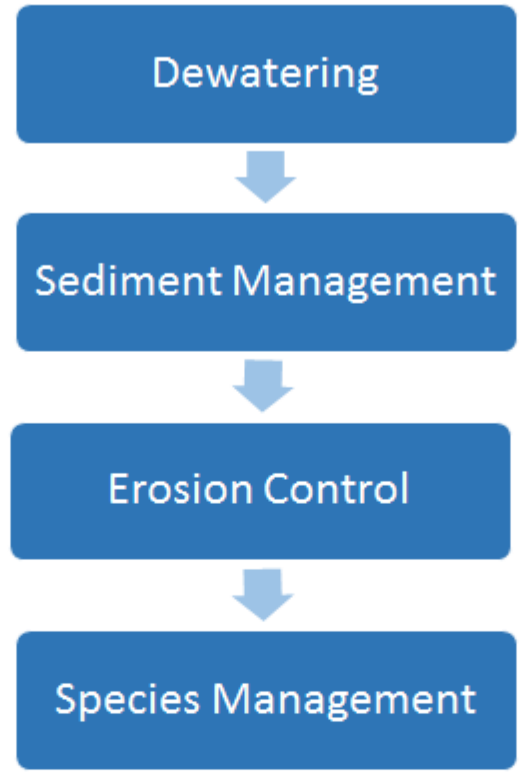


Figure 1: *The Four Key Stages of Dam Removal*

Dewatering

To avoid abrupt mobilization of large volumes of sediment by the river's current, engineers will commonly remove water from an impoundment before construction, especially for larger dams. There are different approaches to dewatering. The most common approach is to conduct instantaneous dewatering, where the dam is notched down in a certain section and the water behind the impoundment flows through the newly created divot. Phased dewatering, where the height of the dam is notched down incrementally, is another technique used to gradually draw down the reservoir over a period of time. If the dam has functional sluice or mud gates, gradual drawdown can be achieved by controlling the opening capacity of the gates or structures. Stop logs can also used by installing them on the dam and removing them incrementally to allow for staged dewatering. Alternatively, diversion structures, such as cofferdams, can be utilized for dewatering to direct the flow over a divot, in addition to acting as a control structure in phased drawdown. Typically, cofferdams can be constructed from fill, bulk bags, or drilled into stable structures for structural support. They can also serve as a water control structure to facilitate phased drawdown. Another option to dewatering from around an impoundment is to create a diversion channel that goes around the impoundment.

Sediment Management

Of the dams we reviewed, the greater a dam's height, typically the greater the volume of sediment trapped behind the dam. Others in the research community would support, however, that the greatest indicator of sediment volume is the reservoir width to river channel ratio (Katopodis, 2006). Smaller dams, especially run of the river dams, are less likely to have significant sediment build up because large storms can easily mobilize trapped sediment. As described earlier, a large pulse of fine sediments have a high potential of smothering downstream habitat and filling interstitial spaces that would otherwise be habitat for benthic organisms. As such, designers and state regulators make sure sediment release is controlled. Excavating sediment instead of releasing it all downstream has been found to reduce the negative short-term effects on biota in up and downstream reaches, as well as decrease the ability of invasive species to colonize newly exposed surfaces (Winter, 1990). Coarser sediments are less likely to have as serious a detrimental impact and therefore, when dams in rivers with coarse sediment are removed, potentially there is less need for mechanical sediment removal.

Erosion Control

In addition to the release of sediment trapped behind the dam impoundment, project managers have to account for both short term and long term erosion of river banks and sediment that gets mobilized due to construction activity. Dam removal projects that stabilize sediments can minimize downstream impacts by reducing the rate at which sediment remaining in the river channel is transported downstream (Wildman and Macbroom, 2005). Mechanisms of short-term erosion control include silt fences, floating silt or debris booms, and cofferdams to divert the water and conduct construction in the dry to minimize turbidity. Long-term erosion control can include rip rapping banks, placing erosion matting, grading banks, revegetating exposed soils, and placing in-stream rock vanes.

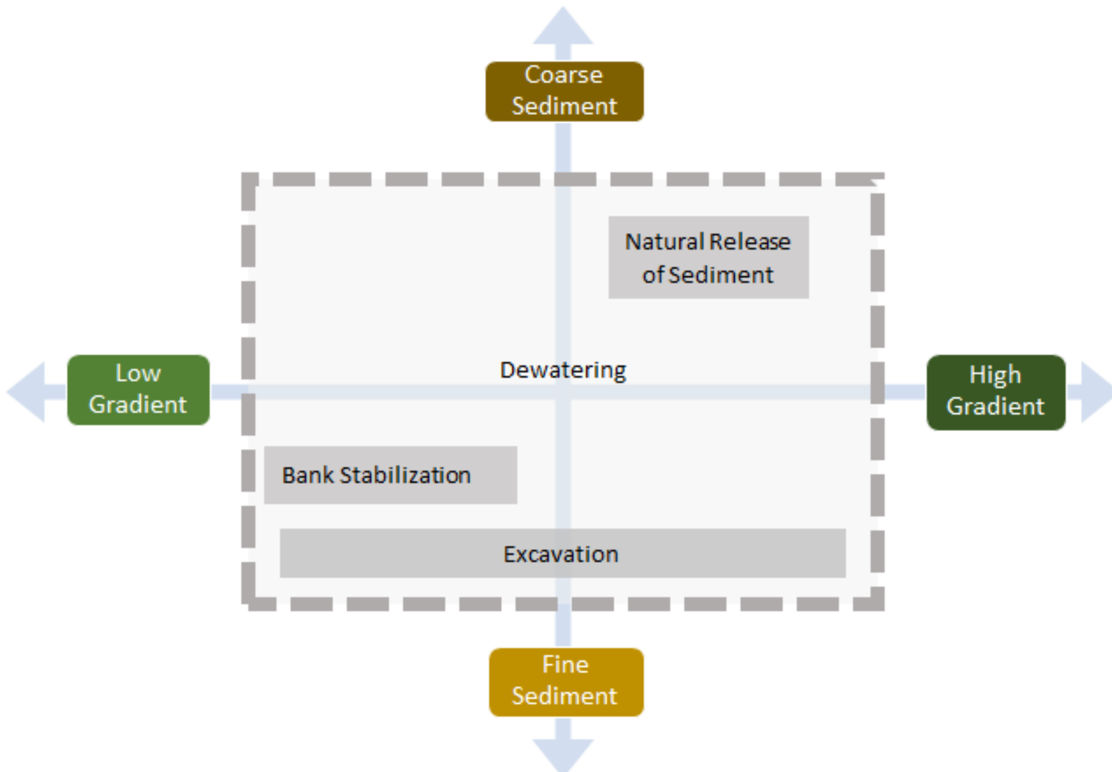
Constructed Habitat

Rivers regulate energy through riffles, runs, and pools along the river bottom. These features provide critical habitat and are important to the biological productivity of streams (Gordon et al., 2004; Burroughs et al 2009). Recognizing this, constructed habitat or riffles and pools have become a popular practice in stream restoration. It has been suggested that restoring riverbed form to create habitat could decrease recovery time following dam removal (Burroughs et al 2009).

BMPs Based on River Characteristics

Given that the best management practice depends on the physical characteristics of the river system, we created a diagram to showcase the best management practices along with the driving system characteristics, sediment grain size and river gradient (*Figure 2*).

Figure 2: S*chematic representing sediment management BMPs based on generalized physical characteristics*



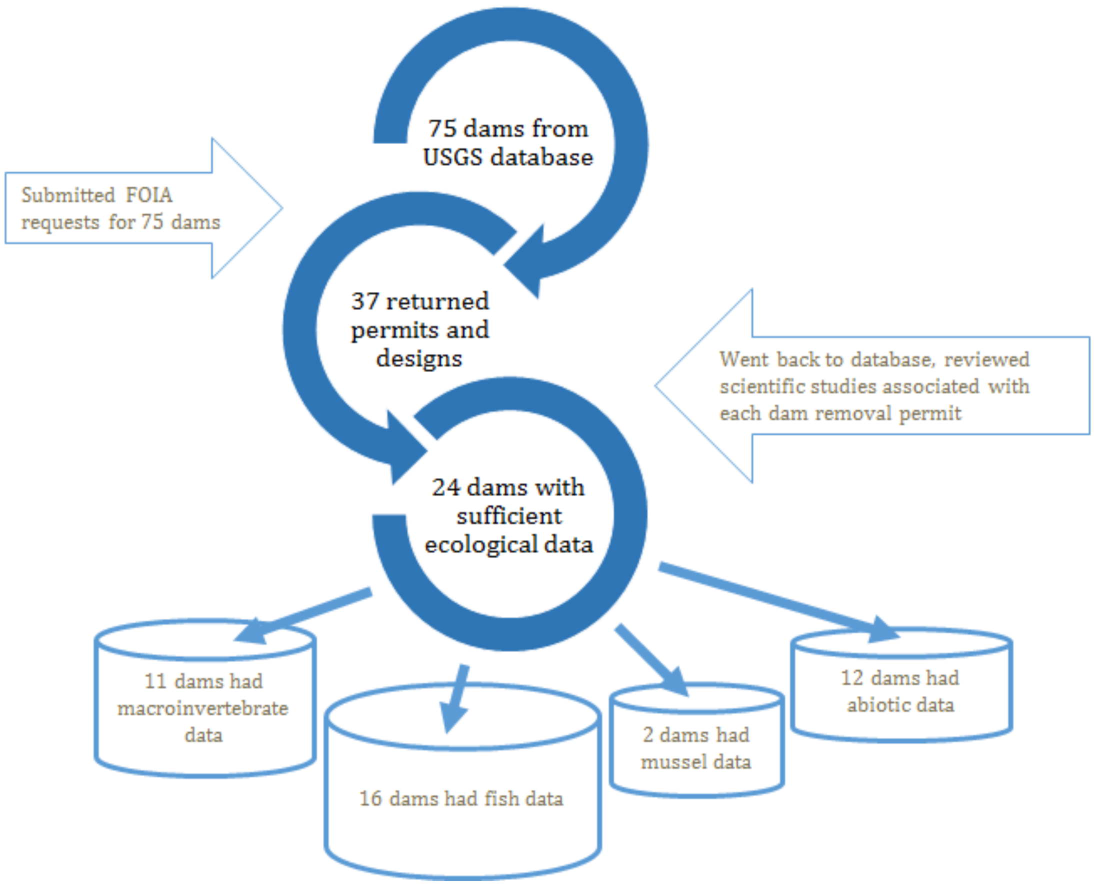
Methods

The objective of our research was to determine which BMPs notably minimized the short term negative ecological impacts of dam removal. Using the USGS Powell Center Dam Removal Database, we identified 75 dams from the database's 130 dam removal sites across the United States that had monitoring before and after its demolition for at least one year. For these 75 identified dams, there are a total of 116 site specific associated peer reviewed studies with either biotic and/or abiotic data analysis (figure 3). To determine the specific dam removal methods associated with these sites, 401/404 permit applications for the removal of these dams were requested through the Freedom of Information Act. These permits would provide additional details about the construction that would not likely be supplied in the scientific research, including design plans, and why the dam was removed.

With our objective being to identify the BMPs of dam removals with the most minimized ecological impact, we designed an objective hierarchy. With the objective of minimizing ecological impact, we selected studies that monitored ecological outcomes before and after removal. Of those studies, we selected only those that highlighted continuous ecological responses rather than categorical responses. Categorical ecological data would not have sufficiently reflected how the dam was removed because it does not convey trends. An example of categorical data's insufficiency would be if downstream fish had moved upstream after the dam was removed. This will not vary depending on how the dam was removed, however, fecundity of fish, a continuous variable, will vary and hopefully will give greater characterization.

Our intention was to conduct a meta-analysis based on these studies with their respective dam's site conditions and construction methods. Figure 3, below, illustrates the process of our data selection.

Figure 3: *Characterization of Data Selection*



General Data Characteristics

We received permit applications for 37 of the 75 dams. Of these 37 dams, there were 63 associated scientific studies, two thirds of which included biotic data and one third, which had abiotic data. Of the studies with continuous biological data, there were 24 associated dams with which we could characterize ecosystem recovery. We defined a system as recovered when downstream communities reverted to pre removal conditions or transitioned to conditions specified by their reference sites. In addition to the ecological outcomes we also looked for trends in river geomorphology. Our dam sites were located in varied physical and climatic environments throughout the country (Figure 4). At this point in our data collection, we decided that due to the variability of the types and quality of biotic and abiotic data, as well as the uniqueness of each dam site, a statistical meta-analysis would not be possible. We would conduct a qualitative analysis instead.

Figure 4: Geographical distribution of dam sites being studied

Over half of the selected studies analyzed dam removals of dams with heights between 1 and 3.3 meters (Figure 5). Three of these dams were greater than six meters: the Savage Rapids Dam (11.8 m), Woodside I Dam (9.4 m) and Woodside II Dam (13.1 m). Most of the studies had between 1 to 2 years of data monitoring following removal (Figure 6). In terms of broader trends we observed, of the 37 dams we initially considered from the 404/401 permit applications, nearly all dam removals were a phased removal rather than an instantaneous removal, or commonly referred to as 'blow and go'. We will discuss the generally positive outcome of phased removal for sediment management later.

Figure 5: *Height of Studied Dams*

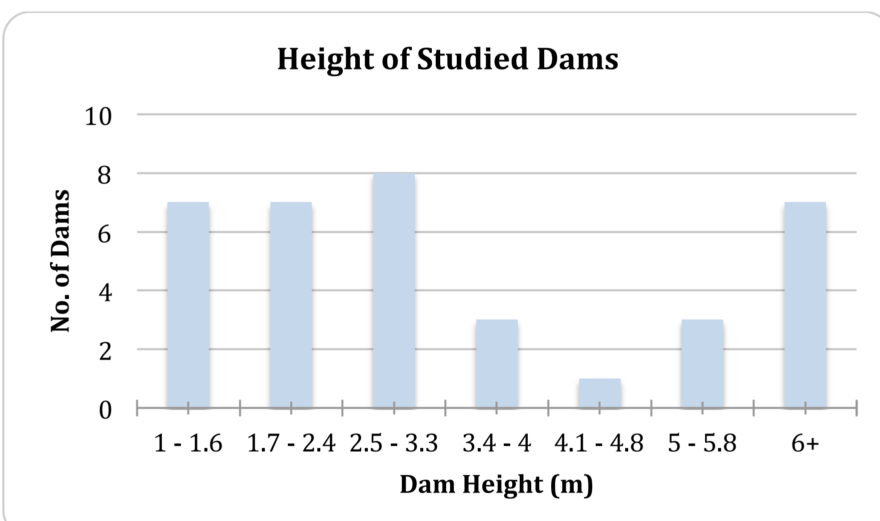
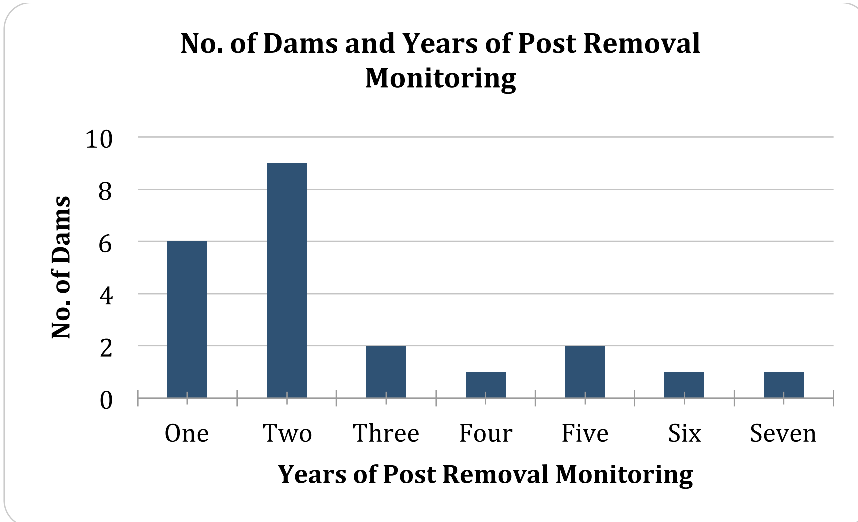


Figure 6: *Years of Data Monitoring of Selected Dams*



Findings

To discern the dam removal methods that best protected the ecological integrity downstream of the dam sites, we compared the trends of chosen removal methods and the varied geomorphology between the selected dams. We found that the driving factors influencing the chosen BMPs for removal were environmental, specifically with regard to river sediment, geomorphology, and the types of species present. Overwhelmingly, 75% of the twenty four dam sites experienced either no ecological disturbance or, if there was disturbance, recovery occurred within three years of removal. Of the reviewed dam removal projects, 25% could not report recovery after up to three years of monitoring, the reasons for which will be discussed in the following sections.

The nineteen studies analyzed populations of benthic macroinvertebrates, fish, and mussels in varying degrees and most had monitoring data for two years, usually one year before removal and one year post removal. Of the reviewed dam removal studies, eleven of nineteen (57%) studied macroinvertebrate assemblages. Among those eleven studies, eight reported downstream benthic macroinvertebrate recovery within the studies' respective monitoring periods, which varied between one to two years after removal. The remaining macroinvertebrate studies did not report recovery during their monitoring periods, which ranged from one to three years. Doyle et al. 2011 suggests that given the short life cycle of macroinvertebrates and their relative mobility, it's realistic to expect assemblages to have a rapid recovery time if compromised by dam removal. This recovery period would be constrained by the rate of geomorphic adjustment following removal. Of the sixteen dam removals that have associated analysis of fish communities, twelve (75%) of them reported downstream fish recovery within 2 years of removal. Only two studies monitored for mussel recovery. One dam removal process had no impact on mussel populations (Heise et al., 2014). In the other removal process, the entire mussel population was terminated, buried in fine sediment and desiccated following removal (Sethi et al., 2004).

Figure 7, below, illustrates the general trend we noted from the selected studies' monitoring of ecological disturbance and recovery period following a dam removal. We note that three years is very short on environmental time scales, so to consider these sites as permanently compromised solely due to the discontinued monitoring could be a hasty conclusion. Table 1 features the dams associated with each recovery trend generalized in Figure 7.

Figure 7: Representation of Ecological Recovery

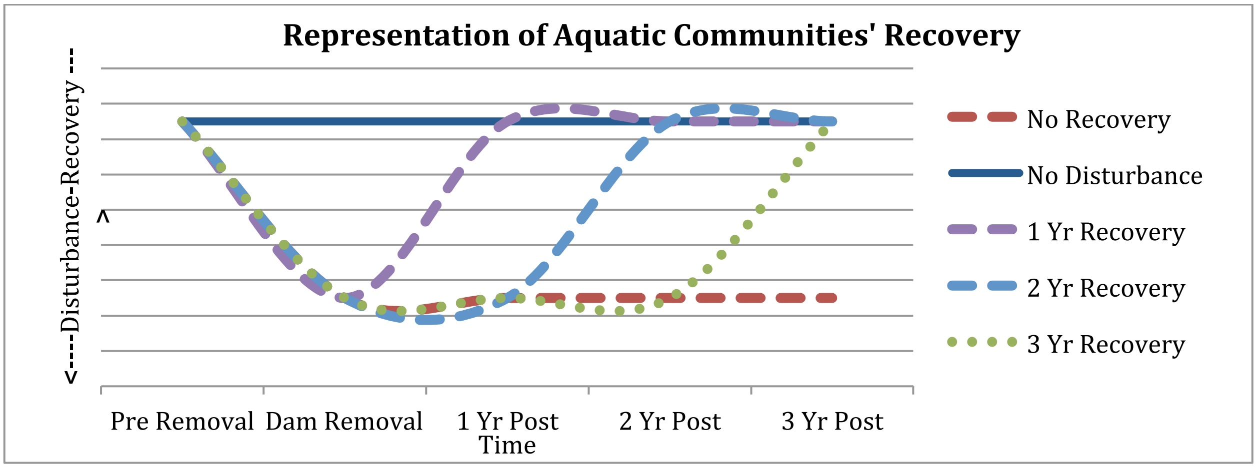


Table 1: Time to recovery for selected dams

No Recovery w/in 3 yrs	No Disturbance	1 Yr Recovery	2 Yr Recovery	3 Yr Recovery
Big Spring Dam, WI	Boulder Creek Upper Dam, WI	Brewster Creek Dam, IL	WaterWorks Dam, WI	Simkins Dam, MD
South Batavia Dam, IL	Boulder Creek Lower Dam, WI	Woodside I Dam, SC	Oak Street Dam, WI	
Linen Mill Dam, WI	Shearer Dam, OR	Edwards Dan, ME	Lavalle Dam, WI	
Woodside II Dam, SC	Sodom Dam, OR	Savage Rapids Dam, OR	Carbonton Dam, NC	
Zemko Dam, CT		Brownsville Dam, OR	Dead Lake Dam, FL	
Sandstone Dam, MN				
		Nashville Dam, MI	Mill Dam, ME	
			Dinner Creek Dam, OR	

Case Studies

Following our comprehensive review of dam removal permits and associated studies, it was obvious that managing the sediment release during and following a dam removal is the driving consideration when designing each step of the removal process. Before removing the physical structure of a dam, steps are taken to control and minimize the amount of sediment that could travel downstream, which is a potential detriment to downstream water quality, based on the site’s geomorphology and the types of species living in the river. What follows are case studies of the different removal approaches of the selected twenty four dam removals and the potential ecological impacts associated with those design decisions, grouped by best management practice.

Dewatering

As described in the introduction, there are different approaches to removing water from the construction site of the dam removal. Of the dam removals we reviewed, 15 conducted notching, 8 conducted phased dewatering through notches or gates, and 1 constructed an artificial diversion channel around the dam. Below are specific case studies of the varied outcomes of different phased dewatering methods.

Phased Dewatering

Research has shown that periods of staged drawdown of the reservoir water level behind the dam can minimize the negative downstream impacts of dam removal (Sethi et al., 2004). Removals that dewater the dam in stages reduce the rate of sediment deposition eroded behind the former impoundment compared to removals that implement a single large sediment pulse (Sawaske & Freyberg, 2012; Randle et. al, 2015). In systems with cohesive or consolidated sediments, the gradual release of water can reduce head cutting upstream of the impoundment, which results in increased downstream deposition (Robinson et al., 2003). Based on the studies we reviewed, the success of phased dewatering is largely dependent on the when in the hydrologic period and season it was conducted. The following dam removal case studies exemplify various dewatering approaches and their ecological outcomes.

1) Brewster Creek Dam: experimental notching based on storm events
2) Carbonton Dam: used the dam's mud gates to gradually release sediment laden water
3) Sandston Dam: A breach of the dam showcases what could happen with one sediment pulse
4) Zemko Dam: A two year dewatering process with channel diversion

1) Brewster Creek Dam

The Brewster Creek Dam was a 2.4 meter tall, 9 meter long dam on Brewster Creek in St. Charles, Illinois. Dam was situated on a mid-gradient part of the creek, with average flows around 0.29 cubic meters per second (cms). The volume of sediment behind the impoundment was 17,849 m^3 and was primarily fine-grained. The removal was conducted in 2004 to restore the river function as well as conduct an experiment on downstream sedimentation through phased notching.

To evaluate the impact of phased notching, a series of five, 305-457 mm notches were made to drawdown the water and to remove the structure, beginning June 2003 and completed in February 2004 with the full removal. The first three notches occurred between June 16, 2003 and November 16, 2003 and the final notches occurred in December and February. The time between notches varied as the goal was to have at least one storm occur after each notch so as to allow sediment to erode before taking out another notch. A storm occurred between all notches except between Notches 1 and 2 (Straub, 2006). The sediment load during the first three notches was approximately six times lower than the load during notches 4 and 5, and after the first storm following Notch 5. During the spring of 2004, 56% of the total sediment erosion occurred. Overall, about 20% of the impounded sediment ended up eroding downstream (Timothy Straub, personal communication). According to the Straub 2006 study, the first three notches could have been combined into one large notch in order to minimize cost and without risking the release of large amounts of sediment. Combining the first notches would allow for impoundment dewatering, channel development, and vegetation colonization as well as allowing more time in between the final notches, resulting in more gradual loading (Straub, 2006). These notches were performed toward the center of the dam, allowing the channel to slowly take form over the notching period.

After the dam was removed in February 2004, data was collected in August 2004, following the period of highest erosion in spring of 2004. The monitoring found a slight decrease in the number of fish species above and below the dam, but slightly increased IBI at both locations. The study deemed neither of these differences significant, however, and therefore reported no meaningful change in fish assemblages above or below the dam. Thus, there was no noticed ecological depression following removal, even though the monitoring occurred after the high erosion period. This could be attributed to the fact that some aquatic communities are adapted to sediment pulses during high flows (Catalano et al., 2001; Schmidt et al. 2008).

The stepwise notching of the dam used in the Brewster Creek Dam removal released less sediment during and after than if the whole dam was removed instantaneously (Straub, 2006). Despite the volume of fine sediment behind the dam, the Brewster Creek Dam avoided having to conduct excavation, build rock stabilization mechanisms, or construct refugia and still did not notice any decline in ecological communities (Straub, 2006). Rather than engineered mechanisms of sediment management, the Brewster Creek removal utilized the timing of storm events and seasonality to manage the sediment. The initial notch, conducted in early summer, at the transition from high to low flows, allowed a substantial amount of water to leave the impoundment, without mobilizing large amounts of sediment. Because it was during the growing season the newly exposed sediments became colonized with vegetation a few weeks following drawdown after being seeded, allowing them to stabilize and become less vulnerable to erosion than if the initial drawdown occurred during the dormant season (Straub, 2006). The seasonal phased dewatering approach used in the Brewster Creek Dam removal was an inexpensive, effective dam removal project with limited artificial intrusion, such as using rip rap or grading the banks with machinery. However, the project's duration could be problematic

2) Carbonton Dam

Carbonton Dam was a 5 meters high, 82 meter long, run of the river dam located in the low gradient, central piedmont region of North Carolina on the on the Deep River, a system with an annual discharge of 38 m^3/s. The dam was dewatered in phases from mid-October to mid-November of 2005 through the mud gates located near the floor of the powerhouse. Utilizing the mud gates allowed lower, more sediment-laden water to be flushed out, as well as provided operators sufficient control over the timing and flow of the dewatering process. This process occurred during low flows to minimize stresses to downstream biota given that there are higher dissolved oxygen concentrations at that time as well as cooler temperatures, a different approach than the one taken at Brewster Creek. Another benefit to using a low flow period was to capitalize on the infrequency of precipitation events to prevent backwatering during the dewatering process that could occur because of the limited flushing capacity of the gates. Final dewatering occurred when 26 meters of the Southern spillway were demolished at the end of November.

The Heise et. al (2013) study monitored freshwater mussels one year prior and three years following dam removal found that post-removal, the proportion of fine sediment in the downstream reach increased from 38.3% to 49.4% in the first year, but then declined to 24.7% by the third year following removal. Howard (2007) reported that upstream fish and macroinvertebrate communities recovered to lotic assemblages within two years of removal, but did not provide information on these species for the downstream reach. The Heise et. al (2013) study reported that the change in sediment did not have a significant impact on downstream mussels in any of the years following dam removal. A few mussels (<10) were exposed upstream after the stream narrowed following dewatering, however this could have been avoided through a mussel relocation effort. Gough et al. (2012) suggested that the limited impact on mussels was due in part to the slow dewatering process. Yet, unlike Brewster Creek Dam, the Carbonton Dam implemented mechanisms of erosion control including grading and riprap toe stabilization along the banks in the vicinity of the dam. The need for increased erosion control could be due to the fact that dewatering occurred during a low flow period, which resulted in less sediment flushing out of the upstream reach.

3) Sandstone Dam

The Sandstone Dam was a small structure (<1 meter) located on the Kettle River in East Central, Minnesota and was removed in 1995. The impoundment was supposed to be dewatered over a 2 week period but the sluice gates broke and the impoundment was accidentally dewatered all at once, releasing previously impounded sand downstream (Sandstone Dam 404 Permit, 1994). Although the dam was located on a steep gradient, it was characterized by a riffle/pool habitat structure. Following removal, mussel populations in the downstream pools were decimated (Katopodis, 2010). Sandstone Dam highlights the importance of vigorous structure inspection prior to removal.

4) Zemko Dam

Zemko Dam was 1.5 meters tall and 42 meters long. It was removed in October 2007 from the Eightmile River in Salem, Connecticut. The river has an annual average discharge of 0.4 cms and is a mid to low gradient system. The dam had an impounded area of 24,281 m^2 and the impounded sediment was a combination of sand and silt. The removal began with the construction of cofferdams and the slow dewatering of the impoundment through the removal of stop logs in the fall of 2005. This was done 2 years prior to removal to allow sediments to stabilize and revegetate naturally to decrease erosion upon full removal (Zemko Sediment Transport Analysis, 2005). The Poulos et al. 2014 study monitored fish assemblage for 2 years prior and 3 years after removal. The study showed significant community shifts rapidly after dam removal, due to changes in substrate, temperature, flow, and depth. However, while the communities were shifting towards resembling reference sites downstream of the removal, the fish assemblages still remained relatively distinct even three years after removal and there was no major change from lentic to lotic species. Even though this dam removal took precautions such as phased dewatering, rock erosion control measures, and channel excavation, the community still had not recovered within a 3 year period. This could be due in part to the downstream change in depth post-removal that occurred from deposition of sediment, changing from 14.1 cm in 2005 to 10.2 cm in 2010, while upstream cobble-sized rocks began to emerge resembling a natural riffle (Poulos et al., 2014). Based on our findings, this incremental deposition could have been minimized if the initial dewatering took place during a period of high flows rather than low flows, over a longer period of time. Additionally, conducting dewatering during the growing season rather than in the fall could have provided for increased sediment stabilization through re-vegetation of the newly exposed sediment.

Cofferdams

Cofferdams are temporary structures put in place to divert stream flow. Different types of cofferdams are used depending on the size of the dam and the river. While no obvious trends were found among different dam removals with cofferdams and ecological outcomes, the possibility of cofferdam failure was stressed in many dam removal planning processes and their use is sometimes avoided for that reason. It can be assumed that dam removals conducted during periods of high flows heighten the risk of cofferdam failure due to the increased pressure on the structure.

Below we highlight how the Edwards Dam removal project effectively used cofferdams to assist in the dewatering process.

Edwards Dam

Edwards Dam was a 6 meter high, 275 meter long structure located on the Kennebec River in Augusta, Maine. The Kennebec River is one of the largest rivers in Maine and is a low gradient system with an average discharge of 250m^3/s (Edwards 404 Permit). The Edwards Dam created an impoundment that extended 24 kilometers upstream and had a total area of 4.6 km^2 (Edwards 404 Permit) and the impounded sediment was predominantly sand and gravel (Casper et. al 2006). The dam was removed in July, 1999 after FERC denied an issuance of a new license.

The Edwards dam removal was completed in four phases over 5 months. The first phase being erosion control staging and project set up, involving installing upstream and downstream debris curtains. The second phase began in June 16, 1999 when construction of the upstream 18 meter cofferdam constructed from fill began. On July 1st the center section of the dam, immediately downstream of the cofferdam, was breached with dynamite. The cofferdam was notched down 0.7-1.2 meters per day to initiate a slow drawdown following the initial breach. The third phase, on August 13, 1999, involved breaching the dam further with dynamite and lowering the water level from 4.3 meters to 1.5 meters in 0.7-1.2 meter increments. While this was a relatively quick phased drawdown process for a 6 meter dam (consisting of two periods of less than a week), the sediment behind the dam was predominantly sand and gravel (Casper et. al 2006) and the project managers deemed post-drawdown sediment to not be an issue given its grain size, chemistry and volume (Edwards 404 Permit). Any movement of sediment was projected to be a fraction of the annual sediment load carried by the river, and given the timing between the two drawdown periods, it should have the ability to revegetate and self-stabilize. The construction of the cofferdam behind the center of the dam allowed the channel to take form as the cofferdam was removed incrementally as well as minimize in-stream ecological disturbance from demolition.

Following the removal of Edwards Dam, the Casper et al. study was published in 2006. This study conducted zoobenthic monitoring in June and September prior to and post removal of the Edwards Dam. The research found that there were no significant detrimental impacts to zoobenthos following the Edwards Dam removal. Their findings also included stagnant richness, but with tolerant species replaced by lotic taxa, which represents a shift to a free-flowing, healthier ecological environment following removal of the Edwards Dam. This can be attributed to the coarse grain of the sediment as well as the ecologically safe dam removal practices that were implemented.

Sediment Management

Natural Release of Sediments

Of the dam removals we reviewed, when coarse sediment was the dominant substrate and did not contain toxic chemicals, natural release of sediment downstream was the BMP typically chosen, though it should be said that this was not exclusive to coarse sediments. Natural sediment removal allows the hydrologic regime of the river to remove the sediments in keeping with the system's cycling, typically being released slowly as sediments erode over time (Schmidt, 2008). When there are high-energy flows, greater amounts of sediments will be mobilized and transported downstream. We found that efforts were made to minimize the downstream delivery of all the newly released sediment in one pulse. Below are four examples of dams that did not excavate sediment, albeit with different sediment size distributions, and saw ecological recovery within two years of removal.

1) South Batavia Dam: an accidentally breached dam with little downstream detrimental impacts
2) Boulder Creek Upper & Lower Dams: small dams, small disturbance
3) Carbonton Dam: sediments returned gradually
4) Brewster Creek Dam: seasonal phased dewatering

1) South Batavia Dam

South Batavia Dam is an example of the most natural release of sediment: an accidental dam break. South Batavia was a low, but long run of the river dam with a height of 1.2 meters and total length of 194 meters on the low gradient Fox River in Batavia, Illinois. The dam was breached due to natural causes in 2000, allowing 15,291 cubic meters of coarse grained sediment to be released downstream. Biotic monitoring had been conducted 3 years prior and 3 years following the natural dam breach. Two years following the dam breach, downstream Ephemeroptera, Plecoptera and Trichoptera (%EPT) levels returned to pre-breach levels, but the initial decline was not deemed statistically significant. Downstream fish assemblages did not change significantly following the breach either. Upstream, the habitat became comparable to free-flowing sites within one year, with macroinvertebrate assemblages resembling free flowing sites in two years while fish populations only partially shifted to free flowing assemblages three years following the breach (Maloney et. al 2008).

We suspect part of this lack of ecological response is because the impoundment was coarse grained and run of the river. Coarse grains have been shown to increase habitat heterogeneity and run of the river dams are not too different from regular river.

2) Boulder Creek Upper & Lower Dams

For low head dams, sediment management is not usually deemed an important consideration because a lack of significant deposition. This lack of deposition is attributed to the high flux capacity of high-gradient systems (Orr et. al 2008). The Boulder Creek dams lacked fine sediment and this toadied the dam removals' success.

The Boulder Creek Upper and Lower dams were 0.9 meters and 1. 8 meters respectively (Stanley et. al 2007). Both dams were removed from Boulder Creek in Baraboo, Wisconsin, a small waterway with a mean discharge of 0.2 m3/s with a mid to high gradient. The removals occurred quickly, within weeks, in July of 2003 and did not implement any precautionary sediment management practice mechanisms such as dewatering or excavation.

Post-removal, the exposed sediments were planted with native species and no rock stabilization structures were used. While the volume of the impounded sediments is unknown, the majority of the sediment behind these dams was coarse grained and natural sediment release was chosen as the best sediment management practice.

Two years after removal there was a noted shift in fish populations from adults to juveniles in the downstream reach, but no significantly negative effects to trout populations were discovered (Stanley et. al 2007). The deposition post-removal was not considered significant and did not differ from in-river sediment changes that had occurred previously in this creek (Orr et. al 2008).

3) Carbonton Dam

The Carbonton Dam, also described in the dewatering section, was a run of the river dam located in the low gradient, central piedmont region of North Carolina on the Deep River. The impounded sediment was cohesive clayey sand and fine to medium-sized gravel. Project managers saw an opportunity that the coarse sediment could be used to provide bed load for the sediment-lacking downstream reach. To accomplish this, without overloading the downstream reach, a unique sediment management technique was designed. Rather than allowing the sediment to be released instantaneously with removal, the sediment was dredged and place on top of a debris island that had formed in the upstream reach during dewatering. This kept the sediment in the stream, slowly feeding into the system over time during periods of high flow rather than one large pulse.

Howard's 2007 study of ecology downstream of the Carbonton Dam saw recovery after two years of the dam's removal. While there are many factors that contribute to the recovery of a downstream species, there is nothing to suggest that the project's sediment management compromised downstream ecologic recovery.

4) Brewster Creek Dam

The Brewster Creek Dam, which was also introduced in the previous section for its dewatering methods, was an exception to those dams with coarse sediments, such as Carbonton Dam. The Brewster Dam had fine sediment, however it was possible to safely release the fine sediment into the downstream reaches because of the very gradual drawdown of the water through the staged dewatering process. Rather than engineered mechanisms of sediment management, the Brewster Creek removal worked with the hydrologic cycle and seasonality to manage the sediment. This dam removal did not conduct any excavation, stabilization, and did not notice any depressed ecological conditions. Yet, longer and more robust monitoring would need to be conducted to fully validate this claim.

Sediment Excavation

We found that in most cases when sediment was removed from behind an impoundment and excavated out of the river, the sediment was fine or cohesive, though there were always exceptions. For these cases, not all sediment was removed and a portion was left to erode downstream naturally. These efforts to simply minimize the sediment pulse are similar to mimicking the natural release of sediment. Notable examples of sediment excavation plans with varying outcomes for ecological recovery are:

1) Nashville Dam: had a successful ecological recovery
2) Dexter Dam: used excavated sediment for multi-purpose objectives
3) Woodside Dams I and II: due to complications, did not have as positive a short term ecological recovery
4) Simkins Dam: combined sediment excavation and natural release but was stymied by interfering downstream structures

1) Nashville Dam

The Nashville Dam was a 2 meter tall, 50 meter long structure on the Thornapple River in Michigan, a low gradient, agricultural region of central Michigan. The dam was removed in 2009 by the Michigan Department of Natural Resources because it was deteriorating and unsafe. The dam was replaced with a stabilized natural channel design. During the project, 694 cubic meters of sediment was excavated from behind the impoundment in order to place large boulders in the stream to create new channel margins as well as bring high banks down to a stable bankfull elevation. The sediment behind the impoundment was 77% sand and 33% silt (Gibson et. al 2011).

The Gibson et al. 2011 study, conducted one year before and one year after the Nashville Dam removal, found a 28% increase in sediment below the dam after removal and no significant decrease in macroinvertebrate integrity in the downstream reach one year following dam removal. The study also found that there was a decrease in isopod taxa, which are more tolerant of polluted systems, and a significant increase in the percentage of organisms that are all indicators of good water quality (Ephmeroptera, Plecoptera, and Trichoptera (EPT)).

Considering that the Nashville dam was located in a low gradient river that would not easily mobilize sediments downstream, the positive ecological outcome downstream following the Nashville Dam removal can be attributed in part to the project's sediment management of the system. In addition to excavating sediment from behind the impoundment, the project also stabilized exposed sediment following the dewatering process, which will be discussed further in the following section.

2) Dexter Dam

Dexter Dam, introduced in the dewatering section, was 2.4 meters high and located on Mill Creek in Dexter, Michigan, a low gradient waterway (Dexter Public Notice Plan, Permit). Due to the presence of Cadmium in the impounded sediments, extensive measures were taken to minimize downstream deposition following removal at this site.

During the early phases of the dam removal, 573 cubic meters of sediment were excavated with a multi-purpose objective: to create an access that would also serve as a sediment trap. The access road was placed 9 meters upstream of the impoundment and captured the estimated 3,693 cubic meters of sediment that would be mobilized during the reservoir drawdown process between the dam structure and access (Dexter DEQ2, Permit). This captured sediment was excavated regularly until the head-cutting of the dam structure had ceased. By creatively using the access road for two purposes, they decreased the amount of extra sediment that would be mobilized in the construction process.

As mentioned earlier, the dam removal did not result in any notable detrimental ecological outcome (Knittel, 2010). No impacts of sediment loading were evident one and two years after removal. This positive benthic response to a dam removal in a low gradient system is testament to the effective and multi-purpose sediment management methods that were chosen.

3) Woodside Dams I and II

Woodside Dams I and II were removed from Twelvemile Creek in Cateechee, South Carolina in 2011 through the planning of CH2M Hill and Arcadis. Twelvemile Creek has a watershed area of 13 m^2 with an average daily flow of 5.7 cm/s. (Woodside Restoration Plan) Woodside Dams I & II were 9.4 and 13 meters tall, respectively. Extensive excavation of sediment was performed on both dams prior to removal due to the trace (<1 ppm on average) presence of PCB toxins stored in the sediments. Both dams were hydraulically and then mechanically dredged and sediments were disposed of offsite. Dredging lasted March 2010 through August 2011, with the dam structure being removed March 2011. Woodside II was dredged beginning in April 2011 and completed in July 2011. The Woodside II dam structure removal took place from July 2011 to September 2011.

While ecological outcomes surpassing pre-removal conditions were reported within eight months of removal, tailrace sites of both dams differed in their ecological response (Marion et.

al 2012). Downstream habitat of Woodside I following removal was a similar to habitat and biotic community profile as before the removal. In contrast, habitat downstream of Woodside II dam developed lower average depths, larger stream widths, and increased small sand substrates as well as increased tolerant species abundance. This contrast of response may be due to increased deposited sediments below Woodside II dam, resulting in decreased depths and velocities (Marion et al., 2012) and increased habitat homogenization.

There are three contributing factors to the increased sediments found below Woodside II. First, the Woodside II has a larger impoundment size relative to Woodside I. Second, the timing of Woodside I in late winter/early spring was the high flow season, which increased the sediment deposition in the impoundment above Woodside II. Thirdly, sediment behind Woodside I was unintentionally excavated in a way that channelized the water towards the stream banks. This resulted in increased erosion along the edge of the stream due to the new flow dynamics associated with the excavated stream bottom configuration (Woodside Removal Plans, 2012). Restoration efforts to engineer the stream away from the banks did not occur until a year after the removal.

Taking the removals of these two dams individually, the Woodside Dam I removal showcases the benefits of sediment excavation and habitat response. The Woodside II removal, coupled with the upstream removal of Woodside I, exemplifies the importance of considering flow seasons and geomorphological changes when planning dam removal and excavation.

4) Simkins Dam

The Simkins Dam was a 3 meter high, 52 meter long dam removed from the Patapsco River in Maryland in 2010. The Patapsco River has a mean discharge of 139 cms and low gradient of 0.25%. The removal of the Simkins Dam was an experiment in the release of stored, non-toxic, coarse to very coarse sand. The dam removal was designed to mimic natural flows as much as possible and as such only excavated unstable sediments along the river banks. The flow was lowered by notching down one section of the dam about 1.5 meters and allowing the water to flow over that section. Because natural sediment transport was a major part of the design, no other dewatering or diversion occurred. Banks were stabilized with grading, blankets, seeding, and gravel and cobble. As mentioned, most of the sediment was left in the impoundment to be naturally transported downstream. The project managers allowed between one to two weeks of natural sediment transport, after which they excavated 9,940 cubic meters of sediment equivalent of 11% of the total impounded volume in areas that needed enhanced bank stabilization.

Ecological impacts were not expected. Following the Simkins Dam removal, the upstream reach above the dam site transitioned from sand and gravel substrate to 95% riffle and the downstream reach below the dam site transitioned from free flowing channel to slow-flowing sand-dominated substrate (Harbold et. al, 2014). The sediment release negatively impacted the downstream macroinvertebrate community and persisted beyond 4 years after removal.

Based off observed trends from other dams (Baraboo River and the Woodside Dams), this accumulation of sand dominated substrate could be in part due to the 10.4 meter high Bloede dam, located just less than a mile downstream. It is possible that the barrier of the Bloede Dam is impeding the sediment that had previously been trapped behind the Simkins' dam. Simkins Dam had one of the longest monitoring studies, with a full length of 6 years, 2 years prior and 4 years after.

Erosion Control

Erosion control reduces the rate at which sediment is transported downstream. In addition to the release of sediment trapped behind the dam impoundment, project managers have to account for both short term and long term erosion of river banks and sediment that gets mobilized due to construction activity. Dam removal projects that stabilize sediments can minimize downstream impacts (Wildman and Macbroom, 2005).

Short Term Erosion Control

Implementing mechanisms of short-term erosion control are important for decreasing turbidity in the stream channel. While silt fences are implemented in every removal, the following mechanisms vary between removals:

1) Cofferdams
2) Dual purpose structures
3) Silt curtains

1) Cofferdams are used to construct in the dry, however these structures are perilous because they run the risk of failing. Savage Rapids Dam, located on the Rogue River in Oregon, a large structure with a height of 12 meters and a length of 152.4 meters, required a dry environment. The project managers constructed a cofferdam to divert the flows around the main part of the structure so the removal could occur in the dry. Because of the size of the dam and the river, a drilled-in, stabilized cofferdam had to be installed upstream of the dam. Despite the precautions taken, a small flood occurred in May of 2009 resulting in a partial cofferdam failure that deposited sandy sediments downstream (USSD, 2011). Tullos et al., 2014 conducted macroinvertebrate monitoring one year prior and two years following dam removal. Despite the partial cofferdam failure, the study found limited negative impacts on benthic macroinvertebrate assemblages downstream, with a recovery time of less than a year (Tullos et al., 2014). This system rebounded quickly most likely because of the high discharge moving through the river. Understanding how the system will respond to cofferdam failure should be evaluated and understood, or if a cofferdam is even needed, before using such a structure in the removal process. If a cofferdam failure should detriment a system, it should not be used.

2) To minimize repeatedly kicking up sediment, project managers have been known to give their in stream structures dual purposes to minimize disturbance. As was seen with the Dexter Dam removal, excavated sediment was used to construct a temporary access road that also served as a barrier. Shearer and Sodom Dams are another example.

Shearer and Sodom Dams were removed from the Calapooia River and the Sodom Channel to the Calapooia River, respectively. The Sodom Channel was originally constructed as a diversion structure to divert water from the Calapooia. The dam along the Sodom Channel was about 1 meter tall and 8 meters long with an impounded sediment volume of 4,590 cubic meters of primarily coarse grained material. The removals occurred in the late summer to early fall during low flows, and began with work area isolation through the construction of a cofferdam at the confluence of the Sodom Channel and the Calapooia River that also served as an access road. A culvert was installed in the cofferdam that allowed a controlled amount of flow to reach the project area.

3) Another commonly used and effective method to keep mobilized sediment out of the river is sediment curtains or turbidity curtains. For the Shearer Dam, a sediment/turbidity curtain was floated downstream during project activity and fish that were caught between the dam and the turbidity curtain were rescued and released downstream. Turbid water was pumped from the construction area away from the stream to mitigate turbidity downstream. The Mill Dam also used turbidity curtains and had a similar experience with trapped fish.

Long Term Erosion Control

Long-term erosion of the riverbanks is of concern after a dam is removed and the system's flow typically becomes faster and shallower. Sixteen of the twenty four dam removals we studied stabilized the riverbanks. Common materials used to stabilize banks are riprap, plant vegetation, grading upstream banks, or using erosion matting. Instream stabilization methods include using rock veins to reduce head-cutting. This was used on Sodom Dam, Woodside II, Sandstone, Nashville, and Dexter Dam. Log cross veins can also be used, such as for Carbonton Dam and might be better because they can biodegrade.

As an example of what happens when sediments are not adequately stabilized, Dinner Creek Dam in Oregon didn't use bank stabilization mechanisms and saw ultimately detrimental impacts on downstream ecology. Dinner Creek Dam was a 3 meter high, 10.7 meter long dam located on Dinner Creek in Cottage Grove, Oregon, a somewhat mountainous region of the state with a mid gradient. The Dam was removed in August of 2003 in about five days, during its specified in-water work window. Initially, there were no adverse impacts on downstream macroinvertebrate communities. However, in December a storm eroded over 1,070 cubic meters of sediment in less than two days and there was a significant decline in macroinvertebrate abundance and richness. Macroinvertebrate abundance rebounded quickly but richness remained depressed and the population did not recover until two years after the removal. Other points to note regarding the dam removal, there was very little excavation and no mechanisms of rock stabilization in the channel or on the banks, because the permits encouraged as little rip rap as possible.

Constructed Habitat

Of the dam projects we studied, eight of the twenty four (33%) constructed refugia. When comparing the average recovery time between projects with constructed refugia and no constructed refugia, we found average recovery times of 2 years and 1.7 years, respectively.

Though this is not statistically significant, it could suggest that sites with constructed habitat saw no decrease in recovery time relative to sites that do not. In fact, for many sites that did not construct manmade riffle pools, the naturally occurring steepening of the river channel and increased river velocities following dam removal uncovered existing riffle habitat upstream of the former impoundment. This was the case with the Zemko, Simkin, Carbonton, Brewster, Waterworks, Oak Street, and Linen Mill dam removals (Catalano et al. 2007). For those dams that did construct habitat, we found that the success of the constructed refugia were limited by poor understanding of the natural river system and how the river would change following the removal. Constructed habitat should not be utilized in non-optimal systems because it can impede the already limited sediment flux capacity of the river.

The following case studies of the Barraboo River Dams, the Sodom Dam, and the Condit Dam discuss the consequences of poorly planned constructed habitat and showcase the implications on ecological recovery.

1) Barraboo River, WI (Linen Mill, Lavalle, Waterworks, and Oak Street Dams)

A series of four dams were removed from the Barraboo River in Wisconsin between April of 1998 and October of 2001. The Lavalle Dam, the upstream most dam, and Linen Mill, the downstream most dam, were both roughly 2.4 meters fall. The second most upstream dam, Oak Street Dam, was 5.6 meters tall and the third dam, Waterworks Dam, was about three meters tall. The river had an average annual discharge of 10.36 m^3/s and the impounded sediments were predominantly silt underlain by a coarse stream floor (Catalano et al., 2007). The three upstream dams were characterized by a steep gradient (0.75–7.25 m/km), while Linen Mill dam, the downstream site, had a lowest gradient and slowest stream velocity. Being the last dam to be removed because it was the most downstream dam, and because of its low gradient and stream velocity, the Linen Mill Dam had accumulated sediments from the previous two removals within its impoundment. Prior to its removal, the Linen Mill Dam had an impounded sediment depth of 4,418 square meters (Glenville Environmental Assessment, 2000).

A riffle/pool gradient was installed in place of the Linen Mill structure after its removal to provide habitat and reduce head-cutting (Glenville Environmental Assessment, 2000). However, the presence of the riffle/pool structure actually decreased sediment mobility within the reach (Catalano et. al 2007). This attributed to the increased deposition and ultimately decreased IBI at the Linen Mill site (Catalano et. al 2007).

Of all the dams removed on the Baraboo River, Linen Mill dam was the only site to not recover within two years (Catalano et. al 2007), thus the constructed habitat resulted in the opposite of its intended outcome. This is attributed to Linen Mill site's difficulty with flushing a large volume of sediment given its gradient and water velocity. Thus, it was a non-optimal system. This also demonstrates that accommodating for previous dam removals on the same river is important to consider when planning multiple removals on one river.

2) Sodom Dam

The Sodom Dam removal project constructed riffle habitat that ultimately failed, but at no cost to the river ecology.

After the mechanical removal of the 3.3 meter Sodom dam, as discussed in previous sections, the streambed was regraded and a bulk bag cofferdam was removed incrementally to slowly restore flows to the newly graded area. In order to provide suitable flow regimes for fish passage, boulders were installed to stabilize banks. Knick-points were also installed to slow the velocity of the incoming water (Shearer & Sodom Department of the Army Permit, 2011). In total, three engineered riffles and pools, wooden habitat structures, vegetated soil lifts, and a constructed channel at the inlet to the Calapooia River were installed in the project reach.

In late June and early July of 2012, following seasonal high flows, a total volume of approximately 3,823 cubic meters of material had eroded. Five out of the nine vegetated soil lifts were fully intact and proliferating, but one third of the material for the remaining four had eroded (Tullos et al, 2013). These failures could have occurred because the river was originally created as a diversion channel and was not a natural system, therefore making it difficult to predict how the system would respond to removal. Despite the erosion and restoration failures after the Sodom dam removal, however, no negative changes in fish species composition or percent natives were observed the summer following dam removal when data was collected. In fact, it was observed that the number of fish species increased following removal (Tullos et. al 2013).

3) Condit Dam

The Condit Dam removal recovery, a 38 meter dam, (a significantly larger dam than most of those discussed in this paper) had complications stemming from a lack of anticipated geomorphic response. During its removal in 2011, extensive efforts were made to relocate salmon from below the dam to above the dam in order protect the salmon from down stream sedimentation and allow them to spawn in the upstream reach (Engle Report, 2012). However, upon removal of the dam the upstream channel narrowed considerably more than anticipated and exposed the salmon's newly established redds. As a result, 24% of the upstream redds were lost (Engle Report, 2012). This case study emphasizes the importance of understanding the specific system and how it will respond to the removal.

Methods to Minimize Short Term Ecological Impacts Following and During Removal

System Considerations

As described in the previous sections, dam removal design and the methods to remove a dam are highly dependent on the physical system of the dam site. We identified five physical variables that will impact how the ecological community will respond to a dam removal: grainsize distribution, sediment transport capacity, ratio of impoundment width to stream width, species present, and surrounding structures. The impacts of each attribute are described below.

Physical Attributes

Grain Size Distribution

How sediment impacts downstream ecological communities is in large part determined by the characteristics of sediment collected behind the impoundment (Randle et al., 2015). Of the dam removals we looked at with known sediment grain size, dams with coarser sediment load resulted in little ecological change or had a recovery time of less than one year. Noting this, we might assume sediments with larger grain size distribution are a driver of biotic success following dam removal. Prioritizing dams with coarse impounded sediments for removal would allow for decreased potential for detrimental short-term ecological impacts, should sediment no be managed correctly. That said, this recommendation is not taking the long-term benefits of dam removal on greater river connectivity into account and it could be short sited to select dams for removal solely on short term ecological impacts.

Sediment Transport Capacity

Based on the studies we reviewed, removing run-of-the-river dams on rivers with steep gradients required little to no sediment management and had a greater chance of minimal to no short term ecological impact compared to non-run-of-the-river dams on low gradient systems, should the same minimum sediment management be applied. Streams that have high gradients and fast water velocities will flush fine sediments at a faster rate. This is termed 'higher sediment transport capacity'. Ecological restoration is dependent on the rate of fine sediment transport (Chiloquin Dam USGS Study, 2005). Similar to grain size distribution, it can be assumed that removing dams in high gradient systems, combined with applying appropriate BMP practices, will have minimized ecological impacts compared to applying the same BMP practices in a low gradient system.

Ratio of Impoundment Width to Stream Width

It is important to correctly anticipate the amount of sediment that will be released from a dam removal. Streams that have a large reservoir width to stream width ratio are generally going to have more sediment trapped behind the impoundment. Modeling river response is not an exact science and hydrologists are still developing the best science to tackle these questions. However, quantifying the ratio is a simple way to determine how severe the release will be on the reach downstream. In our analysis, we did not have the quantitative data to determine this number, but we did see that run of river dams, which have equal inflow and outflow, had a shorter ecological recovery time than dams that were not run of river.

Species

Naturally, if the objective of a dam removal is to protect the ecology of a river, it is imperative to understand the types of species in the river and their life history traits. As example of species sensitive methods, the Savage Rapids Dam removal had no in-water work during the migration period for salmon and steelheads. For project designers, knowing the needs of the local river species also aids in relocation efforts prior to the dam removal. This is highlighted very well the Brewster Creek dam removal project where mussels were relocated from the reach immediately downstream of the dam to an area further down the reach. By moving the mussels further downstream, they avoided any negative impacts to the mussel population (Straub, 2006). This is in contrast to the Sandstone Dam removal, which did not address the presence of mussels in the downstream pools and did not conduct any relocation efforts, resulting in the burial of mussel populations downstream.

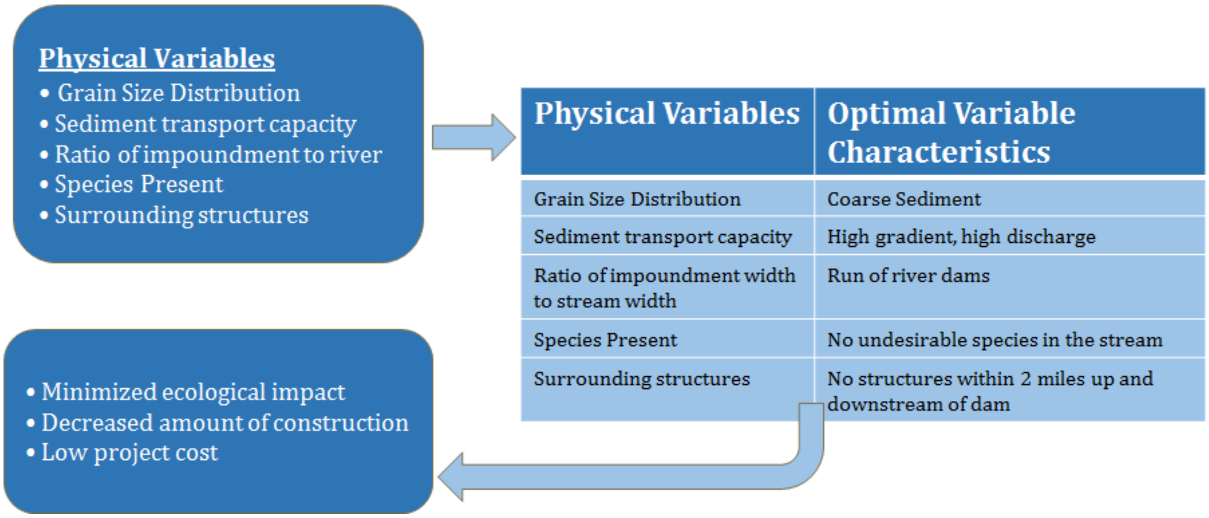
Alternatively, if undesirable species are present in a river system, it could diminish the benefits of removing a dam. Just as dams are barriers to movement of native species, they can also protect upstream fish species from invasive fish. Dams could serve as barriers protecting native fish species from tolerant outside species inhabiting reservoir beyond the impoundment. In the case of the Big Spring Dam from the Big Spring Creek in Friendship, Wisconsin in 2008, invasive species traveled farther into the river system after the dam removal, compromising the upstream or downstream restoration efforts. Though fish populations remained stable as the habitat changed and there was a transition to lotic species as the water cooled, there was a decrease in beta diversity after removal due to the increased connectivity with undesirable species from a reservoir downstream (Kornis et al., 2013). This increased connectivity decreased the integrity of the fish community and compromised the well-intended efforts of the dam removal. When prioritizing dam removal, it is important to determine if there are undesirable species present in the system and if they have the capacity to compromise restoration efforts following removal.

Surrounding Structures

In-stream structures, particularly other dams, up and/or downstream of the dam of interest could compromise the rate of ecological recovery by disrupting a natural sediment flux capacity for structures that are downstream. The Woodside II, Simkins Dan, and Linen Mill dam removal case studies highlighted examples when sediment did not flush through the system as expected, most likely due to these in-stream structures. In both cases of the Woodside II and Linen Mill dams, the dams were about 2.4 km downstream of another dam (Glenville Environmental Assessment, 2000; Lance Ketchum, Woodside Project Manager, Personal Communication).

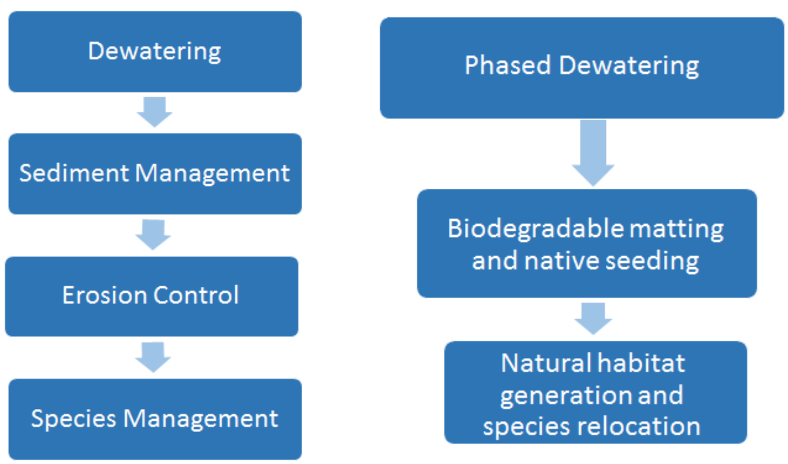
From these physical variables we can recognize optimal variable characteristics that will allow for the least amount of ecological impacts downstream. Prioritizing dams for removal that possess these characteristics will result in minimal ecological impact, decreased construction, and a lower cost (*Figure 8*).

Figure 8: *Physical Variables and Optimal Variable Characteristics*



To discern which management practice is best for non-optimal systems, we went back to the common stages of dam removal and created proposed stages based on our research (Figure 9).

Figure 9: *Proposed Dam Removal Stages for Non Optimal Systems*



Project Specific Choices

Below are descriptions of the 3 proposed Best Management Practices for non-optimal systems. These include phased dewatering, natural habitat generation, and species relocation.

Phased Dewatering & Seasonality

Phased dewatering is an effective control for sediment release (Sawaske & Freyberg, 2012). Additionally, phased dewatering can result in a natural meandering channel following dam removal without direct restoration efforts such as natural channel design (Straub, 2006). The timing of dewatering phases administered in the Brewster Dam removal were synchronized with the hydrologic regime and growing season and resulted in minimal sedimentation impacts. This project boasted an effective outcome with minimal artificial channel construction. However, because this project was conducted as an experiment its conditions were different than a typical dam removal. For example, they had the ability to wait to conduct certain notches until after a storm had occurred. This would not likely be an economically feasible option if the project were contracted out to a private firm, but the same principles can be applied by predicting storm timing through analyzing past climatology data. This would allow project managers to schedule notching times based on storm predictions.

While this approach worked for Brewster Creek, which is representative of a low gradient, fine sediment system, it may not necessarily be ideal for all systems. In Brewster Creek, most of the sedimentation occurred in the spring during high flows. In some systems, this period may coincide with fish migration patterns. This is an especially important consideration in systems that harbor protected or endangered species that migrate at this time. In this instance, initial notching could begin earlier in the summer or spring so that the final notch could occur during the winter and therefore the final sedimentation could be more gradual and have less interference with migration patterns. The timing and sizing of notches will be unique to every system. However, it should be reinforced that many species have adapted to higher sedimentation volumes during periods of high flows and that should be considered when scheduling notching times.

Practitioners in the field find that the most favorable sediment management method is to allow the sediment to flow downstream rather than remove sediment from the system (Peyton, 2015). To minimize loading from natural sediment release, dewatering should be conducted in phases, beginning during high flow periods. Additionally, draining reservoirs during periods of high flow has the highest potential to benefit plant communities up and downstream (Schmidt, 2008). Conducting the first notches during the growing season will facilitate vegetation growth on the newly exposed sediments. Increased vegetative success can decrease erosion upstream and ultimately sedimentation downstream. This can also result in fewer efforts needed to control invasive species (Schmidt, 2008) as well as the installment of less erosion control structures. Conducting phased dewatering correctly can eliminate the need for sediment management, as well as allow for more environmentally sound mechanisms of erosion control to be implemented, such as biodegradable matting and native planting rather than rip-rap and bank grading, as we saw with Brewster Creek.

Natural Habitat Regeneration

Based on our limited number of case studies, we found better ecological recovery rates associated with natural riffle exposure than with constructed riffles, implying that constructed refugia may not be a necessary component of dam removal projects that occur in non-optimal systems. This is due to the fact that the gradient is lower in non-optimal systems and the sediment is fine and in-stream structures can inhibit the already limited sediment transport capacity. This was the case with the Linen Mill Dam, where the presence of a constructed riffle was the main driver of the ecological recovery period to be greater than 3 years. Furthermore, in four of the case studies we examined natural riffles became exposed post removal after the sediment had cleared out of the system, allowing for natural habitat regeneration. Hence, if habitat is constructed, careful consideration should be given to system characteristics prior to installation, specifically to the sediment flux capacity and natural channel substrate.

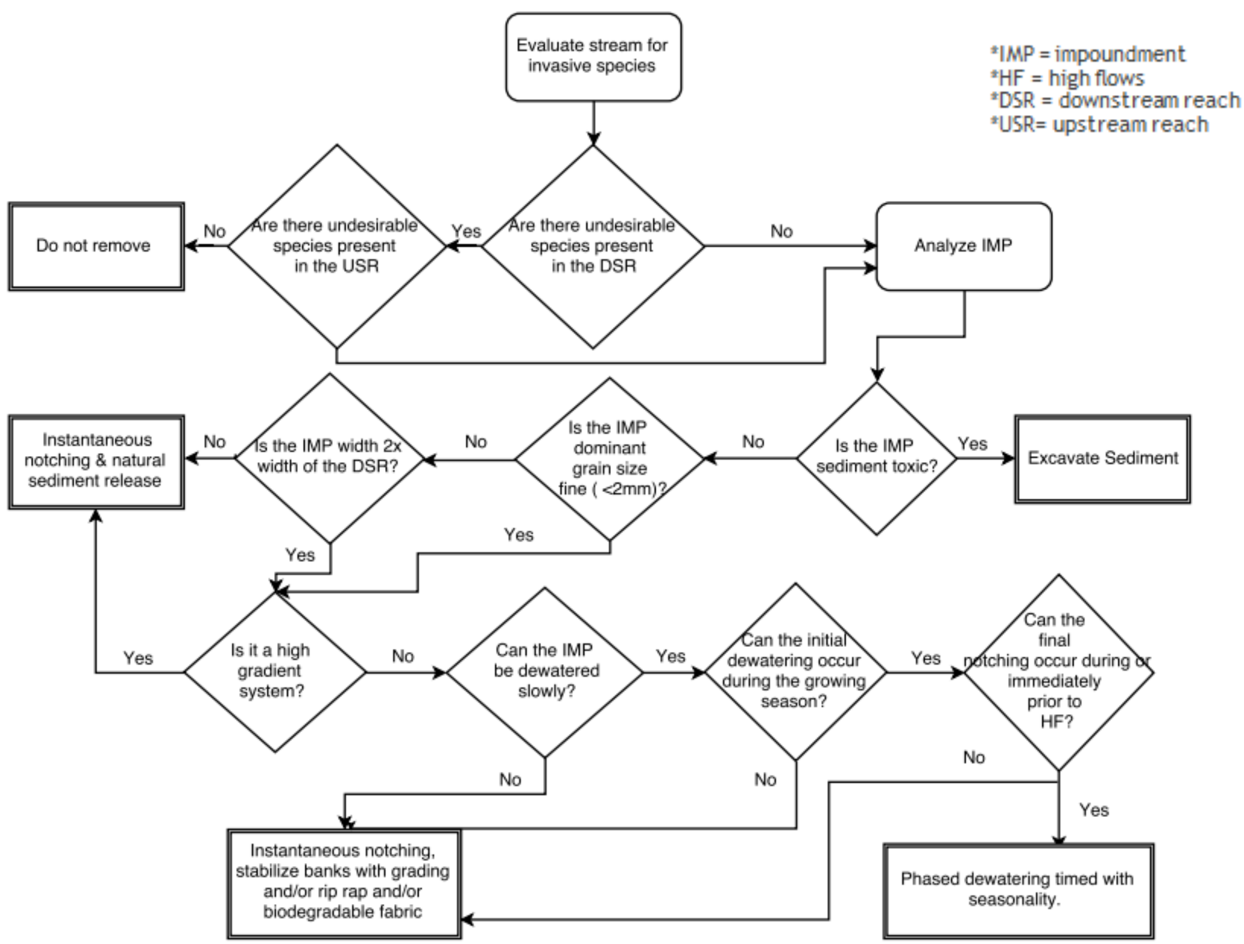
Species Relocation

Species relocation is a simple way to decrease the ecological mortality rate from dam removal in non-optimal systems. This is especially important for benthic species like freshwater mussels that will likely get buried by fine sediment during and after these removal processes and are often times endangered or protected species. Species relocation consists of transporting species in buckets of water to a stream that is representative of their native habitat. In the studies we looked at that conducted relocation for freshwater mussels, the mortality rate of relocating was less than the mortality rate of allowing them to remain in the stream.

Removal Method Decision Tree

Given that the best management practices are system specific, we created a removal method decision tree that outlines which BMP you should implement given the type of system you have (Figure 10). In the diagram, double lined boxes represent the BMPs for selected systems.

Figure 10: *Removal Method Decision Tree*



Need for a Standardized Monitoring Framework

Our biggest limitation in statistically determining effective and ecologically responsible methods of dam removal was the lack of long term data associated with dam removal. Our findings support that more systematically collected data is needed to conduct a robust meta-analysis of research of dam removal impacts on stream ecology. It would require a standardization in the type of data collected, the frequency, and the duration of data collection. At this present time, the pressing need would not only be to increase the number of dam sites with long term data, but also have a standardized monitoring framework that encourages collection of both abiotic and biotic data for a single dam site. This would help with characterizing relationships between the dam removals' impacts on physical habitat, which ultimately affects the food web. It is not sufficient to assume that all BMPs will have the same outcome on river habitat because sites are so variable. Broadly speaking, specific areas of interest that were repeatedly called for in the literature were 1) understanding sediment mobilization following removal of large dams, and 2) better understanding the differences between outcomes of channel restoration versus natural sediment release. Recognizing this, we require abiotic data in conjunction with biotic data for individual sites to analyze statistical relationships of a BMP's impact.

The Gulf of Maine Council published recommendations for a standardized monitoring framework in 2007, which outlined four critical parameters, and the metrics needed to evaluate them. We reviewed these metrics and based on our research, contributed and modified the metrics so that if these metrics were applied across dam removal projects, a meta-analysis could be more feasible (Table 2).

Table 2: *Dam Removal Critical Monitoring Recommendations*

Critical Parameters	**Gulf of Maine Council (2007) Recommendations**	**Our Recommendations**
Hydraulic/Hydrologic/Sediment	• Monumented cross-sections • Longitudinal stream profile • Stream bed sediment grain size distribution	• Monumented cross-sections • Longitudinal stream profile • Stream bed sediment grain size distribution • **Reservoir width to stream width (pre-removal only)** • **Stream bed gradient**
Wetland and Riparian Habitat	• Riparian plant community structure	• **Invasive species monitoring**

In stream Habitat	• Macroinvertebrates
	  ○ State specific
	  ○ Photo stations
	• Water quality
	  ○ Temperature, DO, Conductivity
		• Macroinvertebrates
		  ○ **%EPT**
		  ○ **IBI score**
		• Water quality
		  ○ Temperature, DO, conductivity, **TSS**

Fish Passage Assessment	• Direct fish measurement	• **IBI Score** • **% Tolerant**

For the first parameter, Hydraulic/Hydrologic/Sediment, we added the impoundment to stream ratio metric to understand the sediment volume as well as the stream bed gradient metric to understand the flux capacity. For the Wetland and Riparian Habitat parameter we suggested evaluating the community for invasive species rather than just looking at the plant community structure to better understand the ecological success of the system. For instream habitat there was not a metric for macroinvertebrates so we suggested looking at %EPT as well as IBI score. We found these to be better metrics of recovery than richness and abundance because after the dam is removed, the community begins to shift, typically, from lentic to lotic. During this shift you may see decreased richness and abundance as tolerant species leave, but this lower value does not mean the community is not recovering, it's just changing. For the Fish Passage Assessment parameter we would actually alter that to a continuous data type rather than categorical, so it would become a Fish Community Assessment instead of fish passage. The metrics we proposed here are also metrics that are indicative of ecological success following dam removal.

In order to best understand the most ecologically sensitive approaches to dam removal, we must understand how the system recovers over a long period of time post-removal among various mechanisms of removal. Anecdotally, researchers have a difficult time securing sufficient funding for a significant period of monitoring time. We also recommend that further investment needs to be placed in monitoring dam removal systems over a long period of time in addition to, or in place of, standalone dam removal.

Conclusion

The factors affecting the ecological outcomes of dam removals are highly variable, and greatly dependent on the river system. In order to design a removal that minimizes short-term ecological impacts project managers can prioritize dams for removal that possess optimal physical variable characteristics. For non-optimal systems, dam removers should consider a phased dewatering approach timed with vegetative and hydrologic seasonality to minimize the amount of physical sediment management and erosion control structures that will be needed.. Species management practices such as constructed habitat do not always serve their purpose and allowing the river to develop riffles on its own may be more beneficial to the system. That having been said, short term species management practices, such as species relocation, can decrease the mortality rate of dam removal.

To minimize the short-term ecological impacts, effectively managing sediment is critical. That being said, the long term benefits of removing a dam have potential for increasing food web productivity and improving river connectivity. Thus, system specific best management practices should be employed to balance between minimizing the short term impact for the long term gain

In order to better understand best methods of dam removal and if a meta-analysis of the growing dam removal research is be conducted, the science community needs longer-term monitoring efforts with both biotic and abiotic data collection for individual sites. As the nation's dams increase in age and science supports their removal for improving ecological functioning, the number of dam removals will continue to grow. It will be helpful for environmental managers and professionals involved in river restoration to have the latest science for the most ecologically sound means for removing dam structures.

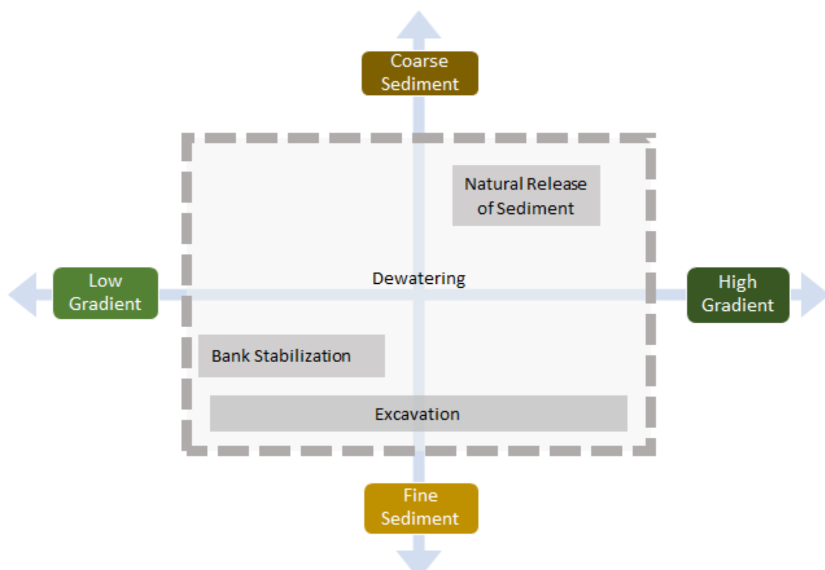
Appendix 1

Minimizing Ecological Impacts of Dam Removal: Best Methods Memo

Dam removal is one of the most effective means of achieving river restoration. However, the sudden release of sediment previously captured behind a dam impoundment after a dam removal can compromise downstream ecological habitat, in some cases permanently (Stanley and Doyle, 2003; Doyle et al., 2003a; Riggsbee et al., 2012). This document is intended to help managers of dam removal projects identify options available to them when prioritizing ecologically responsible dam removal methodology.

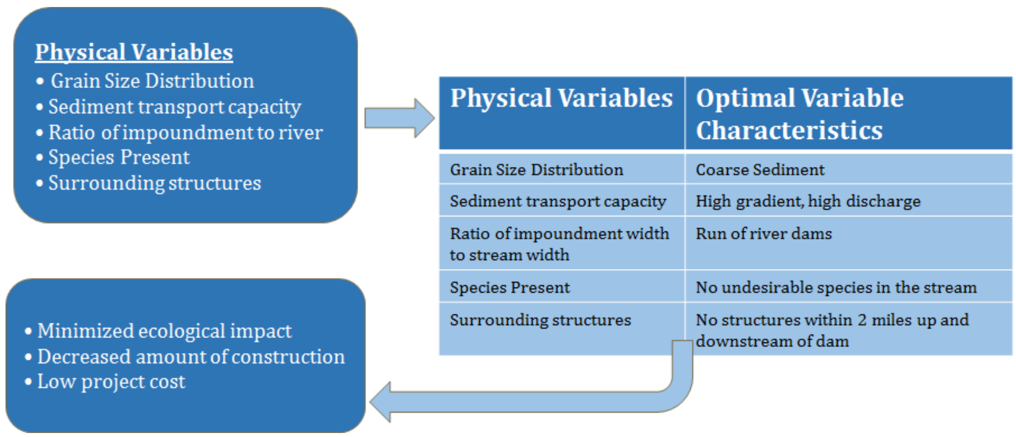
The design of dam removal projects and the methods to remove a dam are highly dependent on the physical system of the dam site (Figure 1). High gradient rivers with coarse sediments are optimal dam removal sites because sediment can easily be moved through the system due to the high energy of the water and the decreased chance for sediments to be stuck in stream substrate, an impediment for quality habitat. A low gradient river with fine sediment on the other hand, is less optimal as it will likely require excavation and other more costly sediment management procedures to prevent impairing habitat and contributing to longer term water quality and erosion problems.

Figure 1: Schematic representing sediment management BMPs based on generalized physical characteristics



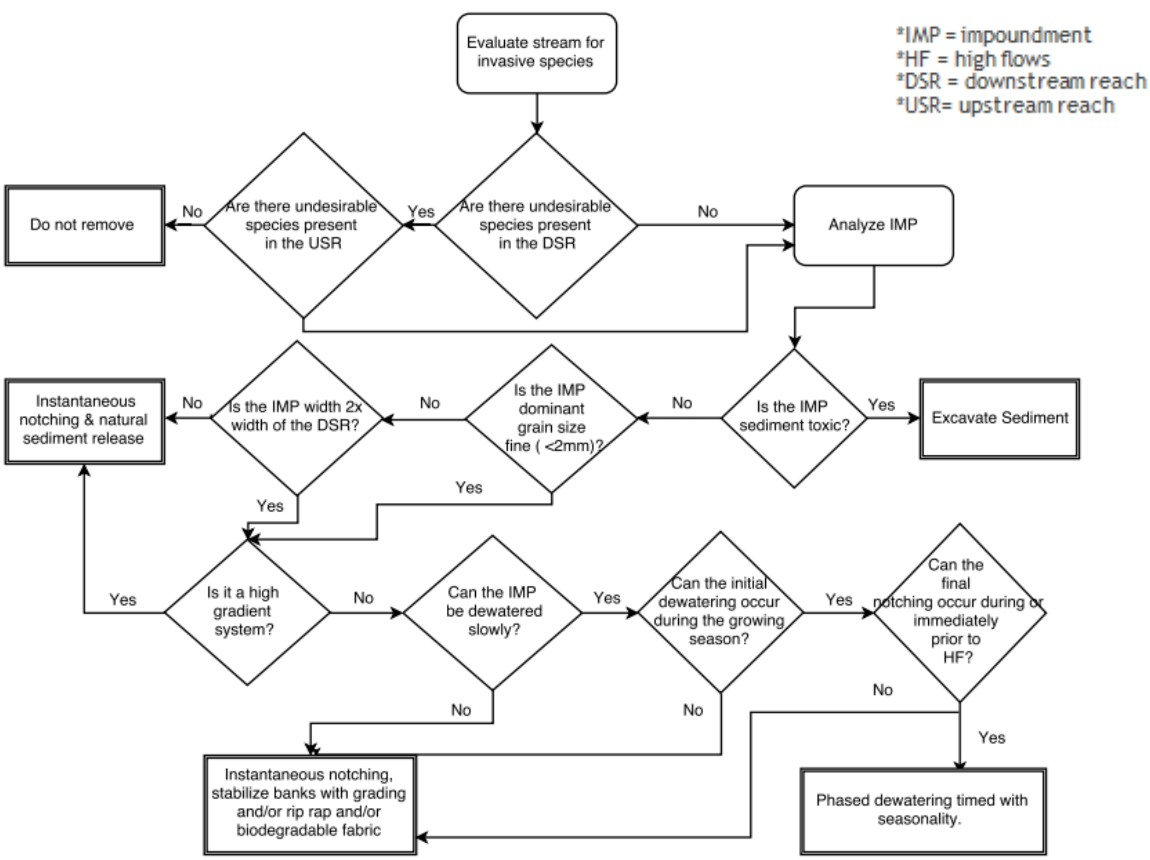
There are other physical variables in addition to grain size and stream gradient that contribute to optimum environmental characteristics or less optimum characteristics. If deciding between a dam to remove with optimal environmental characteristics versus less optimal characteristics, the optimal project will allow for a simpler dam removal design that will have minimized ecological impact and decrease amount of construction and lower project cost (Figure 2).

Figure 2: Physical Variables and Optimal Variable Characteristics



To maintain ecological integrity over the span of a dam removal project and beyond, the following flow chart can help guide project managers through the different considerations of the impacts of dam removal on the in stream ecology and environment.

Figure 3: Removal Method for Ecological Prioritization Flow Chart



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