Guidelines for Removal of Unused Low-Head Irrigation Dams and Weirs in the Lower Mekong

Wayne Stancill – Civil Engineer, PE
US Department of Interior, International Technical Assistance Program

Washington, DC

Prepared for the Mekong River Commission in collaboration with Charles Sturt University and Australasian Fish Passage Services, with support from the US Agency for International Development

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Nations worldwide are searching for sustainable solutions to meet food security and water demands. Dams have been used for centuries to irrigate lands, control floods, and store water for municipal and industrial uses. The United States contains more than 2 million small low-head dams (Fenci et al. 2015). Because many of these dams are no longer needed, the rate of dam removal now far exceeds the rate of dam construction.

In contrast, increased food demand across the Mekong River Basin is spurring the construction of new irrigation infrastructure and upgrades to existing structures at increasingly rapid rates.(Baumgartner et al. 2021). While dams and associated irrigation infrastructure support increased rice production, they may also negatively impact the freshwater fisheries which are relied on by more than 80% of rural households in the Mekong River Basin for protein (Hortle, 2007).

In these guidelines, the terms *dam, low-head-dam* and *weir* are used interchangeably. A formal definition of low-head dam is provided in the Glossary. A discussion on removing irrigation headworks is included in the Construction Activities section.

When the operational purposes of the dam are no longer needed, or can be met through alternative means, decommissioning a dam can be a viable option for restoring important riverine functions including increased fish production. Dams and irrigation projects in the Mekong River basin that were constructed decades ago are now scheduled for upgrades or reconstruction (Nguyen et al., 2005). Before these irrigation structures are replaced, a cost-benefit analysis should be conducted to determine if the benefits of removing the dam to restore fish passage, with the resulting increase in fish production, outweighs the benefits of the dam's continued use in support of irrigation and/or other water development benefits.

The following dam removal guidelines have been developed to provide engineers, scientists, and resource managers in Water Resources, Irrigation, Environment, Agriculture, and Fisheries Ministries with a risk-based approach for determining the level of data collection and analysis needed to evaluate a dam removal project and the type of sediment management actions that may be needed. These guidelines have been developed primarily for dams with little sediment stored in the reservoir but contain information to help guide users facing more complex projects.

Complex dam removal projects typically include reservoirs with more challenging sediment management issues. Developing a Conceptual Model is recommended as a first step in analyzing a dam removal's complexity in those instances when removing the dam will result in little (negligible) or no sediment being evacuated from the reservoir ("**Case of Negligible Reservoir Sediment").**

The following low-head dam removal guidelines provide an iterative analysis approach, starting with readily available information, and then proceeding to an initial site visit to review the project and determine its potential level of complexity (Figure 1). Additional data collection and analysis for increasingly more complex projects is identified in subsequent sections.

Step	Action
1.	Identify sediment concerns
2.	Collect reservoir and river data.
3.	Evaluate potential for contaminated sediment:
3A	If potential for contaminants are negligible then proceed to step-6.
3B	If there is a potential for contaminants in the sediment then proceed to Step-4.
4.	Determine if sediment concentrations exceed sediment quality criteria.
4A	If contaminants do not exceed sediment quality criteria then proceed to Step-6.
4B	If contaminants do exceed sediment quality criteria then proceed to Step-5.
5.	Conduct biological analysis and estimate impacts to the environment if the sediments are released.
5A	If biological assessment indicates the contaminated sediments can be released without significant impacts to the environment then proceed to Step-6.
5B	If biological assessment indicates the contaminated sediments cannot be released without significant impacts to the environment then proceed to Step-9.
6.	Determine relative reservoir sediment volume and probability of impacts to the upstream and downstream environments if the sediment is instantaneously released.
6A	If relative reservoir sediment volumes are negligible then sediment analysis is completed and proceed to Step-7
6B	If relative reservoir sediment volumes are not negligible then proceed to Step-8
7.	Develop and implement dam removal plan. Proceed to Step 10.
8.	Develop sediment management plans. Proceed to Step-7.
9.	Cap, stabilize, or remove sediment. Based on sediment management procedure selected, either proceed to Step-7 or Proceed directly to Step-10.
10.	Develop Monitoring and Adaptive Management Plan.

Figure 1: Conceptualized Flow Chart for Sediment Analysis Guidelines and Steps for Dam Removal. Modified from BOR 2017.

1. INTRODUCTION

Dams are typically removed because they no longer serve their original function, are deemed unsafe, and/or are too expensive to maintain (American Rivers, 2002; Heinz Center 2002), but ecological restoration has recently been recognized as another important reason for removing dams (Poulos 2014). Limited and short-term ecological consequences are often associated with removing a dam but numerous studies indicate the long-term ecological benefits exceed the short term impacts (Casperi et. al. 2006; Ahearn et. al. 2005; Doyle et. al. 2005). Field studies following dam removal have documented an increase in diversity and abundance of fish and invertebrates, both up and downstream, within a year of the dam being removed (Marion et al, 2012, Mark et al., 2010; Poff and Zimmerman, 2010).

With time, sediments settle out in the bottoms of reservoirs (impounded pools) behind dams and the waters that pass through or over the dam are sediment deficient, often referred to as "clear-water-releases" (Kondolf, 1997). These clear-water-releases often regain sediments by eroding deeper into the downstream river channel, eroding stream banks, (Church 1995), (**Figure 2**) and in general, those erosion processes negatively impact downstream habitats (Chisholm and Aadland, 1994). Natural river flows facilitate sediment-size variations, which in turn, increases the variety and availability of habitats fish use for feeding and spawning (Church, 1995; Marion et al. 2012; Marks, 2010). Diverse sediment-habitats also contribute to increased macroinvertebrate abundance (Casperi et al., 2006; Quinn and Hickey, 1990) which are important food items for fish.

The lower Mekong River Basin supports high aquatic biodiversity, particularly fish, and those fish are an irreplaceable source of food and livelihoods for local residents. All fish move and migrate among habitats at different life stages and fish production declines when migration routes are blocked by dams and weirs (American Rivers 2002; Magilligan et al., 2016). Some fish move along rivers and between rivers; some fish move within or between wetland habitats, and other fish seek floodplain habitats. Fish move to spawn, feed, utilize nursery areas, or seek seasonal refugia. Providing opportunities for fish to migrate is essential for them to complete their life cycles.

Figure 2: Eroding stream downstream of an impounded site experiencing habitat degradation due to clear-water releases.

2. FACTORS TO CONSIDER FOR DAM REMOVAL PROJECTS

When evaluating the feasibility of a dam removal project, understanding the response of a river system, relative to a project's specific restoration objectives, is critical when deciding if and how a dam should be removed (Pizzuto, 2002; Sawaske and Freyberg, 2012, Simon, 1989, Tonitto and Riha, 2016). While dam removals have been shown to benefit fish and return riverine functions, not all dam removals provide equal benefits (Katapodis and Aadland 2006), Tullos et al. 2016, Tullos et al., 2014). Geographic location, among other variables, can influence the effects of dam removals. Dam removals within watersheds with few other dams can restore connectivity to a high proportion of the watershed (Magilligan et al., 2016). Removing dams that reside a short distance upstream from other dams open a limited number of river kilometers and can have an adverse impact on downstream dams if the upstream dam releases large volumes of sediment into the downstream reservoir (Catalano et al., 2007). Likewise, removing dams high in the watershed should be carefully evaluated as they often open a limited number of river-kilometers and usually exhibit ephemeral (seasonal) flows (Kibler et al. 2011).

Dams provide many important benefits and it's understood that not all dams are viable candidates for removal when the sole benefit is to restore fish passage. A dam removal project must evaluate the dam's socioeconomic benefits to the local community and must also assess the local communities' attachment to the structure and its real and/or perceived benefits. In the United States, a nationwide cost-benefit analyses of low head dams determined that the costs of bringing them into regulatory compliance typically exceeded the costs of removing them (Belmore et al., 2017). If a dam no longer meets its original purpose, or the costs of rehabilitating a failing structure exceeds its economic benefits, then that structure likely warrants a thorough appraisal of being removed.

All dam removal projects should include a thorough evaluation of reservoir-sediments to assess contaminant levels before the dam is removed. Contaminants enter the waterway via polluted runoff in urban and agricultural areas. Discharge of contaminants into surface water can result in contamination of the waterbodies' sediments. Contaminates contained on, or in, sediments can be incorporated into the tissue of fish, invertebrates, wildlife, plants and humans. Sediments eroded from agricultural areas often contain remnants of agriculture pesticides. Agriculture pesticides, even in small quantities, can contribute to human illness, birth defects, and contribute to various forms of cancer. Some contaminants enter waterways via manufacturing industries involving chemical processes while other contaminants are transported to the waterway from mining and related extraction sites. In many cases, contaminated sediments are relatively immobile and long-lived. This includes petroleum products, metals, and radionuclides. Some contaminants (metals and petroleum products) pose a primary risk to benthic organisms present in the sediments. Chemicals and toxins that bioaccumulate (polychlorinated biphenyl and dioxins) are more likely to impact higher trophic organisms including fish, wildlife, and humans.

Three major phases in a dam removal project include:

1) Dewatering the reservoir,
2) Sediment management with its associated erosion control, and
3) Physically removing the structure.

Project designs often include dewatering the reservoir before removing the dam to minimize impacts to downstream areas and to avoid abruptly mobilizing large volumes of reservoir sediment (Sawaske and Fretyberg, 2012; Tonitto and Riha, 2016). The dewatering phase can be implemented by drawing the impoundment down through gates **(Figure 3)**, removing the water by progressively lowering or notching the dam **(Figure 4)**, bypassing the water around the dam via pumps **(Figure 5),** or diverting the water through a bypass canal **(Figure 6)**. The timing of a drawdown relative to high flows can have a significant impact on the rate and total volume of sediment evacuated from the reservoir (tullos et al., 2016). Wildman and MacBroom 2005). Timing of the reservoir drawdown, relative to the vegetation growing season, can have a significant impact on the volume of sediment evacuated from the reservoir as vegetation reestablishment on exposed mudflats helps control sediment erosion (Tullos et. al., 2016, Johnson 2002).

Figure 3: Gates are an option for lowering a reservoir during a dam removal project.

Figure 4: Reservoir pool being lowered through an armored dam-notch.

Figure 5: Reservoir being lowered via pumping operation.

Figure 6: Reservoir being lowered by diverting flow around dam via a bypass channel.

Grosse and Doherty (2016) summarized twenty-six dam removal case studies. Their summary noted project managers were most challenged addressing the sediment accumulated behind the dam. Katopodis (2010) indicated sediment moves downstream after dam removals primarily in response to: 1) volume of sediment stored in the reservoir behind the dam; 2) whether the sediment is primarily fine or coarse grained; 3) magnitude and duration of flows shortly after the dam is removed; and 4) the river's gradient. The volume of reservoir sediment (relative to the stream's average annual sediment load), concentration of sediment contaminants, and potential impacts to upstream and downstream habitats are key parameters for evaluating environmental impacts from a dam removal project and for selecting a sediment management alternative (Aheam and Dahlgren, 2005; Kibler et al., 2011; Pearson and Collins, 2011). Dam removal projects that implement measures to stabilize reservoir sediments, before the dam is removed, help to minimize impacts to downstream habitats once the sediment is evacuated from the reservoir (Wildman and MacBroom 2005).

These guidelines incorporate options for reservoir sediment management that, depending on identified risks and uncertainties, allow sediments to be eroded and released downstream, stabilized in place, or excavated and relocated.

It is commonly recognized that the reservoir landscape that develops after a dam removal will depend on the thickness, size gradation, and cohesive properties of the reservoir sediment (MacBroom, 2012; Pearson et al., 2011; Simon, 1989). Narrow reservoirs (Less than three times the active channel width) **(Figure 7)**, and reservoirs with predominately non-cohesive coarse sediment are expected to erode the greatest proportion of sediment as a result of dam removal (MacBroom and Shiff, 2013). The greater the proportion of cohesive soils in the reservoir sediments the slower the rate of lateral erosion and the greater the volume of sediment that will remain in the reservoir (MacBroom, 2012). Most streams transport fine sediments (silt and clay) at relatively low discharge and typically transport them without long-term significant impacts to downstream environments (Doyle et al. 2005; Grosse and Doherty, 2016).

Figure 7: Depicted reservoir containing predominately coarse sediment and it would be designated as a "narrow-reservoir" (reservoir width < 3 times active-channel-width) and an Aspect Ratio approximately = 1.

Freyberg (2012) evaluated 12 low-head dam removal projects and found that within the first year, sediment volumes eroded from reservoirs ranged between 8% and 65% with an average value of 28%. Channel slope, discharge, and bed roughness are primary hydraulic-controls determining coarse sediment transport (Kibley et al., 2011, Pearson et al. 2019; Sawaske and Freyberg, 2012). For reservoirs dominated by coarse sediment, Major et al. (2017) found that, in the first year, the sediment volume eroded from the reservoir ranged between 1% and 77% with an average of 43%. Coarse sediments tend to travel downstream in waves, primarily as bedload, with the greatest deposition occurring just downstream of the dam removal site (Kibler et al. 2011).

A conceptual model of channel evolution for the downstream channel, in response to a release of coarse sediment after a dam removal, is provided by Kibler et al. (2011). Initially following the release of coarse reservoir sediment, sediment deposition in the downstream channel tends to fill in the pre-removal channel thalweg which results in low habitat complexity. As the coarse sediments are reworked, with subsequent flows, the channel forms a more heterogeneous channel which often results in improved channel habitats.

There are a number of Best Management Practices (BMP) available to manage the mobilization of sediment accumulated behind dams. Dams located in low gradient rivers with large quantities of fine sediment accumulated behind the dam will likely require a phased dewatering process coupled with measures to prevent sediment erosion from the reservoir and the banks (Grosse and Doherty, 2016). Dams in high gradient systems tend to accumulate a minimal amount of highly mobile sediment and those accumulated sediments will usually flush out after the first high flow event using an “instantaneously dewatered” dam removal approach (Church, 1995; MacBroom, 2012). Generalized channel evolution models (MacBroom, J.G, 2012, Doyle 2005, Simon A. 1989) have been used to aid in predicting the volume, extent, and pattern of erosion in reservoir sediments after dam removals. Numerical modeling of sediment transport is often used for complex dam removal projects (Downs et al., 2009; Cui et al., 2017) but is considered beyond the scope of this paper.

In addition to addressing the release of sediment trapped in the dam’s impoundment, dam removal designs need to account for short term and long-term erosion of river banks both upstream and downstream of the dam. Short term erosion control methods include silt fences and floating debris booms. Long term erosion control includes grading banks, placing erosion control matting, revegetating exposed soils, rip rapping banks, and installing in-stream structures such as bendway weirs.

Methods used to remove the dam’s physical presence, and its associated infrastructure, are often based on the dam’s material (compacted soil vs concrete), physical size (primarily height) and whether the dam will be removed in the wet or in the dry.

3. ENGINEERING DESIGN PROCESS

SITE RECONNISSANCE

The first step in developing a dam removal project is to collect existing information to help determine what additional information needs to be collected during the site reconnaissance. Most projects have a great deal of available information that needs to be compiled and summarized to reduce redundant and unnecessary field work. The following provides a lengthy list of data and information for many, but not all, dam removal projects. In the Mekong Basin, much of these data may not be available. Ministry officials will need to rely upon their own and contracted expert opinion.

Collect Existing Data

1. Collect pre--impoundment photos to identify historical channel alignment and indications of legacy-dams and associated structures that potentially hamper sediment being evacuated from the reservoir.
2. Collect dam design or construction plans, dam inspection reports, and past studies.
3. Collect project-area maps/aerial photographs, natural resources information and geological data.
4. Collect discharge gauging data.
5. Collect existing suspended and/or bed load sediment data.
6. Locate construction documents for infrastructure upstream and downstream of the project (bridges, water intakes, upstream buried pipes and cables) that might be impacted by sediment being evacuated from the reservoir after the dam is removed.
7. Determine if a partial drawdown is an option to aid in site-surveying, identify legacy structures and evaluate sediment conditions in the reservoir

Conduct Initial Site Reconnaissance

1. Conduct a topographic survey of the dam and adjacent structures, such as bridges, both upstream and downstream of the dam **(Figure 8).** Temporarily dewatering the reservoir will expedite the survey.
2. Identify important site-features that might aid in the dam removal design (**Figure 9).**

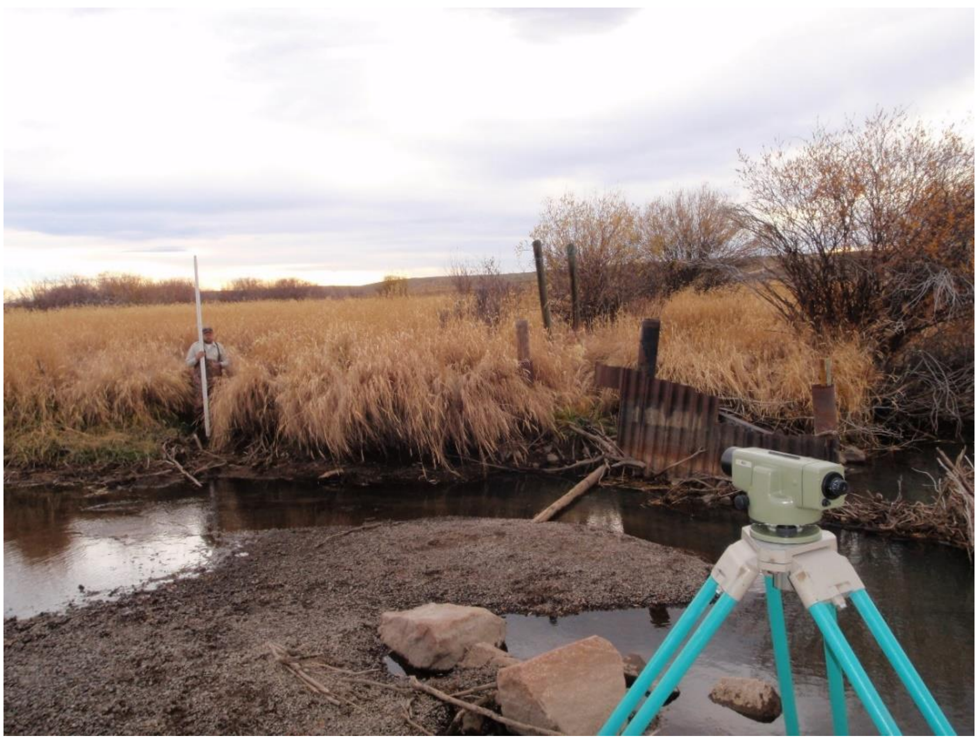

Figure 8: Topographic survey of dam-site and reservoir after draw reservoir down.

Figure 9: Abandoned penstock-canal located at an abandoned dam-site during an initial site visit. The canal could be used to divert water around the dam during the removal phase.

3. Measure channel-width upstream and downstream of dam. This ratio is termed the “aspect ratio” and provides an index for predicting the extent that the newly formed channel in the reservoir-sediments will meander and aid in estimating the volume of sediment that will be evacuated from a reservoir when a dam is removed.
4. Determine elevations for tributary inlets located upstream and downstream of the project.
5. Starting downstream of the dam and extending upstream of the reservoir sediments, conduct a longitudinal survey, parallel with the channel thalweg or centerline of the channel.
6. Conduct cross section surveys of the stream-channel both upstream and downstream of the dam.
7. Determine elevations of adjacent wetlands upstream of the dam as dewatering the reservoir can lower adjacent wetlands via groundwater.
8. Collect reservoir sediments for contaminant analysis. Collect one sediment core for every 765 m^3 of sediment that will be mobilized. For removals resulting in >

7,650 m^{3}, of mobilized sediment, collect one sediment core for every 2,300 m^{3}. Sediments comprised of silt, clay, and fines tend to accumulate contaminants. If substrate is mostly cobble and gravel, fewer samples may be sufficient.

9. Probe reservoir sediments to identify lateral extent and depth of silt and sand/gravel (**Figure 10).** Temporarily dewatering the reservoir will expedite the survey.
10. To assess the depth of the reservoir sediments, probe upstream reservoir sediments to a point that the probe will no longer extend into the reservoir sediments (depth-of-refusal). Depth of refusal should probe to original streambed if possible.
11. Collect between 5 and 10 reservoir sediments for soil analysis using a hand auger.
12. Identify houses and associated structures adjacent to streambanks that might be impacted by eroding banks.

Figure 10: Reservoir-sediment being probed to identify sediment depths. The point that the probe could no longer be extended into the sediments was assumed to be the original channel bottom. Probe points are cataloged via GPS to develop profiles.

Characterize Site Hydrology

Using stream gage data or hydrological estimation methods, identify the key hydrological parameters for the project site that could influence the dam removal methods and sediment release timing. In locations where stream gage or more refined methods for identifying hydrological conditions are not available, the investigator may have to use flow lines as surrogates for the more refined methods.

1. Identify low-flow and high-flow volumes and periods.
2. Determine discharge volumes for interval periods, 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year periods.
3. Identify flood control dams upstream of the site that alter the sites natural hydrology and might also be used to control high flow events during the dam removal.

DEVELOP DAM-REMOVAL CONCEPTUAL MODEL AND DIAGRAM

Use data collected up to this point to develop a conceptual model **(Figure 1)** of the project site that summarizes the existing data and identifies areas of potential concern for sediment impacts. The conceptual model is primarily a qualitative description, with supporting-information and graphics, used to describe the physical processes expected to occur when the dam is removed and the reservoir sediments are released. The conceptual model should address sediment impacts both upstream and downstream of the project. The complexity of the conceptual model should be proportion to the risk of sediment impacts including contamination levels. MacBroom (2012) and Wildman and MacBroom (2010) developed a classification system for dam removals that can aid in predicting the nature of the reservoir and downstream sites after the dam is removed. A narrative synthesizing existing information and data collected to this point should be included. The Conceptual model can be used to determine if the **"Negligible Reservoir Sediment Approach**" is a viable option (included at the end of Chapter 3). The Conceptual Model can also aid in identify solutions for problems that might occur if the Negligible Reservoir Sediment Approach is coupled with an instantaneous dam removal design. The conceptual model can also help determine the need for more extensive field data necessary for developing a more comprehensive Sediment Management Plan, as outlined in Chapter Four.

The conceptual model and data synthesis should include the following information.

Develop Topographic and Bathymetric Maps

1. Display cross sections depicting the existing elevations and original elevations or sediment probe depth. This information will help estimate the volume of sediment in the reservoir. **(Figure 11).**

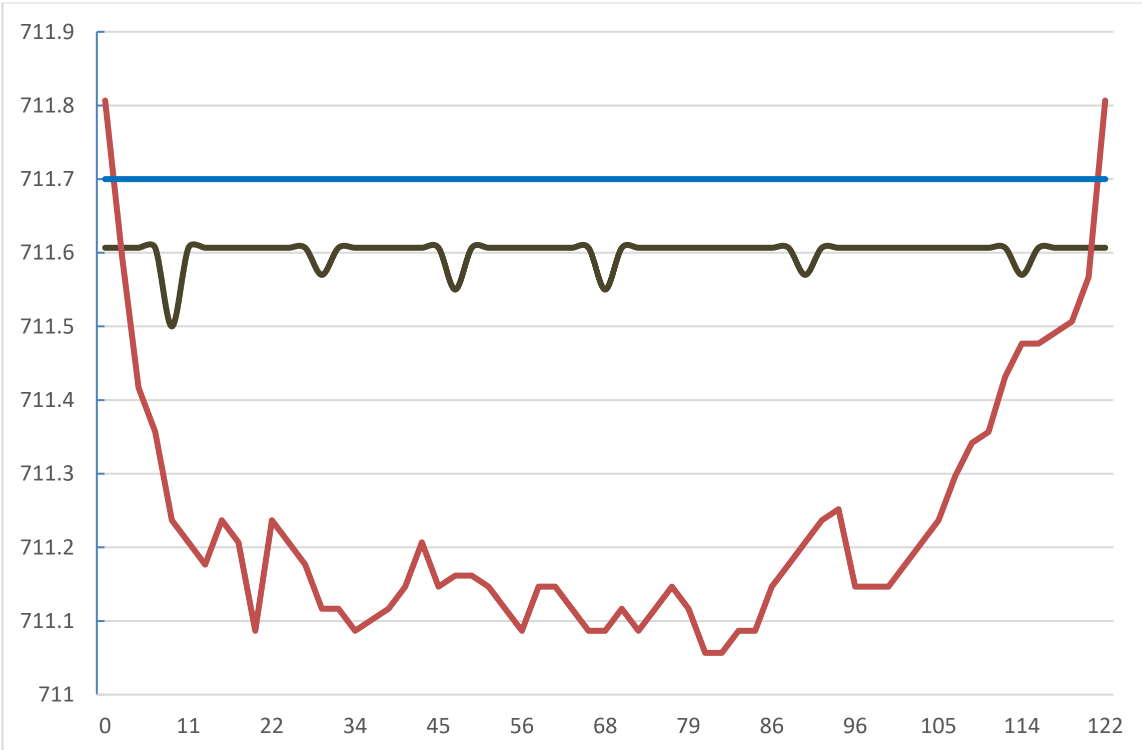

Figure 11: Cross section of a reservoir. Water surface is displayed as blue line. Sediment surface is displayed as brown line. Cross section bottom is assumed by probing sediments to point of refusal (until probe could no longer be extended any dee

2. Develop longitudinal profile depicting the downstream streambed surface elevation and the upstream sediment surface elevation at the time of survey **(Figure 12).**
3. Extend the downstream channel slope through the reservoir sediments to estimate the distance that a headcut might progress through reservoir sediments when the dam is removed **(Figure 12).** This will also provide a graphical estimate of the extent and depth of the reservoir sediments.

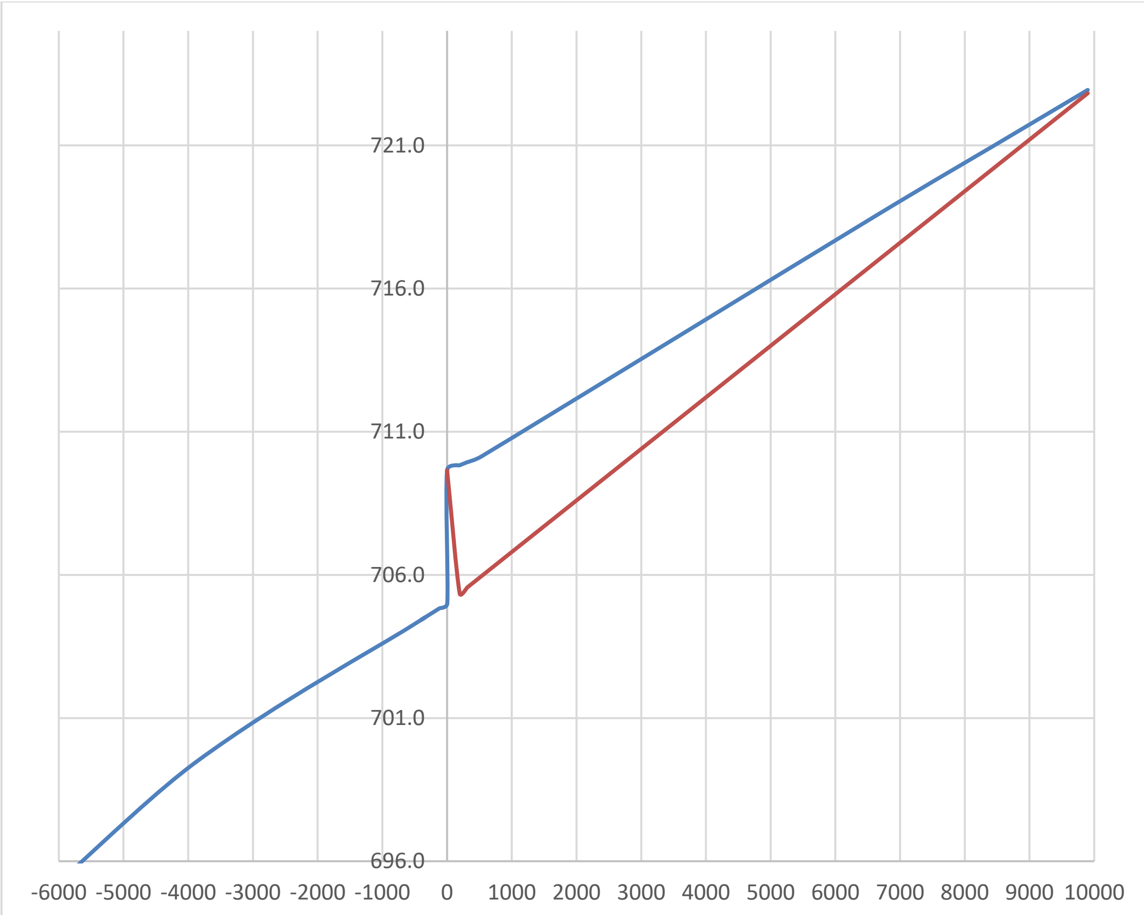

Figure 12: Display of elevations (blue line) collected through a dam site along the channel thalweg. Survey extends from point downstream of dam to a point upstream of the impoundment reservoir. Red line is a projection of the downstream channel-slope through the reservoir sediments. The two upstream lines merge to estimate the upstream location point that reservoirs sediments would be eroded after the dam is removed.

The following data collection and analysis would be required for a more complex Sediment Management Alternative (Chapter Four) and should be included in a detailed synthesis report and design.

Estimate Quantity of Impoundment-Sediment Mobilized by Dam Removal

1. Calculate the reservoir trapping efficiency. A reservoir trap efficiency (< 5%) is an indicator that the reservoir has not accumulated significant quantities of sediment. An indicator of high trap efficiency (> 80%) indicates the reservoir has accumulated a large volume of sediment (Dendy, 1974; Strand and Pemberton, 1982).

2. Project the downstream channel cross sectional area onto the upstream cross section areas. Set the downstream cross section's bottom-elevation onto the upstream cross section based on where the slope line extended through the upstream reservoir sediments predicts the channel will erode to. The overlapping cross sections will provide an estimate of the area of reservoir sediment that will be evacuated at that location **(Figure 13).**

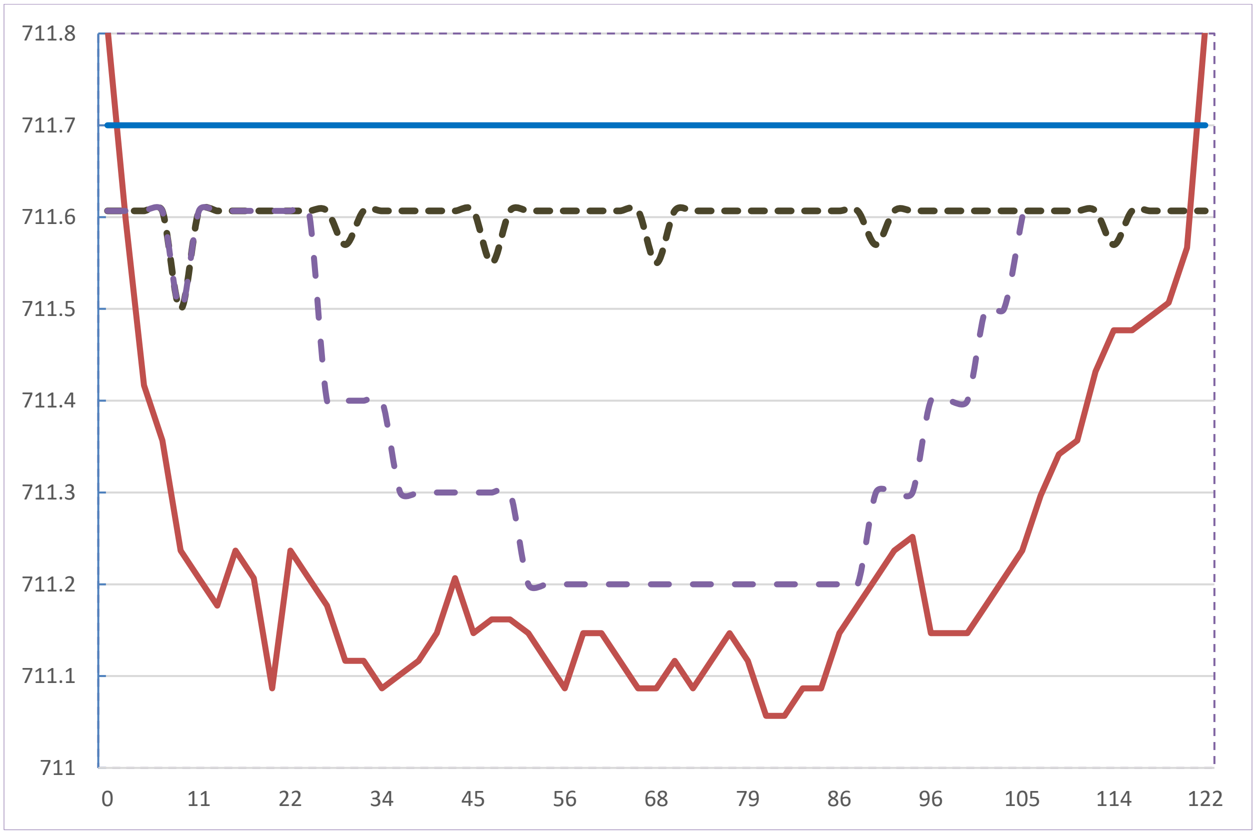

Figure 13: Blue dashed-line depicts the cross section geometry collected downstream of a dam. The downstream cross section is projected onto the cross section collected through the reservoir sediments (red dashed-line) at a distance 3000m upstream of the dam (See figure 11). The low-elevation of the downstream cross section is located at the elevation extrapolated through the reservoir sediment using the downstream channel slope (See figure 12).

3. Estimate total volume of sediment predicted to be evacuated from the reservoir by summing the cross sectional areas along the slope line. The areas summed along the slope line will produce a wedge shaped volume

Estimate Impacts of Sediment Being Evacuated From the Reservoir

1. Estimate impacts to downstream tributary-channels and infrastructure based on volume of sediment evacuated from the reservoir and elevations of the impacted structures.
2. Determine if releasing contaminated sediments into downstream areas will outweigh benefits of removing dam.
3. Identify threats to upstream infrastructure when reservoir sediments are evacuated post dam removal. Determine if the channel that erodes into the reservoir sediment will expose buried infrastructure or compromise bridge supports **(Figure 14).**

Figure 14: Bridge located 2000 m upstream of dam. Evacuating sediment from the reservoir following a proposed dam breach was expected to compromise the displayed bridge supports and remediation methods were proposed.

4. Identify whether infrastructure protection is required and, if needed, what it will entail.
5. Determine if channel and riparian habitat restoration will be incorporated into the design.
6. Identify bank stabilization (e.g., rip rap) or thalweg management structures (e.g., bendway weirs) that will be incorporated into the design **(Figure 15)**.

Figure 15: Figure 15. Bank stabilization and bendway weirs used to minimize erosion.

7. Determine if evacuating reservoir sediments will initiate headcuts in tributary streams **(Figure 16)**.
8. Determine extent of evacuated reservoir sediment on downstream habitats. Will the short term impacts on downstream habitats outweigh the benefits of improved fish passage?
9. Assess if a partial dam removal with the addition of a fish passage structure is a better option than a complete removal. **(Figure 17)**
10. Determine cost and benefits of losing the dam's primary function (e.g. irrigation) to the ecological benefits of improved fish passage.

Figure 16: Headcut moving upstream through a stream. The headcut was initiated at the streams junction with reservoir sediments that were lowered after a dam breach.

Figure 17: Partial dam removal and installation of a rock ramp fishway.

11. Can a non-structural alternative be substituted for the dam? For instance, move upstream and divert water through a side weir and transport the water to the original diversion site via a pipeline or canal **(Figure 18)**.

Figure 18: Structure displayed in the picture was used to divert water into an irrigation system to replace a dam previously located downstream of this site.

Develop Construction Documents

1. Identify site location.
2. Identify extent of project impact area and property lines.
3. Identify existing conditions including: survey control points, elevations, physical features, water surface elevations, and infrastructure.
4. Identify proposed conditions including: 1) water control methods, 2) soil erosion and sediment controls methods, 3) infrastructure protection measures, 4) channel work, 5) post-removal channel-plan and channel profile, 6) dam removal extent and elevations, 7) site revegetation, and 8) bank stabilization.

Develop Cost Estimates

Develop cost estimates for preferred alternatives including cost of design, permitting, construction, and construction oversight.

CASE OF NEGLIGIBLE RESERVOIR SEDIMENT

There is no need for extensive sediment data collection and analysis for dam removal projects where the volume of reservoir sediment behind the dam is negligible. For designs outlined in this document, "Negligible Reservoir Sediment Volumes" is based on interpretation of the information summarized in the flow chart in **Figure 1.**

If sediment volume is determined to be negligible, the design can focus on structural and river hydraulic issues. Reservoir impoundments with negligible amounts of reservoir sediments are typically located behind low-head dams operated as run-of-river facilities **(Figure 19).** Stream flows would be expected to rapidly erode and transport such a sediment load with little downstream deposition or no significant changes to the reservoir bottom topography.

Figure 19: Low-head dam operated as a run-of-river facility.

Assuming no contaminated sediments are deposited in the reservoir pool, the dam removal design can proceed to the dam removal planning phase.

4. SEDIMENT MANAGEMENT

Sediment management is often a critical issue related to dam decommissioning when the reservoir sediment volume is greater than the mean annual sediment load delivered to the reservoir (Shuman, 2002). Sediment related impacts following dam removal can occur in the reservoir and in the river channel upstream and downstream from the dam site. Depending on local conditions and removal methods, impact can range from negligible to significant. For example, removing a small diversion dam that had trapped only a small amount of sediment would not have much impact on the downstream river channel. But, if a dam removal results in large volumes of sediment being released, then the impacts to both the upstream and downstream channels could be significant (Greimann, 2004) **(Figure 20)** and require substantial stream restoration.

Figure 20: Sediment eroded from a reservoir after a dam removal initiated channel and bank erosion in the downstream areas.

Potential extent of sediment management problems can be evaluated using the following five indicators.

Relative Reservoir Sediment Volume

The ratio of the reservoir sediment storage volume to the annual sediment load is a key index for a dam removal project. This index can be used to estimate the level of impact that the sediment releases would have on the downstream river channel. When the reservoir sediment storage volume is small (less than the mean annual sediment load) then the impacts to the channel downstream of the dam would be expected to be short-term and minimal. Reservoirs can trap a finite amount of sediment and once that volume is reached then additional sediment transported into the reservoir is subsequently transported downstream of the dam (Dendy, 1974; Strand and Pemberton, 1982). Reservoir pools behind small dams are typically filled within the first or second year of operation. When reservoirs exhibit multi-year storage volumes of sediment then the dam removal plan should consider phased dam removal over a period of months or years to avoid excessive volumes of sediment being released into the downstream channel.

Relative Reservoir Sediment Trap Efficiency

The relative size of the reservoir, expressed as the ratio of the original reservoir storage capacity, at normal reservoir water surface elevation, compared to the average annual inflow volume, can be used as an index to estimate the reservoir trap efficiency (Dendy, 1974; Strand and Pemberton 1982). The greater the relative size of the reservoir, the greater the sediment trap efficiency and the amount of reservoir sedimentation. For a given reservoir storage capacity, the sediment trap efficiency would tend to be greater for a deeper and longer reservoir, especially if flows passing over the spillway crest are uncontrolled. Based on relative reservoir size and sediment loads delivered to the reservoir, empirical relationships have been developed to estimate the long-term reservoir trap efficiency (Brune 1953, Churchill 1948; Dendy, 1974). Reservoirs capable of storing more than 10% of the average annual inflow would be expected to trap between 75% and 100% of the inflowing sediment. Reservoirs with the capacity to store 1% of the average annual inflow would be expected to trap between 30% and 55% of the inflowing sediment. When reservoir storage capacity is less than 0.1% of the average annual inflow then sediment trap efficiency ranges between 0% and 12%.

Relative Reservoir Width

Reservoirs exhibiting large widths, relative to the natural channel, can indicate how much sediment would be eroded and released from the reservoir both during and after dam removal. When a reservoir is many times wider than the un-impacted river channel, especially if the reservoir contains cohesive sediments, then a relatively straight channel will form in the reservoir sediments and much of the reservoir sediment will remain. In reservoirs with little cohesive sediments, dominated by coarse sediments, a wide, braided channel may form and erode a substantial portion of the reservoir sediment, even when no floods occurs **(Figure 21).**

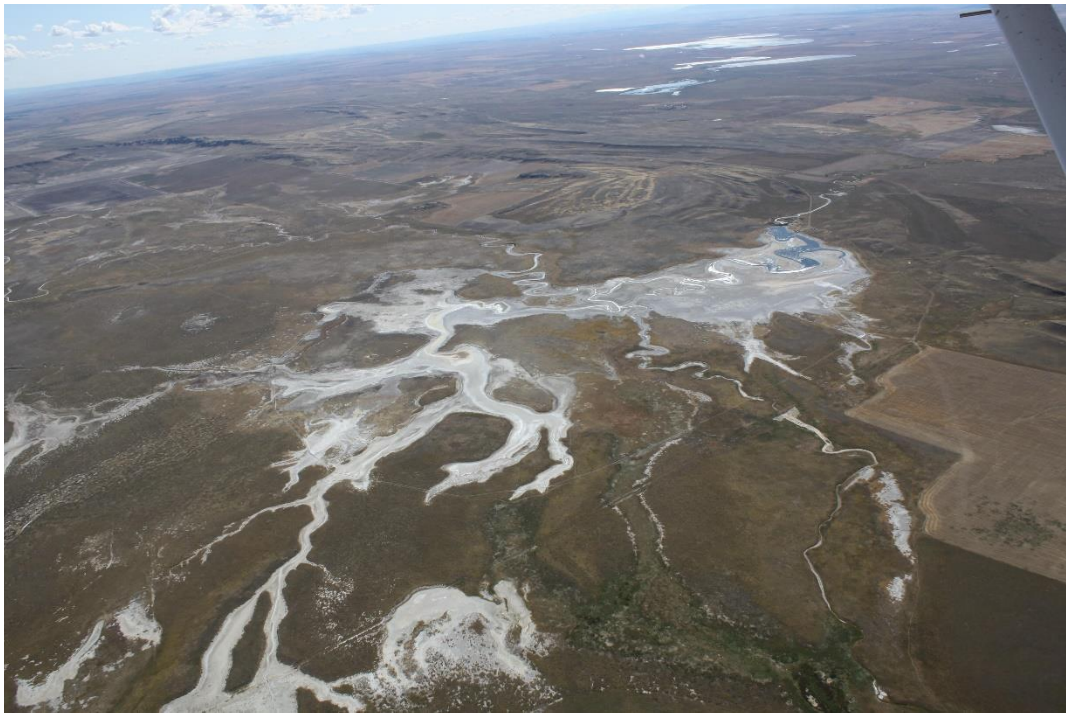

Figure 21: Reservoirs with aspect ratios greater than three and dominated by coarse sediments tend to develop braided channels in the reservoir sediments after the dam is removed.

Reservoir Operations

A reservoir's operation will influence both the sediment trap efficiency and the spatial distribution and particle-size of sediments deposited within the reservoir. The trap efficiency of a given reservoir will be greatest if substantial portions of the inflows are stored during flood flows as sediment concentrations are typically highest during these events. If the reservoir is normally kept full, such as a run-of-river operation, flood flows would be passed through the reservoir and trap efficiency would be less. Coarse-sediment deposits are usually deposited at the upstream ends of a reservoir (a delta). Fine sediments remain in suspension and are usually deposited farther downstream in the reservoir or transported past the dam.

Extent of Contaminants in Reservoir Sediments

The presence of contaminants, above some predetermined level, would likely require mechanical removal, stabilization by capping, or partially removing the dam down to an elevation that traps the contaminated sediment layers.

Sediment Related Issues

Primary issues related to sediment management associated with dam removal projects include downstream and upstream water quality impacts, increased flooding potential in down-stream areas that trap large volumes of sediments and reduce channel capacity, impacts on existing infrastructure both upstream and downstream of the dam, and ecological impacts on fish and wildlife.

If large volumes of coarse sediment erode from a reservoir and are then deposited in the downstream channel then the following conditions can occur: 1) the downstream river channel can widen due to bank erosion; 2) deposition of sediments on the channel bottom can reduce channel capacity and contribute to flooding; and 3) sediment can deposit at water intakes and other infrastructure leading to increased maintenance costs and loss of the structures utility. A phased dam removal approach should be used to minimize these potential effects.

If large volumes of fine sediments erode from the reservoir then turbidity in the downstream river channels could negatively impact fish and wildlife but these impacts are typically short-lived.

Sediment released from a reservoir could be transported downstream into another reservoir reducing that reservoir's storage capacity and negatively impacting the reservoir's fish, wildlife, and infrastructure.

If a reservoir contains large quantities of contaminated sediments then releasing those sediments into downstream areas could negatively impact fish and wildlife and contaminate downstream water supplies. Mechanically removing those sediments can add significant costs to the project.

Lowering the reservoir-pool water-levels can reduce ground water levels and possibly impacts wells and wetlands adjacent to the reservoir.

If the channel downstream of a dam has down-cut then the dam is functioning as a grade control structure. Removing the dam will result in a head cut proceeding upstream through the reservoir sediments and possibly lowering the upstream channel below its historical elevation.

REDUCING SEDIMENT IMPACTS

The potential impacts from erosion, transport, and deposition of reservoir sediments are a major consideration for dam removal projects. A sediment management plan should be incorporated into the dam removal plan if sediment impacts will likely be significant. The sediment management plan should be developed to minimize impacts from releasing reservoir sediments.

The rate of dam removal and reservoir drawdown can have a strong influence on the rate that sediments are eroded and transported to the downstream river channel. The impacts from releasing a large volume of reservoir sediment into downstream channels can be reduced by slowing the rate of reservoir drawdown. Based on the dam's size and volume of sediment anticipated to be released from the reservoir, the drawdown could be completed as a phased dam removal project by lowering the reservoir over a period from weeks, to months and in some cases years.

EVALUATION OF SEDIMENT MANAGEMENT ALTERNATIVES

River Erosion Alternative

If downstream impacts can be accepted or mitigated, allowing reservoir sediments to erode and discharge into the downstream river channel through natural processes **(Figure 22)** is usually the least costly alternative. Conceptual models predicting the geomorphic response of reservoir sediment deposits to dam removal have been developed and employed on numerous dam removal projects (Doyle eta al, 2005; Cannatelli and Curran 2012, Sawaske and Fereyberg, 2012; and Wildman MacBroom 2012). Results from the Elwha River and Marmot Dam removals in the United States (Randle et al., 2015) were consistent with the conceptual models.

Figure 22: Channel downstream of dam breach three days after the dam was removed.

Stabilization Alternative

The sediment stabilization alternative includes stabilizing the reservoir sediments by constructing a river channel through **(Figure 23)** or around the reservoir sediments. Costs for the stabilization method typically exceeds the river erosion alternative but is less than the sediment removal alternative.

Figure 23: Channel being constructed through reservoir sediments after a dam breach. Channel was excavated to minimize the volume of sediment evacuated from reservoir and to control its alignment.

In the cases of a partial dam removal, the lower portion of the dam could be left in place to retain the existing reservoir sediment **(Figure 24)**. A narrow portion of the dam could be removed to the pre-dam channel river-bed but the remaining dam length could be left in place to help retain sediment deposed along the reservoir margins. Vegetation is often planted to help stabilize the remaining sediment from surface erosion.

Figure 24: A partial dam removal that resulted in retaining sediments in the original reservoir.

Mechanical Removal Alternative

Several methods for mechanically removing sediment are detailed in USSD 2015. Conventional excavation may require lowering the reservoir so sediment can be dewatered and dried before excavation equipment is mobilized onto the sediments. After the sediments have dried enough to support heavy equipment, the sediment can be excavated by dozers and front-end loaders and hauled by truck to a deposition site. Mechanical dredging is performed using a dragline, without dewatering the site, but excavated material is normally allowed to drain before being transported to the deposition site. Hydraulic dredging is often the preferred approach to removing large amounts of fine-grained sediment.

EVALUATION OF SEDIMENT MANAGEMENT ALTERNATIVES

The preferred sediment management alternative for a particular project is associated with the dam decommissioning alternative (Table 1). For example, the rate of reservoir sediment erosion is directly influenced by the rate of dam removal and the volume of flow that occurs during the removal. The river erosion alternative is often the least costly and most commonly implement alternative (Table 2). Therefore, the river erosion alternative should be first evaluated to identify sediment-related impacts and whether the risks are acceptable. If risks of sediment impacts from the river erosion alternative are not acceptable, then proceed to reservoir stabilization and/or mechanical removal. The cost of mechanically removing sediment from deep reservoirs would be less if the sediment could be removed as the reservoir is drawn down.

Table 1: Relationship between Dam Decommissioning and Sediment Management Alternatives. (Modified from Bureau of Reclamation 2006).

Sediment Management Alternatives	Dam Decommissioning Alternatives		
	No Action	Partial Dam Removal	Full Dam Removal
No Action	*Reservoir sedimentation continues at existing rates. *Upstream sediment loads could possibly be reduced through watershed conservation practices. *Reservoir operations could be modified to reduce reservoir sediment trap efficiency.	*Only applicable if most of the dam is left in place. *Reservoir sediment trap efficiency would be reduced. *Some sediment may be eroded from the reservoir.	*Not applicable.
River Erosion	*Drawdown the reservoir to flush sediment from the reservoir to the downstream river channel.	*Partial erosion of reservoir sediment due to partial dam removal to the downstream river channel. *Additional erosion of reservoir sediment through reservoir drawdown.	*Erosion of reservoir sediment into the downstream river channel. Erosion rates depend on the rate of dam removal and reservoir inflow. Amount of erosion depends on the ratio of reservoir width to river channel width and sediment cohesion.

Mechanical removal	*Remove sediment from shallow depths by hydraulic or mechanical dredging or by conventional excavation after reservoir drawdown.	*Remove sediment from shallow depths before reservoir drawdown. *Remove sediment from deeper depths after reservoir drawdown.	*Remove sediment from shallow depths before reservoir drawdown. *Remove sediment from deeper depths during or after reservoir drawdown.
Stabilization	Sediments are already stable due to the presence of the dam and reservoir.	Retain the lower portion of the dam to prevent the release of coarse sediments or retain most of the dam's length across the valley to help stabilize sediments along the reservoir margins. *Construct a river channel around or through the reservoir sediment.	*Construct a river channel through or around the existing reservoir sediments. *Relocate a portion of the sediment to areas within the reservoir area that will not be subject to high velocity river flows.

Table 2: Summary Comparison of Sediment Management Alternatives Assuming Complete Dam Removal (modified from ASCE, 1997).

Sediment Management Alternative	Advantages	Disadvantages
No Action	*Low cost *No short-term sediment impact. *Contaminated sediments, if present, would be retained in reservoir.	*Continued problems for fish and river boat passage. *If reservoir is not full of sediment, continued reservoir sedimentation and reduced sediment supply to downstream river channel.
River Erosion	*Potentially least cost alternative. *Short term impacts for long term environmental benefits. *Sediment supply restored to the downstream river channel. Reservoir area restored to more natural conditions.	*Generally, largest risk of unanticipated impacts. *Temporary impairment of downstream water quality and impacts to aquatic habitats. *Potential for river channel aggradation downstream from the reservoir. *Contaminated sediments, if present, would be released downstream.
Mechanical Removal	*Generally low risk of reservoir sediment release. *Reservoir area restored to more natural conditions. *Low impacts to downstream water quality and aquatic habitats. *Avoid short term aggradation of the downstream river channel.	*High cost. *Suitable disposal site may be difficult to locate. *Environmental impacts associated with disposal site.

	*Contaminated sediments, if present, would be removed to disposal site.	
Stabilization	*Moderate cost. *Off-site disposal not needed. *Low to moderate impacts to downstream water quality. *Low potential for short-term aggradation of the downstream river channel. *Contaminated sediments, if present, would be retained in reservoir area.	*Long-term maintenance costs of the river channel through or around reservoir sediments. *Potential for failure of sediment stabilization measures. *Reservoir area not restored to natural conditions.

5. CONSTRUCTION ACTIVITIES

CONSTRUCTION OVERSIGHT AND ON-SITE INSPECTION

Very few or no contractors in the Lower Mekong Region have experience with dam removal projects and many of the details of infrastructure protection and safety must be reiterated to the contractor during the on-site work. To oversee work and respond to unforeseen events, the designer or his representative (inspector), should be on site during all phases of a dam removal project. Several dam removal projects have had serious and unexpected outcomes, including rapid release of reservoir sediments that lead to serious infrastructure damage and long-term ecological impacts (East et al. 2015; Major et al. 2012). The inspector should visually inspect the site to ensure that construction drawings appear to display the site and the required work. The inspector should spot check-elevations before and again during construction.

The inspector should track contractor-supplied materials, to ensure they meet project's specifications, and determine if the contractor's equipment is sufficiently large enough to complete the project. If water will be diverted around the site, the inspector should determine if the contractor's equipment and measures are sufficient to accomplish this task for all but the most unexpected high-flow event. The inspector should ensure that erosion and pollution control methods are being used and maintained.

RESERVOIR WATER MANAGEMENT

In some cases where the dam and reservoir pool is small, and the cost of failure is acceptable, the dam can be instantaneously breached and the water allowed to erode the dam and reservoir sediments in an uncontrolled fashion **(Figures 25 & 26)**.

Figure 25: Example of an instantaneous dam removal project.

Figure 26: Site through a dam breach where the channel was allowed to erode reservoir sediments in an uncontrolled fashion.

Reservoir Drawdown

The reservoir size, streamflow characteristics, and reservoir drawdown capabilities, relative to passing normal flows, are critical for the removal of a dam. The size and location of gates and other drawdown structures greatly influence options for removing a dam. Maximum release rates should be dictated by the sediment management plan and potential impacts to downstream areas. Sometimes it is best to draw the reservoir down as quickly as possible to promote establishment of vegetation on the exposed reservoir soils before high flows initiate further erosion. Other times, based on the sediment management plan, it might be better to draw the reservoir down slowly to encourage consolidation of the reservoir sediments and to minimize impacts of evacuated sediments on downstream sites.

Stream Diversion

On larger dams, and where the cost of failure is significant, safely passing the reservoir storage pool and incoming flows is a critical component of a dam removal project. This is especially important for removing embankment dams as they are more susceptible to erosion and failure if overtopping occurs. In general, sufficient freeboard should be maintained between the elevation of the excavated embankment surface and the reservoir pool-surface to reduce the potential for flood overtopping and embankment failure. To accommodate inflows, diversion channels **(Figure 27)** can be constructed to transport flows around the dam or the reservoir pool can be evacuated by pumping the water around the dam through pipes **(Figure 28)**. Stream diversions can be aided by installing cofferdams at the diversion site and the cofferdams have the benefit of keeping the construction site dry which aids in removing the dam **(Figure 29)**. The coffer dams can be earth or rockfill embankments, sheet-piling, or commercially available water-filled bladders. In case the stream diversion method is overwhelmed, rip rap or articulating blocks should be installed on the downstream face **(Figure 30)** to help minimize the effects of overtopping of embankment dams. A stream diversion would not often be used for smaller concrete dams as these dams can typically accommodate overtopping flows without significant structural failure **(Figure 31).**

Figure 27: Temporary channel constructed to divert water around a dam site during decommissioning.

Figure 28: Pumping system used to transport water around dam during deconstruction.

Figure 29: Coffer dam used to keep construction site dry during dam decommissioning project.

Figure 30: Downstream dam face temporarily stabilized to protect the dam face in case of overtopping while the dam was being removed.

Figure 31: Dam removal site where the water continues to flow through the site while the decommissioning work continues.

Phased Drawdowns

A series of notches can be excavated on alternating sides through a concrete dams to draw the water down in a controlled fashion. The reservoir pool can be drawn down, in support of the goals outlined in the sediment management plan, by continuing to notch the dam at a rate that the downstream channel can accommodate the flows.

A phased drawdown can also be used at embankment dams but a more detailed design is required. On embankment dams, the dam is excavated to approximate the reservoir pool level and a notch is excavated through the dam and then reinforced **(Figure 32)**. The site is then demobilized. After the seasonal high flow period has passed and the reservoir pool has been lowered through the notch and by evaporation, the dam surface is again excavated down to the reservoir-pool surface. The proceeding procedure is iterated until the dam has been excavated to an elevation that the remaining reservoir pool can be instantaneously evacuated by notching the dam and allowing the remaining pool to erode the dam down to the final elevation.

Figure 32: Reservoir being evacuated in stages by notching the dam. The notch was not armored during the final stage and the dam eroded to its final elevation during subsequent high flow events.

DAM DEMOLITION AND REMOVAL

Earth Embankment Dam Removal Methods

Earth and rockfill dams may be removed using common excavation methods and earth-moving equipment **(Figures 33 and 34)**. The excavated material can then provide a source of materials for site restoration or for local commercial use. The removal sequence should generally be from the top down to avoid the formation of steep slopes. When the impacts are deemed to be minimal and/or short-termed, a controlled breach under reservoir-head may be considered for removal of a small, low hazard embankment dam, or for removal of the lower portion of a large embankment dam. Embedded sheet-pile/concrete walls, roadway pavements, and concrete embankment slope protection should first be removed to the extent possible for offsite disposal.

Figure 33: Embankment dam being removed using traditional earth-moving equipment.

Figure 34: Embankment dam being removed using traditional earth-moving equipment.

Concrete Dam Removal Methods

Mechanical demolition methods are most commonly used for smaller dam removal projects. Impact equipment includes boom-mounted hydraulic impact hammers **(Figure 35),** crane operated wrecking-balls, and jack-hammers. Hoe-rams are very effective for demolition of small structures constructed of masonry or low-strength concrete, that contains little or no reinforcement. Jack hammers are most often used in confined areas on low-strength concrete structures or slabs.

Diamond-wire sawcutting **(Figure 36)** produces a smooth cut, without vibration, through heavily reinforced concrete. Depending upon the concrete strength and amount of reinforcing steel, typical sawcutting rates average between 3 and 13 m^2 per hour. The concrete can then be removed in blocks by a crane and loaded onto flatbed trucks **(Figure 37)**. This method is more expensive than blasting or mechanical demolition, but may be used for special conditions such as removal of a concrete gravity-weir without impacting an adjoining abutment wall.

Figure 35: Boom-mounted hydraulic hammer removing the concrete infrastructure at a dam decommission site.

Figure 36: Diamond saw-cutting concrete infrastructure at a dam decommission site.

Figure 37: Removing material at a dam decommissioning site.

For large concrete dams, drilling and blasting **(Figure 38)** is generally the most economical and effective method for demolition but it may not be economically feasible for demolition of small gravity-weirs. Removal of concrete rubble, following blasting, is generally accomplished by front-end loaders, excavators, and dump trucks. Concrete gravity-dams are typically unreinforced except at the dam crest and around the water-works outlets. Construction drawings should be consulted to determine if embedded materials may be encountered.

Figure 38: Deconstructing a concrete dam using drilling and blasting.

A structure's stability should always be considered during demolition. Removal of a downstream stability berm at the toe of a concrete gravity-structure under reservoir loads could result in a sliding failure or a foundation blowout so the structure may require the toe to be stabilized with rock while the dam is being removed. **(Figure 39).** Similarly, a drainage blanket and downstream berm may have been added to an embankment dam to control seepage and protection against internal erosion failure. The long-term stability of any structures to be retained should be considered, especially those which may continue to impound water.

Figure 39: Toe of dam being stabilized with rock to prevent the dam-toe from sliding and failing during a dam decommission project.

SITE RESTORATION

Following removal of the dam and associated structures, the dam-site and reservoir areas may require reshaping and revegetation. Stilling basins, plunge pools, and canals may need to be backfilled. Stability berms or retaining walls may be required to stabilize slopes or landslide areas. Buried pipelines should be removed or stabilized to prevent further deterioration and collapse. Formerly inundated areas should be restored by re-contouring the slopes and planting vegetation. **(Figure 40).** Short term erosion control methods include silt fences **(Figure 41)** and floating debris booms **(Figure 42)**. Long term erosion control includes grading banks, placing erosion control matting, revegetating exposed soils, rip rapping banks, and installing in-stream structures such as constructed riffles **(Figure 43).**

Figure 40: Site restoration using bank-contouring and erosion control.

Figure 41: Silt fence at bankline restoration site used to control silt erosion.

Figure 42: Floating boom used to control sediment movement downstream through an instream construction site.

Figure 43: Riffle being constructed at a dam decommission site.

6. MONITORING AND EVALUATION OF DAM REMOVAL PROJECTS

Monitoring data are necessary to measure a river's response to a dam removal project and to determine whether the project's objectives are being met. If the project's original objectives are not being met then the monitoring plan provides project-planners with an opportunity to intervene early and change or modify on-going actions to bring the project back in-line with the project's original goals. The degree of monitoring associated with a dam decommissioning project should be determined by the project's complexity, degree of scientific uncertainty, and risk of unforeseen circumstances occurring when the dam is removed. In all circumstances, monitoring should be included in the project's original scoping effort.

There are many site-specific factors that need to be considered when developing criteria to evaluate the ecological results of dam removals. For instance, water quality criteria may be achieved rapidly for some dam removal projects whereas it may take years for that same criteria to be met at other sites. Similarly, migratory-fish criteria may be met within a year in watersheds with few dams whereas a watershed with many dams may not meet migratory-fish objectives for many years, or ever, unless additional dams are removed.

Grosse and Doherty (2016) noted that "the biggest limitation to statistically determining effective and ecologically responsible methods of dam removal is the lack of long-term data associated with dam removals". Hart (2012) noted, that to date, fewer than 5 percent of the dam removal projects completed in the United States included published ecological studies and details of physical changes associated with dam removal projects. From a practical perspective, monitoring plans are largely driven by the project's monitoring budget. Bellmore et al. (2017) noted the greatest challenge to establishing Best Management Practices for dam removal projects was the lack of post-dam removal monitoring information. To the extent possible, prescribed monitoring should be explicitly funded within the project's budget (Collins et al., 2007). Collection of pre-removal data is critical to monitoring the success and failure of dam removal projects. Data should be collected from several locations, upstream and downstream of the dam that may be impacted by the project. Both long-term and short-term monitoring should be conducted as conditions being monitored may change over time.

At least one year of pre-dam removal monitoring should be conducted. Entities conducting the monitoring should have a thorough understanding of the physical and biological processes and characteristics of the river as it responds to dam removal actions. If possible, at least one person should be involved throughout the monitoring period to ensure consistency and uniformity in implementing the monitoring program (Collins et al., 2007).

The specific parameters that need to be monitored should be tailored to the project site and restoration goals. Project funding typically constrains monitoring programs so monitoring should prioritize the most important physical and biological issues relative to that site and the issues most important to the stakeholders. Project evaluation may include both technical data collection/analysis in conjunction with the stakeholder's concerns about potential impacts. Stakeholders may have similar or opposing views of whether physical and/or biological impacts to the site are positive or negative. A systematic approach to monitoring and data collection may be necessary to quantify and evaluate the effectiveness of the dam decommissioning project.

For large dams, with significant storage capacity, removing the dam can produce higher downstream flood peaks, greater flow fluctuations, reduced water supply, and lowered groundwater levels that potentially impact adjacent wetlands and wells. For many small dams, the reservoir pool is too small to have a significant effect on flood hydrology and changes in downstream flooding are generally not realized. But, the stakeholders may perceive that downstream floods can, or does, occur after a dam is removed and the monitoring program may need to address this issue.

PHYSICAL MONITORING

The amount and rate of reservoir-sediment that is eroded and released into the downstream river channel contributes to short-term and long-term impacts so monitoring periods may need to be modified when the release rates are greatly different than predicted. Monitoring should continue at periodic intervals (1, 2, and 5 years) after dam removal or; 1) until reservoir sediments have either fully eroded or stabilized in the reservoir; 2) eroded-sediment has been stabilized with vegetation in the downstream sections; or, 3) the sediment has been flushed from the downstream river channel.

Physical Monitoring Outcomes

The Heinz Center (2002) provides an extensive list of physical-outcomes associated with dam decommissioning projects and the following is a pared-down list of likely outcomes for dam removal project in the Mekong River Basin.

1. Changes to downstream hydrology.
2. Sediment degradation within the impounded area and upstream of the reservoir.
3. Sediment aggradation downstream of the former dam site.
4. Changes in suspended sediment concentrations and associated water turbidity.
5. Change in sediment grain size, both upstream and downstream of the former dam site than can have significant impacts on the river’s physical attributes deemed important for fish.
6. Changes in cross-sectional and longitudinal channel morphology.
7. Changes in frequency of inundation to the floodplain with potential benefits to fish.
8. Changes in groundwater flow with resulting impacts to adjacent wetlands and wells.

Physical Monitoring Techniques

1. Longitudinal profile surveys can document the pre-dam and post-dam bankline positions both upstream and downstream of the project site.
2. Cross section surveys, both upstream and downstream of the project-site can be used to document the extent of reservoir sediment evacuation and resulting downstream deposition.
3. Turbidity and suspended sediment concentrations can be measured upstream and downstream of the dam-site to document the timing of the erosion and potential impacts to the associated biological community.
4. Bed-material size-gradation can be measured to document changes caused by sediment erosion and deposition.

BIOLOGICAL MONITORING

The primary goal of many dam decommissioning projects is to improve and/or restore fish passage that results in increased fish production as they gain access to additional habitats. The Heinz Center (2002) provides an extensive list of potential biological outcomes for dam removal projects and the following is a pared-down list of likely outcomes for dam removal projects in the Mekong River Basin.

Biological Monitoring Outcomes

1. Changes in fish community assemblages and abundances.
2. Changes in benthic macroinvertebrate diversity and abundance.
3. Change in freshwater mussel beds.
4. Fish movement and range expansion

Biological Monitoring Techniques

1. Fish and macroinvertebrate habitat-surveys along the river channel, both upstream and downstream of the project-site, can be used to document changes (improvements and negative impacts) to fish and macroinvertebrate habitats. Habitat surveys could include water depth, flow velocity, channel substrate, and vegetation cover.

2. Abundance, species composition, and distribution of fish and macroinvertebrates should be collected upstream and downstream of the project site.
3. Telemetry and other tracking technology

SOCIAL-ECONOMIC ASPECTS

Dams often become a significant part of the local community's identify and the community may associate the site with important seasonal events and life experiences.

Based on one's aesthetic perspective, removing a dam, lowering reservoir levels, and exposing mudflats can produce negative, positive, or mixed responses from local stakeholders. Socioeconomic impact assessments may include changes in fish concentrations near the former dam site, which in turn impacts subsistence fishing, commercial fishing, and fish-processors. These impacts can be significant to local communities. Socioeconomic impacts generally include cultural, historical, aesthetics, recreation and land use. The loss of the dam and associated reservoir may affect water supplies and public health.

Social-Economic Outcomes

1. Change in public attitudes over time to the removing the dam.
2. Change in perceptions of public safety.

LITTERATURE CITED

Ahearn, D. S., and R. A. Dahlgren. 2005. Sediment and nutrient dynamics following a low head dam removal at Murphy Creek, California. Limnology and Oceanography 50:1752-1762.

American Rivers. 2002. The ecology of dam removal: a summary of benefits and impacts. Washington DC. 15pp.

American Society of Civil Engineers (ASCE). 1997. Guidelines for retirement of dams and hydroelectric facilities. New York. January 1997. 452pp.

Baumgartner, L.J. et al. (2015). Achieving fish passage outcomes at irrigation infrastructure, a case study from the Lower Mekong Basin. Aquaculture and Fisheries 6:113-124.

Belmore et al. 2017. Status and trends of dam removal research in the United States. WIREs Water 2016. DOI: 10:1002/wat2.1164.

Cannatelli, K.M. and J.C. Curran. 2012. Importance of hydrology on channel evolution following dam removal: case study and conceptual model. Journal of Hydraulic Engineering 138:377-390.

Casperi, A.F., J.H. Thorpz, and S.P. Davies. 2006. Ecological response of zoobenthos to dam removal on the Kennebec River, Maine, USA. Achieves Hydrobiological Supplement 158: 541-555.

Chisholm, L. and L. Aadland. 1994. Environmental impacts of river regulation. Minnesota Dept. of Natural Resources, St. Paul, Minnesota. 31pp.

Church, M. 1995. Geomorphic Response to river flow regulation: case studies and time scales. Regulated Rivers: research and management 11:3-22.

Collis et al. 2007. Stream barrier removal monitoring guide. Gulf of Maine Council on the Marine Environment. December 2007.

Cui et al. 2017. Analyses of the erosion of fine sediment deposits for large dam removal project: An empirical approach. International Journal River Basin Management 15:103-114.

Dendy, F.E. 1974. Sediment trap efficiency of small reservoirs. Transactions of the American Society of Agricultural Engineers 97:898-908.

Downs et al. 2009. Managing reservoir sediment release in dam removal projects: an approach informed by physical and numerical modeling of non-cohesive sediment. International Journal River Basin Management 7:433-452.

Doyle, Martin W., et al. 2005. Stream ecosystem response to small dam removal: lessons from the heartland. Geomorphology 71:227-244.

East et al. 2015. Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. Geomorphology 228:765-786.

Fencl, J.S.; M.E. Mather; K.H. Costigan, and M.D. Daniels (2015). How big of an effect do small dams have? Using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation. PLoS One:10e0141210.

Greimann, B. 2004. Prediction of sediment impacts associated with dam removal, Proceedings of the 24th Annual United States Society of Dam Conference, St. Louis, Missouri, April 2004.

Grosse, K. and J. Doherty. 2016. Minimizing the ecological impacts of dam removal. M.S. Thesis, Duke University Nicholas School of Environment. 39pp.

Hart et al. 2012. Dam removal: challenges and opportunities for ecological research and river restoration. BioScience Academic Journal 52: 117-143.

Heinz Center. 2002. Dam removal: science and decision making. Washington, D.C. 2002.

Johnson, W.C. 2002. Riparian vegetation diversity along regulated rivers. Contribution of novel and relict habitats. Freshwater Biology 47:749-759.

Katapodis, C. 2010. Developing a toolkit for fish passage, ecological flow management and fish habitat works. Journal of Hydraulic Research 45:451-467.

Katapodis, C.and L.P. Aadland. 2006. Effective dam removal and river restoration approaches. International Journal of River Basin Management 4:153-168. 2010.

Kibler, K. D. Tullos, and M. Kondolf. 2011. Evolving expectations of dam removal outcomes: downstream geomorphic effects following removal of a small, gravel-filled Dam-1. Journal of the American Water Resources Association 47:408-423.

Kondolf, G.M. 1997. Hungry water: effects of dams and gravel mining on river channels. Environmental Management 21:533-551.

MacBroom, J. and R. Schiff. 2013. Sediment management at small dam removal sites in DeGraf, J.V. and Evans, J.E. Editors, The Challenges of Dam Removal and River Restoration, Geological Society of America Reviews in Engineering Geology 21: 67-79.

MacBroom, J.G. 2012. Evolution of channels upstream of dam removal sites. Presented at the American Society of Civil Engineers Conference on Managing Watersheds for Human and Natural Impacts.

Major et al. 2012. Geomorphic response of the Sandy River, Oregon, to removal of Marmot Dam. U.S. Geological Survey Professional Paper 1792. 64 pp.

Marion, C.A. M.C. Scott, and K.M. Kubach. 2012. Fish community response to dam removal in Twelvemile Creek, Pickins County, South Carolina. Freshwater Biology 53:1055-1068.

Magilligan, F.J. et al., 2016. River restoration by dam removal: enhancing connectivity at watershed scales. Geology 28:819-822.

Marks, J.C. et al. 2010. Effects of flow restoration and exotic species removal on recovery of native fish: lessons from a dam decommissioning. Restoration Ecology 18:934-943.

Nguyen-Khoa, S., L. Smith; and K. Lorenzen. 2005. Impacts of irrigation on inland fisheries: Appraisals in Laos and Sri Lanka comprehensive assessment research report 7. London International Water Management Institute. Imperial College.

Pearson, A.J. M.P. Snyder, and M.J. Collins. 2011. Rates and process of channel response to dam removal with a sand-filled impoundment. Water Resources Research 47:932-941.

Pizzuto, J. 2002. Effects of dam removal on river form and process. Bio Science 52: 96-107.

Poff, N.L. and J.K. Zimmerman. 2010. Ecological responses to altered flow regimes: a literature review to inform environmental flows science and management. Freshwater Biology 55:194-205.

Poulos, J.M. et al. 2014. Fish assemblage response to a small dam removal in the Eightmile River system, Connecticut, USA. Environmental Management 54: 1090-1101.

Quinn, J.M. and C.W. Hickey. 1990. Magnitude of effects of substrate particle size, recent flooding, and catchment development on benthic invertebrates. New Zealand Journal of Marine and Freshwater Research 24:411-427.

Randle, T.J. and J.A. Bountry. 2015. Progress on dam removal analysis guidelines for sediment in proceedings of SEDHYD: Federal Interagency Conference on Sedimentation and Hydrologic Modeling, Reno, NV, April 19—23, 2015.

Sawaske, S.R. and D.L. Freyberg. 2012. A comparison of past small dam removals in highly sediment-impacted systems in the US. Geomorphology 151:50-58.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. Earth Sciences Process and Landforms 14: 11-26.

Strand, R.I. and E.L. Pemberton. 1982. Reservoir sedimentation technical guidelines for Bureau of Reclamation Sedimentation and River Hydraulics Section Hydrology Branch Division of Planning Technical Services Engineering and Research Center, Denver, Colorado.

Tonitto, C. and S.J. Riha. 2016. Planning and implementing small dam removals, lessons learned from dam removals across the eastern United States. Sustainable Water Resources Management. 2:489-507.

Tullos, D.D. D.S. Finn, and C. Walter. 2014. Geomorphic and ecological disturbance and recovery from two small dams and their removal. River Research and Applications 28:1439-1450.

Tullos, D.D. et al. 2016. Synthesis of common management concerns following dam removals. Journal of American Water Resources Research 52:1179-1206.

US Bureau of Reclamation (BOR) 2006. Erosion and sedimentation manual, Chapter 8, dam decommissioning and sediment management. Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. November 2006.

US Bureau of Reclamation (BOR) 2017. Dam removal analysis guidelines for sediment. Advisory Committee on water information subcommittee on sediment. US Department of Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group Denver, Colorado. December 2017. 192 pp.

United States Society on Dams (USSD). 2015. Guidelines for dam decommissioning projects. United States Society on Dams Committee on Dam Decommissioning. July 2015. 192 pp.

Wildman, L.A. 2013. Dam removal: A history of decision points, in The Challenge of Dam Removal and River Restoration, Volume 21, edited by J.V. De Graff and J. E. Evans. PP 1-10. Geological Society of American. Virginia, United States.

Wildman, L.A. and G. MacBroom. 2010. A broad level classification system for dam removals, paper presented at Federal Interagency Sedimentation Conference. Las Vegas, Nevada. June 27, 2010.

Wildman, L.A. and G. MacBroom. 2005. The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City Dam removals. Geomorphology 71:245-262.

GLOSSARY

Aspect ratio: Ratio of reservoir's top width divided by the channel width outside of the influence of the dam. Dam projects with aspect ratios less than 2 typically contain a minimal amount of accumulated sediment and are ideal for instantaneous removal approach. As a dam site's aspect-ratios increase to a ratio-value greater than 2 the greater sediment management will play into the design.

Bendway weir: A rock weir set below the bankfull depth and orientated at a 60 to 90 degree angle from the bank in in upstream orientation.

Conceptual Model. A conceptual model is a qualitative description or representation of a complex system or set of circumstances. The conceptual model is used to help people understand how systems function of how circumstances are related. Conceptual models are often abstractions of systems, circumstances, or ideas in the real world, whether physical or social.

Dam crest: The dam crest is the top of the dam from left abutment to right abutment and functions as an uncontrolled spillway.

Depth of Refusal: Terminology used when probing reservoir sediments to assess the depth of sediment-deposits relative to the depth of the original channel. A probe is extended into the reservoir sediments until the probe can no longer be forced deeper into the reservoir-sediments using the force exerted by the individual conducting the survey.

Due Diligence: The care that a reasonable person exercises to minimize harm to another person or damage to their property. The legal definition for "due diligence can vary between localities.

Hydraulic height of dam: The dam's hydraulic height is the vertical elevation difference between the normal reservoir pool elevation and the downstream river water surface during the mean discharge.

Instantaneous dam removal. Also referred to as blow-and-go method. A dam removal method where the dam is removed or the reservoir emptied of water in one continuous action. This method exposes the impounded sediment to rapid sediment removal.

Legacy dams: In some areas, land uses in the reservoir's watershed resulted in the reservoir being filled with sediment. In some cases, larger dams were built downstream of the sediment filled dams and reservoirs which resulted in the original dam being buried in the new reservoir's sediment. The old structures can pose significant challenges when they are encountered during dam removal projects.

Legacy dam encountered during a dam decommission project.. Dam prohibited sediment from being evacuated from the reservoir after the dam was removed. 1

Low-head dam: Defined as a dam built across a river with a hydraulic head of less than 8 m designed to pass flows from upstream over all, or nearly all, of the width of the dam crest on a continual and uncontrolled basis. In general, low-head dams do not have a separate spillway or spillway gates and the dam crest functions as an uncontrolled spillway. A low-head dam provides little water storage.

Negligible reservoir sediment volume: For designs outlined in this document, negligible reservoir sediment is defined as a reservoir sediment volume that constitutes less than 0.1 (10%) of the average annual sediment load entering the reservoir. Stream flows would be expected to rapidly erode and transport such a sediment load with little downstream deposition or no significant changes to the reservoir bottom topography.

Phased dam removal: A dam removal method where dam crest is incrementally lowered and the water subsequently released over multiple stages. This method is typically used where controlled release of reservoir sediments are warranted and downstream effects of sudden release of water and sediments can do harm.

Reservoir trap efficiency: Usually expressed in percent, is the proportion of the inflowing sediment that is trapped in the reservoir. See Dendy, F.E. 1974 for detailed methods of calculating this parameter.

Run-of-river-dam. A dam with no regular drawdown of reservoir storage for water supply or flood control. River-inflow at run-of-river-dams typically equals outflows.

Sediment (Reservoir-sediment): Sediments are unconsolidated particulate materials found at the bottom of natural and manmade surface water bodies. They may include clay, silt, sand, gravel, decaying organic matter, or shells.

Thalweg: The lowest point in a river channel.

Appendix A: Dam Removal Checklist

The general steps for removing a dam are listed below. The order that they are listed will not always be the best approach as some tasks will be conducted simultaneously whereas others will be required to determine if the project is feasible and others steps are even warranted. Each project will be unique and some of the steps won't be needed where others will require greater detail.

Assess Scope of Project and Potential Partners

- Determine dam owner and their interest in removing the dam.
- Identify potential infrastructure impacts upstream and downstream of the dam site including utilities, roads, bridges, and adjacent buildings.
- Consider the potential for contaminated sediment.
- Assess support and resistance by the primary beneficiaries of the dam and the local community's interest.

Initial Reconnaissance and Site Visit

- Conduct a site visit with interested parties and the dam owner.
- Collect existing data.
- Survey the site and infrastructure potentially impacted by removing the dam.
- Assess the site's hydrology
- Assess sediment quantity, quality, and mobility.
- Assess whether associated infrastructure (roads, bridges, etc.) are at risk when the dam is removed and determine approaches for stabilizing or avoiding impacts to affected infrastructure.
- Complete pre-project monitoring so post-project assessments will have baseline data to determine the benefits of removing the dam.

- Develop preliminary design plans and conceptual drawings.
- Develop cost estimates for the project and associated monitoring.

Engineering Design

- Develop engineering design plans of dam removal, water management, sediment management infrastructure projection, restoration plans, and environmental protection plans.
- Develop Project Specifications that identify necessary construction equipment, materials quantities and minimum standards, staging sites, project sequencing, and site access.
- Develop an Engineer’s Cost Estimate for the project.

Project Implementation

- Hire a contractor.
- Drawdown impoundment and implement water management practices.
- Remove the dam and associated infrastructure.
- Stabilize remaining infrastructure and sediment, complete environmental restoration efforts.

Post Project Monitoring

- Evaluate changes in fish, invertebrates, and other aquatic species distributions and abundance.
- Evaluate sediment movement and responses to channel and bankline habitats.
- Evaluate both instream and bankline changes in vegetation.
- Evaluate changes in water quality.
- Evaluate changes in river hydraulics as it relates to aquatic species movement and changes in aquatic species distribution and abundance.