D R A F T
Dam Removal Analysis Guidelines for Sediment

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SUBCOMMITTEE ON SEDIMENTATION

In 1939, the U.S. Department of Agriculture, Bureau of Reclamation, Office of Indian Affairs, U.S. Geological Survey, U.S. Army Corps of Engineers, and Tennessee Valley Authority formed the "Inter-Departmental Committee." This committee was formed to oversee a project that would investigate sediment-sampling equipment and techniques with the purpose of developing standardized ways of measuring and analyzing fluvial-sediment loads. From the time of its conception until the present day, this committee has served under several different parent organizations. These include the Federal Interagency River Basin Committee, Interagency Committee on Water Resources, Water Resources Council, and Interagency Advisory Committee on Water Data (IACWD). The IACWD, an advisory committee to the Secretary of the Interior and administratively organized by the USGS Office of Water Data Coordination, was replaced by the Advisory Committee on Water Information (ACWI) in 1996, and the currently named Subcommittee on Sedimentation was re-chartered under the ACWI in 2004.

The objectives of the Subcommittee on Sedimentation are to:

- Determine the major sediment-related problems and issues facing the United States in the 21st century.
- Coordinate the development of countermeasures to reduce sediment problems on our water resources.
- Provide standardized information and data that are scientifically defensible for policy-makers.
- Coordinate and pool the resources of the participating agencies in order to effectively share information and consolidated sediment databases and address important sediment problems.
- Promote the analysis of sediment data from a watershed or river basin perspective.

The Subcommittee on Sedimentation currently reports to the Federal Advisory Committee on Water Information, which in turn reports to the U.S. Department of the Interior, Assistant Secretary for Water and Science (http://acwi.gov/sos/index.html). Current Subcommittee on Sedimentation member organizations include the Agricultural Research Service, the American Society of Civil Engineers, the Bureau of Land Management, the Bureau of Reclamation, the Colorado Water Resources Research Institute, the Federal Highway Administration, the National Center for Earth-surface Dynamics, the National Park Service, the National Resources Conservation Service, the Office of Surface Mining, the Universities Council on Water Resources, the U.S. Army Corps of Engineers, the U.S. Environmental Protection Agency, the U.S. Forest Service, and the U.S. Geological Survey.

DISCLAIMER

The Dam Removal Analysis Guidelines for Sediment are intended to assist users with selecting methods to analyze sediment impacts associated with potential dam removal projects. Analysis guidelines are provided to assist engineers and scientists with evaluating the sediment effects associated with dam removal. The guidelines should not be expected to address every unique dam removal case or circumstance nor uncertainties that may be discovered as a result of dam removal. No warranties are implied or expressed by these guidelines. The guidelines are not intended to be a regulatory document, but are intended to capture the best practices for sediment analysis related to dam removal.

ACKNOWLEDGEMENTS

The development of these guidelines were only possible with the dedication and hard work of many people working under the sponsorship of the Subcommittee on Sedimentation. The guidelines benefited greatly from the input by numerous technical experts working in the field of dam removal representing federal and state agencies, universities, private consultants, and non-governmental agencies.
List workshop participants here alphabetically by name and organization.

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INTRODUCTION

The total number of all dams in the United States is estimated to be as large as 2 million, many of which are small and not well documented (Gray, 2010 [check FISC reference]). The U.S. National Inventory of Dams is a database that includes over 80,000 dams that are at least 25 feet (7.6 m) high, store at least 50 acre-feet (64,000 m^3) of water, or are considered a significant hazard if they should fail (database accessed January 18, 2011 at http://geo.usace.army.mil/pgis/f?p=397:12:4398225106308821). Of the dams in the inventory, less than 2 percent are over 100 ft (30 m) high. The most common purposes of dams and reservoirs are for the diversion or storage of water for industrial, municipal, and agricultural uses; flood control; navigation; hydropower generation; and sediment retention. Reservoirs also provide benefits for recreation, wildlife, and fishery enhancement.

Dams continue to be an important part of our infrastructure worldwide. Many dams were built several decades ago and a few may have safey issues or reservoirs full of sediment. In some cases, the original purpose of the dam is no longer needed or there may be significant environmental benefits achieved by removing a dam. Dam removal may be a viable management option when the lost benefits of a dam and reservoir can be met through alternative means. For example, a pumping plant with proper fish screens may negate the need for a diversion dam that impedes fish passage. Electricity generated from a single purpose, hydroelectric dam could be generated by other power plants. Water storage and flood control benefits provided by many dams would be more difficult to replace if the dam were removed.

Guideline Objective

The objective of the guidelines is to provide a tool for determining the level of sediment analyses necessary for dam removal projects that can be used initially as a scoping tool and evolve to an implementation tool. The guidelines recommend scaling the level of sediment-related investigations to the relative reservoir sediment volume and knowledge of potential risks and uncertainty if the sediment were to be released to the downstream channel as the result of a dam removal project. The relative reservoir sediment volume is the ratio of the sediment volume or mass to the average annual sediment loads entering the reservoir from all tributaries. The recommended level of investigations can be revisited and adjusted as more information is gathered throughout the project.

The guidelines are intended to be applicable to reservoir sediment volumes that are negligible, small, medium, and large. The reservoir sediment volume is considered to be large if it contains decades worth of sediment supply, medium if it contains years of sediment supply, small if it contains months of sediment supply, and negligible if it contains only a month or less of sediment supply.

The guidelines are written for a technical audience with knowledge of river hydraulics and sedimentation processes, but may also serve as a reference and communication tool

for scoping discussions with resource managers, permitting staff, and stakeholders. The guidelines were developed based on the collective experience of a subset of technical experts working in the field of dam removal and reservoir sediment related issues (see Appendix B).

Summary of Dam Removal Alternatives

The U.S. Society on Dams has produced new Guidelines for Dam Decommissioning Projects (USSD, 2013) that provide more detailed descriptions of dam removal activities. Dam removal could mean the complete removal of the dam and all associated facilities, but a partial dam removal could be another alternative. For example, removing only the portions of the dam that block fish passage could be less expensive than completely removing all structures related to the dam (spillways, power plants, and dikes). Some structures could be left behind for historic preservation. A portion of the dam could also be left behind to retain reservoir sediment. This could mean removing only the portion of the dam blocking the old river channel and retaining portions of the dam along the old reservoir margins to retain sediment. Alternatively, the lowest portion of the dam could be retained to store sediment along the reservoir bottom, act as a grade control to prevent any downstream channel degradation from progressing upstream through the reservoir, or act as a barrier to exotic fish to prevent their upstream migration.

Summary of Sediment Management Alternatives

Many small dams do not contain a significant amount of sediment. However, when the amount of reservoir sediment is significant, there are three basic reservoir sediment management alternatives associated with dam removal (ASCE, 1997, Randle and Greimann, 2006):

1. The river erosion alternative is where the stream flows are allowed to erode all or a portion of reservoir sediments to the downstream channel.
2. The mechanical removal alternative is where all or a portion of the sediments are removed from the reservoir. This could be accomplished by hydraulic or mechanical dredging. The mechanical removal alternative needs to consider alternative sediment removal methods, alternative sediment delivery methods, and alternative disposal locations.
3. The reservoir stabilization alternative is where reservoir sediments are stabilized within the reservoir area. This could include excavating a stream channel around the existing reservoir sediments or excavating a channel through the reservoir sediments and relocating the excavated sediment within the reservoir.

Combinations of these three alternatives would also be possible. For example, fine reservoir sediment could be mechanically removed to avoid downstream turbidity impacts while stream flows could be allowed to erode coarse sediments.

The river erosion alternative appears to be the most commonly applied, especially in the western United States. This alternative potentially has the least cost, but results in the

greatest amount of sediment concentration and turbidity in the downstream channel and potentially the greatest amount of uncertainty. The sediment concentration and uncertainly directly depend on the rate of reservoir drawdown, which is often associated with the rate of dam removal.

The mechanical removal alternative is typically the most expensive, but may be necessary if the sediments are contaminated beyond background levels and must be removed from the system. The reservoir stabilization alternative can be a cost effective way of preventing sediments from entering the downstream channel, so long as the stabilization measures do not catastrophically fail at some point in the future.

Literature

American Rivers estimates that 860 dams have been removed in the United States by the close of 2010. In nearly all of cases, the original purpose of the dam was no longer being served or the present function of the dam could be met through other means. American Rivers now publishes annual lists of dam removal projects and noted that in 2009 there were 59 dams removed and in 2010 there were 60 dams removed. The 2010 list includes dams in California, Maine, Maryland, Massachusetts, Michigan, North Carolina, New Hampshire, New York, Pennsylvania, Ohio, Oregon, Rhode Island, Virginia and Vermont. On September 17, 2011, the largest dam removal project began with the concurrent removal of Elwha and Glines Canyon Dams on the Elwha River in northwestern Washington State (Randle and Bountry, USSD, 2012).

Comment [TJR1]: Consider an update for 2011 and 2012.

Because of the growing number of dam removal projects, several publications have been written related to the general aspects of dam decommissioning or removal:

- Guidelines for Dam Decommissioning (American Society of Civil Engineers, 1997)
- Dam Removal - A New Option For a New Century (Aspen Institute, 2002)
- Dam Removal: Science and Decision Making (Heinz Center for Science, Economics and the Environment, 2002)
- Dam Removal Research Status and Prospects (Heinz Center for Science, Economics and the Environment, 2003)
- Dam Decommissioning Chapter of the Erosion and Sedimentation Manual (U.S. Department of the Interior, Bureau of Reclamation, 2006)
- Guidelines for Dam Decommissioning Projects (U.S. Society on Dams, 2013)

Several implementation guidelines for dam removal projects have also been developed (Collins et al, 2007; New Hampshire Department of Environmental Services, Revised 2007; Texas Commission on Environmental Quality, September 2006; Michigan Department of Natural Resources, April 2004). A database has been developed at the University of California at Berkley to facilitate sharing of case histories and lessons learned from dam removal projects (http://www.lib.berkeley.edu/WRCA/CDRI/search.html). For the last several years, many technical conferences have included, and continue to include, specific dam removal sessions.

Informed consideration of the quality and quantity of reservoir sediment is a significant component of properly evaluating the effects of a proposed dam removal project. Sediment effects associated with dam removal can be thought of in terms of ecosystem and river health, as well as water users and infrastructure located within the reservoir and downstream river corridor. There have been some articles describing sediment processes that occur during the removal of a dam (Morris and Fan, 1997; Conyngham. 2009; Conyngham and Wallen, 2009; Doyle, et al. 2003; U.S. Department of the Interior, 2006). The American Society of Civil Engineers produced a valuable reference that includes a series of papers entitled: Monograph on Sediment Dynamics upon Dam Removal (ASCE, 2012).

In addition to the existing guidance and literature, the U.S. Subcommittee on Sedimentation (Subcommittee) recognized the need for technical guidelines addressing sediment analysis for dam removal investigations (see Appendix A for background on the Subcommittee). Dam removal often includes a wide range of activities related to sediment data collection and analysis. Sediment management decisions related to dam removal are also varied. Stakeholders, regulating agencies, and technical staff may have varying thresholds on what constitutes significant sediment impacts, and what level of information is needed to make decisions regarding sediment management. Existing manuals do not provide a framework or guideline for determining the level of analysis needed, the significance of sedimentation issues, or certainty that can be attained with available analysis tools.

Comment [TJR2]: Rather than an Appendix on the Subcommittee on Sedimentation, we could include a link to the website and include the subcommittee full name and logo on the title page

GUIDELINES OVERVIEW

The guidelines are intended to be a tool that can be applied in an iterative approach. Initially, some assumptions may have to be made when applying the guidelines, but these assumptions should be updated as more information becomes available and the guidelines can be re-applied. The user is advised to first apply the guidelines with readily available information and develop the initial scope of sediment data collection and analysis (Planning Level). Once the more detailed data and predictions become available, the user is advised to go back through the guidelines and re-evaluate the questions posed at each analysis step (Analysis Level). This iterative approach to utilizing the guidelines should be employed whenever significantly new information becomes available. Once the analysis level is complete, the user should make one additional pass through the guidelines to refine recommendations of mitigation, monitoring, and adaptive management of sediment related processes from dam removal (Implementation Level).

The level of data collection and analysis for a dam removal project is a function of the level of risk associated with the sediment impacts. The concept of the risk based approach is presented in Figure 1. The risk is the product of the probability of impact and the consequence of impact. The greater the risk, the greater the recommended level of data collection and analysis. The risk is intended to be a qualitative analysis in collaboration with technical experts, stakeholders and resource managers. For the purposes of this guideline, the relative reservoir sediment volume, scaled to the watershed, is used as a surrogate for the probability of impact from releasing sediment as a result of dam removal. If the reservoir sediment contains contaminants above background levels, then the potential release of contaminants to the environment will likely determine the level of risk for the project and if reservoir sediment can be released downstream. For cases of little or no sediment, the risk is assumed to be negligible or low and has a special analysis section in this guideline.

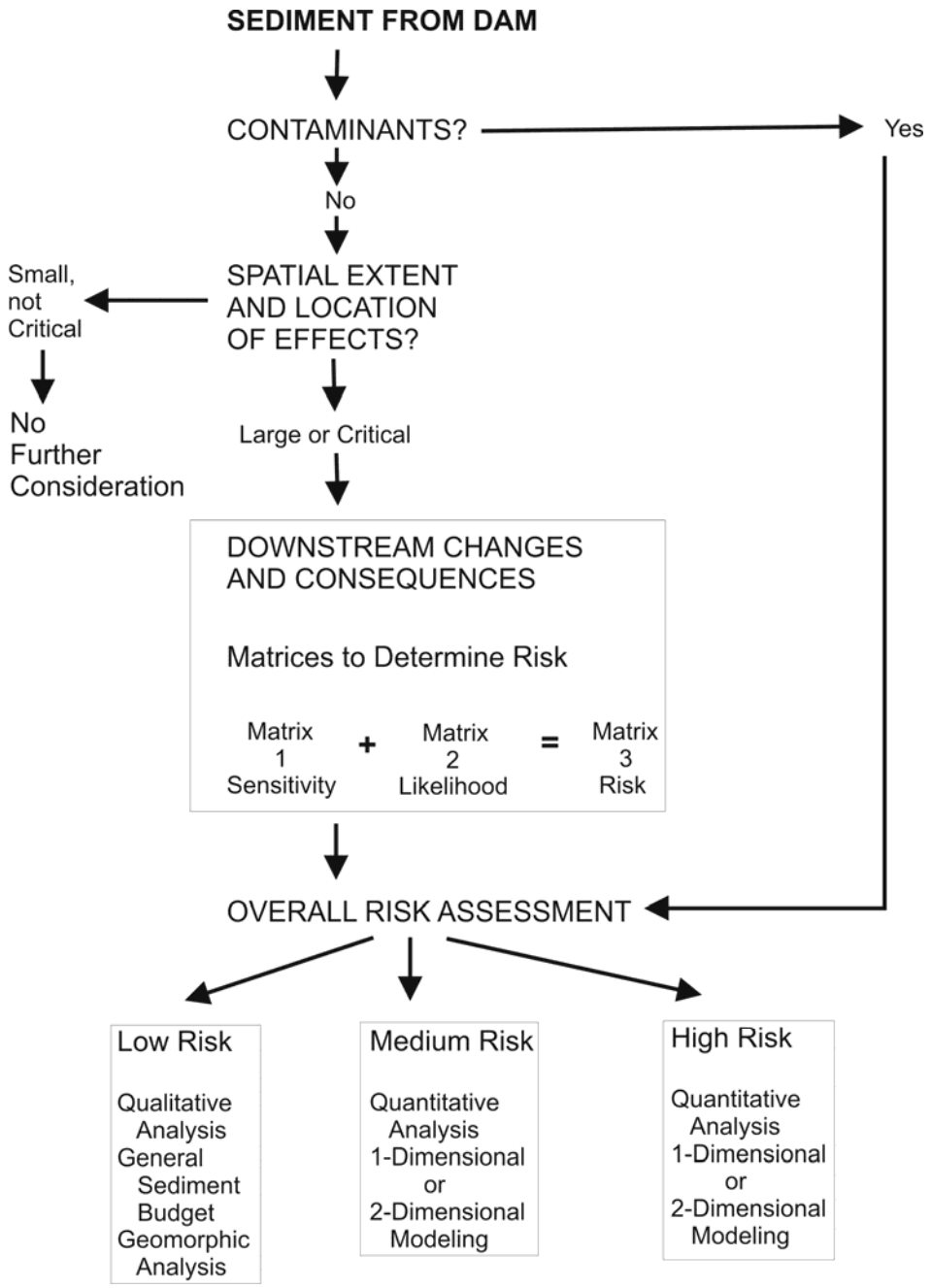

Figure 1. Risk-based approach concept

Establishing the Sediment Analysis Team

Where sediment related impacts could be significant, a sediment analysis team should be established to apply the sediment analysis guidelines and evaluate sediment impacts from dam removal. The recommended expertise and complexity of the team depends on the relative reservoir sediment volume and the potential risks of sediment impacts (Table 1). A sediment analysis team is not needed for a dam removal project with a negligible amount of sediment. As the relative reservoir sediment volume and potential risk of impacts increases, the recommended amount of expertise also increases. If there is a substantial amount of uncertainty in what relative sediment size is or potential risks, it may be worth investing in multiple, independent estimates from different methods or people. If there is a risk that contaminated sediment may be present, specialized expertise in water quality should be included on the team. The expertise of the team may need to be tailored based on the sizes of sediment present in the reservoir (e.g. fine sediment vs coarse sediment) and based on the potential impacts (ecosystem, aggradation, water quality, etc).

Table 1. Recommended expertise for the sediment analysis team.

Relative reservoir sediment volume and/or risk	Recommended Expertise
Negligible	Engineers or scientists conducting the planning study do not need to have specialized expertise in sediment transport and geomorphology.
Small-medium	The analysis and planning study should be conducted by engineers or scientists who have expertise with river hydraulics, sediment transport, and geomorphology.
Large	The analysis and planning study should be conducted by engineers or scientists who have expertise and experience with river hydraulics, sediment transport, and geomorphology and who also have experience with dam removal projects.

CASES OF LITTLE TO NO RESERVOIR SEDIMENT

For cases where there is little or no reservoir sediment behind a dam (negligible volume), there is no need for extensive sediment data collection and analysis. The project can focus on structural and river hydraulic issues related to removing the dam.

For the purposes of these guidelines, a negligible reservoir sediment volume is less than 0.1 (10 percent) of the mean annual sediment load entering the reservoir. This reservoir sediment volume is about the same as the volume delivered by the upstream watershed during a single month. Stream flows would be expected to easily and rapidly erode and transport such a small reservoir sediment volume. Since computation of the mean annual sediment load can require considerable effort, an alternative procedure is provided:

Describe an introductory outline of the steps to determine if the sediment volume is neglegible

- Estimate if you should expect to find sediment
- Conduct field reconnaissance to look for reservoir sediment
- Evaluate if sediment volume is negligible
    - If no sediment is expected and no sediment can be found, then the reservoir sediment volume can be considered negligible.
    - If sediment is detected, then estimate the volume and determine its significance. If the detected sediment volume is small enough to meet the criteria for negligible, then no more sediment analysis is required.
    - Any sediment with contaminants beyond background levels is a special case and cannot be considered negligible.

Estimate if the Reservoir Has the Potential to Store Sediment

The potential for the reservoir to trap sediment can be estimated from the reservoir pool width and dam height. The reservoir pool has the potential to contain a negligible sediment volume if the following two criteria statements are true. If the criteria statements are not true, then the significance of reservoir sediment volume needs to be determined.

- The normal reservoir width (W_{res}) is not more than 1.5 times the typical river width (W_{ch}) in an alluvial reach of stream:
  $W_{res} \leq 1.5\ W_{ch}$
- The hydraulic height of the dam (H_{dam}) (reservoir water surface elevation minus the downstream river water surface elevation) is not more than the typical bankfull depth (H_{bank}) of the stream channel in an alluvial reach:
  $H_{dam} \leq H_{bank}$

Conduct Field Reconnassiance to Look for Reservoir Sediment

- Attempts should be made to find reservoir sediment either visually (looking through shallow water, snorkeling, or diving), by probing, sampling or acoustical measurements.

- If sediment is found or if the attempts to probe for sediment are inconclusive, then conduct a longitudinal profile survey through the reservoir and downstream and upstream river channels. Use a longitudinal plot of this data to detect the presence of reservoir sediment. The profile plots should include the water surface and channel bottom along the upstream and downstream river and through the reservoir pool. If little or no reservoir sediment is present, then the bottom profile slope should be consistent through the river and reservoir pool (provide figure).

Evaluate if the Reservoir Sediment Volume is Negligible

If no sediment can be found by methods that should detect the presence of sediments, then the reservoir sediment volume can be considered negligible.

If reservoir sediment is found, then estimate the volume for comparisons with the downstream channel dimensions and morphology. The reservoir sediment volume (V_{sed}) may be estimated from calculation of maximum thickness (H_{max}, typically near the dam), length of the deposit (L), and average width (W) of the deposit:

$$V_{sed} = \left(\frac{H_{max}}{2}\right) L_D \, W_D$$

Compare the reservoir sediment volume with the downstream channel dimensions and the volume of a typical channel bar. If either of the criteria described below are met, then the reservoir sediment volume can be considered negligible. Calculate the hypothetical length of reservoir sediment volume spread evenly over the downstream active channel in a likely depositional reach assuming a uniform sediment thickness:

Coarse Reservoir Sediments

For reservoir sediments that consist primarily of gravel or cobble, assume that the reservoir sediment would be spread out in a uniform thickness over the downstream river channel as a single layer thickness equal to the D_{90} of the reservoir sediment. Hypothetically, the longitudinal extent of deposition (L_D) can be computed by dividing the reservoir sediment volume (V_{sed}) by the D_{90} of gravel or cobble and the average width of the active channel (W_B):

$$L_D = \frac{V_{sed}}{(D_{90} \, W_B)}$$

Then compute the deposition length relative to the active channel width:

$$L_R = \frac{L_D}{W_B}$$

If the relative deposition length (L_R) is less than or equal to three channel widths, then the reservoir sediment volume can be considered negligible. Also, compute how the reservoir sediment volume compares to a typical gravel bar volume. If the reservoir sediment volume is no more than the volume of a typical gravel bar, then the reservoir sediment volume can be considered negligible.

Fine Reservoir Sediments

For reservoir sediments that consist primarily of sand, silt, or clay, assume a uniform sediment deposition thickness equal to 10 percent of the bankfull channel depth (D_B):

$$L_D = \frac{V_{sed}}{(0.1 D_B\ W_B)}$$

Then compute the deposition length relative to the bankfull channel width [$L_R = L_D / W_B$]. If the relative deposition length (L_R) is less than three channel widths, then the reservoir sediment volume can be considered negligible. Also, compute how the reservoir sediment volume compares to a typical alluvial bar volume. If the reservoir sediment volume is no more than the volume of an alluvial bar, then the reservoir sediment volume can be considered negligible.

Next Steps

If the reservoir sediment volume contains contaminants beyond background levels, then the volume cannot be considered negligible.

If the reservoir sediment is determined to be negligible, then skip the remainder of the guidelines and proceed with dam removal plans.

If the reservoir sediment volume is greater than negligible, then apply the full guidelines starting with step 1.

GUIDELINE APPLICATION

Application of the sediment analysis guidelines is described in the following nine steps:

1. Reconnaissance
2. Characterize reservoir sediment
3. Contaminant assessment
4. Determine the relative reservoir sediment volume
5. Selection of dam removal and sediment management plan alternatives
6. Reservoir and downstream effects analysis
7. Assess prediction confidence
8. Discussion on sediment effects
9. Develop monitoring and adaptive management plan

An overview of the general guideline steps are presented in Figure 2.

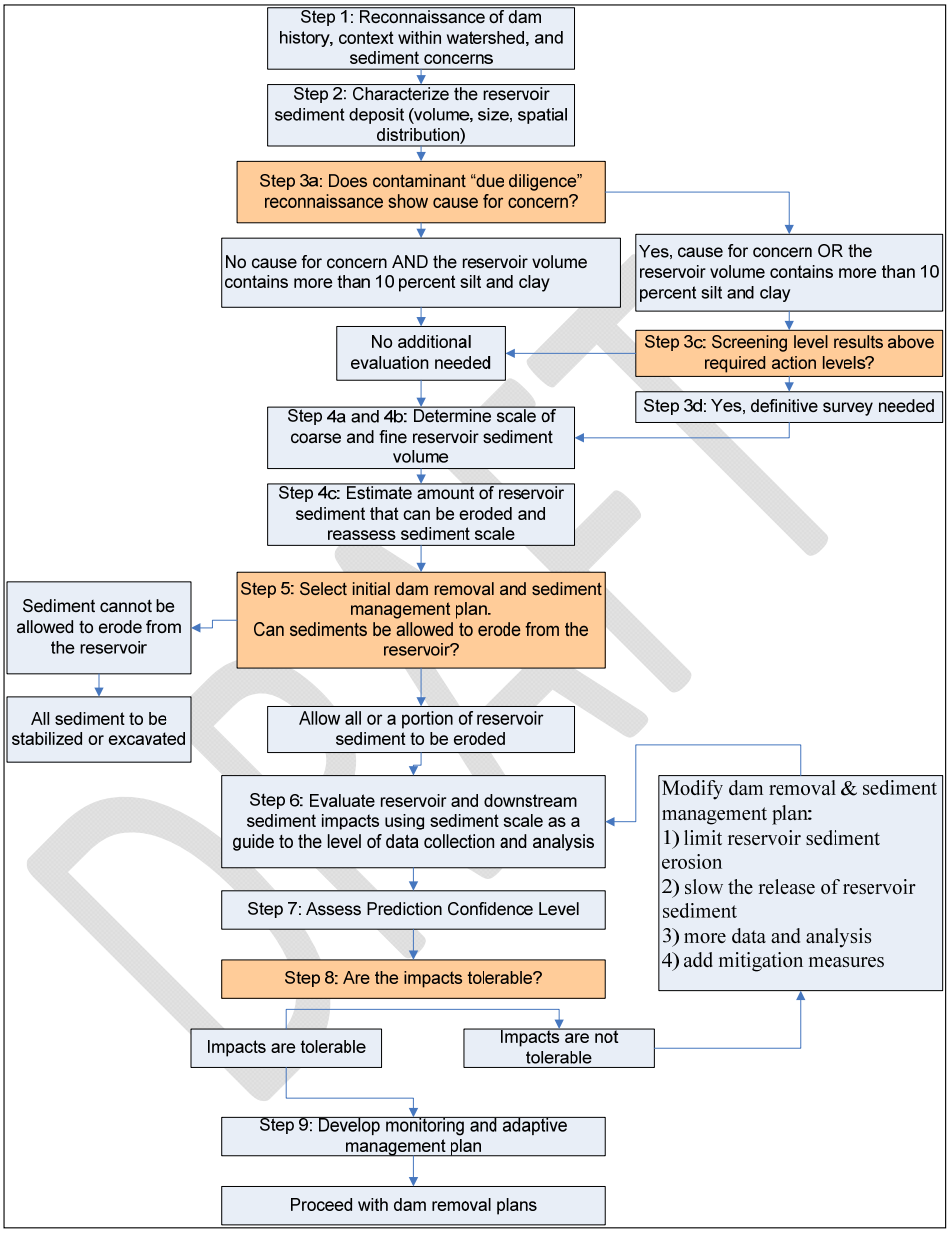

Figure 2. General sediment analysis steps are outlined in a flowchart.

- Add a box, after step 2, for cases of little or no sediment.
- Change box under step 3a from contains more than to contains less than 10 percent.

- Add step 3b, fix arrows; add substep labels and text where missing; consider 11x17. Connect step 3 to stabilize or excavate the sediment.
- In step 4, have a way to exit detailed analysis for cases of little or no sediment.
- For Step 5, rephrase the question to Are there special reasons or unique circumstances that would not allow sediments to be released downstream?
- For Step 6, Change sediment scale to sediment risk. In the box for "Modify dam removal & sediment management plans, present a bullet list of examples rather than a numbered list.

Planning-Level Application of Guidelines

The user of the guidelines is advised to first apply steps 1 through 4 with readily available data or estimates to get a rough idea of what analysis steps might be recommended and where data uncertainties are large. Under this planning-level application, the user would assume in step 5 the full dam would be completely removed and that reservoir sediment would be rapidly released into the downstream river channel. Even if a dam removal or sediment management plan has already been selected, using the full dam removal and sediment release option will provide a valuable baseline for comparison of predicted impacts from other alternatives. During steps 6 through 8 (evaluation of impacts, assessment of prediction confidence, and the significance of impacts), the user can identify and discuss with project managers and stakeholders recommendations for gathering additional data and accomplishing additional analysis where there are data gaps, uncertainties, or large relative reservoir sediment volumes and potential risks that warrant further investigation.

Analysis-Level Application of Guidelines

In the analysis level application of the guidelines, information from a more rigorous data collection program is used to re-evaluate steps 1 through 4. In step 5, more careful selection of the reservoir sediment management alternative may be in order if the sediments can't be released downstream or if sediment volume is more than ten times the average annual sediment load of the stream channel. The prediction confidence level is assessed in step 7. If the impacts are significant and the confidence level is low, then more investigations are needed to reduce uncertainty and the analysis steps are repeated.

Implementation-Level Application of Guidelines

In the implementation level application of the guidelines, the initial sediment management plan may have to be modified to reduce the sediment impacts to a level tolerable to stakeholders. If the sediment impacts from complete and sudden dam removal are tolerable, then there is no need for an expensive sediment management plan. If the impacts are not tolerable, then there is justification for a more expensive sediment management plan that may include staged dam removal, sediment removal, or sediment stabilization.

RESERVOIR DATA GATHERING STEPS

Step 1: Reconnaissance

The reconnaissance step is designed to gather existing data on the dam, reservoir, watershed, and stream channel. Several questions have been created to help guide the initial data gathering for a dam removal study. These reconnaissance questions are divided into two categories:

1. Dam history and watershed context questions
2. Local impact concern questions

The level of effort needed to answer these questions would depend on the size and complexity of the project. At a minimum, each question should be answered with a sentence or short paragraph of description or note that the question is not applicable for the specific project.

Step 1a: Dam history and watershed context questions:

- When was the reservoir constructed and by who?
- Who are the present owner and operator of the dam?
- What were the original and present purposes of the dam and reservoir and are these purposes still needed?
- What is the hydraulic height and crest length of the dam?
- Has the dam been lowered or raised in the past?
- What type of hydraulic feature was the dam located on? (e.g. narrow bedrock canyon, wide river valley, natural lake, etc)
- Were any portions of the natural ground excavated to construct the reservoir?
- Was a new outlet created to drain a lake below the natural outlet elevation?
- Was the vegetation cleared prior to reservoir filling?
- Where is reservoir located within the watershed?
- What are the upstream and downstream longitudinal channel slopes?
- What is the controlling geology at the dam site that could influence channel hydraulics or the extent of reservoir sediment or channel erosion following dam removal?
- What is the hydrologic regime, particularly when do floods and low flows typically occur?
- Where are the major sediment sources and depositional areas in the watershed (e.g. tributaries, debris flows, landslides, etc)?
    - Where are there significant sediment sources upstream from the dam?
    - Are there any upstream or downstream dams and reservoirs?
    - Where are the closest major tributaries that enter the downstream channel?
- What is the bed material size of the upstream and downstream channels (e.g., clay, silt, sand, gravel, cobble, D_{50}, D_{90})?
- What type of dam is proposed for removal (e.g., concrete, earth, or rock; gravity, arch, or buttress, etc.)?
- What is the original and current reservoir storage capacity for water?

- Has the reservoir already filled to its sediment storage capacity?

Step 1b: Local impact concern questions:

- Why is the dam being considered for removal?
- What dam removal plans have been considered?
- Who are the local stakeholders and decision makers?
- What are the administrative jurisdictions that encompass the reservoir and downstream reach of interest?
- What are the downstream reaches of concern or interest?
- What are the likely key impact concerns? Some examples are listed below:
    - Water quality due to release of reservoir sediment
    - Sediment deposition at water diversion structures
    - Sediment deposition impacts to aquatic habitat
    - Flooding in the downstream river channel as a result of reservoir sediment release
- What critical infrastructure may be located along the reservoir or river channel? Some examples are listed below:
    - Surface-water diversion facilities
    - Wells influenced by the reservoir pool or upstream channel
    - Wells influenced by the downstream channel?
    - Bridges or low-flow stream crossings
    - Buildings or road within or near the floodplain
- Are there any threatened or endangered species that utilize aquatic habitats within the reservoir or downstream channel?
- Is improved fish passage an objective of dam removal?
- What recreation activities occur in the reservoir and downstream river channel that could be impacted during or after dam removal?
- Are there cultural resources of concern?
- Has downstream river channel degradation or coastal erosion been observed or documented?
- Is there concern about sedimentation in a downstream lake or estuary?

Potential data collection activities

- Literature review of historical photographs, design drawings, and reservoir operations for the project.
- Gather a collection of aerial photographs, topographic maps, and other GIS data of the project area that document the project history.
- Compile stream gage records.
- Conducting a site visit.
- Conducting oral interviews with people who have first-hand knowledge about the project.

Possible sources of information

- U.S. Society of Dams inventory web site hosted by Army Corps of Engineers

- U.S. Geological Survey stream gage records
- U.S. Geological Survey topographical survey maps
- Local, regional, or national government GIS download sites
- National archives for historical aerial photography
- Local museums or dam owners and operators for historical ground photographs
- Federal Emergency Management Agency (FEMA) flood insurance studies
- Clearinghouse for Dam Removal Information (UC Berkeley) http://www.lib.berkeley.edu/WRCA/CDRI/index.html

Step 2: Characterize Reservoir Sediment

The purpose of this step is to make initial determinations of the reservoir sedimentation volume, mass, and particle size gradation. This is a critical step in the analysis guidelines because it is used to determine the reservoir sediment volume relative to the median annual sediment load entering the reservoir.

*separate out scoping vs data collection (volume, size, spatial distribution, debris and manmade) tasks below
*Is there a logical order to ask the following questions?

Step 2a: Estimate the reservoir sediment volume

A series of questions has been crafted to help guide estimates of the reservoir sediment volume:

- What is the ratio of the original maximum reservoir depth (when the dam was first constructed) to a typical river pool depth in the downstream channel? The closer this ratio is to one, the less likely the reservoir has trapped a significant volume of sediment. Conversely, if the maximum reservoir depth is many times deeper than a typical river pool depth, then the reservoir likely has trapped all the coarse sediment load of the river, at least until the reservoir sediment storage capacity has been filled.

- What are the normal operations of the reservoir pool?
    - Run-of-the river operation where reservoir outflow equals the inflow and the reservoir pool water surface is maintained at a constant elevation. Under this type of operation, sediment tends to accumulate over time, to the extent possible, without erosion due to reservoir drawdown. Run-of-the river operations could apply to dams of any size.
    - Moderate to considerable drawdown and refilling for water supply. Under this type of reservoir operation, sediment that deposits at the upstream end of the reservoir is subject to erosion and transport during periods of reservoir drawdown.
    - Normally empty for flood control. Under this type of reservoir operation, any sediment would tend to accumulate near the dam.

- See Morris and Fan (1998) for more information.

The amount of sediment deposited within a reservoir depends on the trap efficiency. Reservoir trap efficiency is the ratio of the deposited sediment to the total sediment inflow and depends primarily upon the fall velocity of the various sediment particles, flow rate and velocity through the reservoir (Strand and Pemberton, 1982), as well as the size, depth, shape, and operation rules of the reservoir.

Describe any reservoir operations that may have avoided reservoir sedimentation or periodically flushed sediment from the reservoir. For example, a reservoir that is normally drawn down, especially during high flow periods would have a lower sediment trap efficiency. The opening of sluice gates would tend to flush reservoir sediment near the gates. Sluicing combined with reservoir drawdown would flush sediment well upstream from the gates. Describe any past dredging operations in the reservoir to remove sediment.

- Does the dam have a sluiceway or low level outlet, and, if so, has it been used to evacuate sediment and how often? Repeated operation of a sluiceway would tend to reduce reservoir sediment accumulation and supply sediment to the downstream channel.

- Is there exchange or mixing of reservoir sediment due to reservoir drawdown operations during periods of high reservoir inflow? If reservoir sediment is exposed to high velocities during floods, then these sediments are like to erode and accumulate in the downstream portion of the reservoir and grain sizes would be more mixed within the deposit.

- What is the ratio of the original reservoir storage volume (at the normal pool elevation when the dam was first constructed) to the mean annual river flow? This ratio can be used in the equation by Brune (1953) to estimate the reservoir sediment trap efficiency.

- What is the reservoir sediment trap efficiency for fine sediment? A very low sediment trap efficiency (< 5 percent) is an indicator that the reservoir has not accumulated significant quantities of fine (clay and silt size) sediment. In contrast, high sediment trap efficiency (> 90 percent) is an indicator that the reservoir has accumulated a large volume of fine sediment.

- What is the volume of the reservoir sediment within the normal pool? The ideal way to estimate the reservoir sediment volume is from a comparison of predam and current topographic and bathymetric maps. However, predam topographic maps are often not available on small dams. In these cases, the reservoir sediment volume should be estimated from current bathymetric surveys or profiles of the reservoir bottom and the downstream and upstream river channel bottom, and

from drill holes or thickness probes that measure the minimum sediment thickness.

- How far upstream does sedimentation extend beyond the normal reservoir pool? Most reservoir deltas extend a few reservoir widths upstream from the full reservoir pool elevation. The delta deposits often look like a river channel with alluvial bars, but the longitudinal slope is typically about one-half of the natural river channel slope. Longitudinal profile surveys are needed of the reservoir bottom and upstream river channel. Exposed delta sediments can be expected to erode following reservoir drawdown and dam removal.

- What is the ratio of the reservoir sediment volume to the original reservoir storage capacity? This ratio is a measure of how full the reservoir is of sediment. If the reservoir filled long ago to its sediment storage capacity, then sediments are being supplied to the downstream river channel. If the reservoir has not yet filled with sediment, then the age of the reservoir also represents the number of years of coarse sediment accumulation. In this case, coarse sediments have not been released to the downstream river channel.

- If the reservoir has already filled with sediment, over what period of time did the filling take place? The number of years during which coarse sediment was trapped may be only a fraction of the reservoir age. The number of years of reservoir sediment accumulation may have to be computed from sediment yield estimates.

- Has large woody debris been noted to deposit in the reservoir or be transported during floods over the dam? Log jams in the reservoir sediments can locally impede the erosion of exposed sediment during reservoir drawdown. A single log may deflect flow into and erode an exposed sediment bank.

Step 2b: Estimate the reservoir sediment deposition pattern

A series of questions has been crafted to help describe the depositional pattern of the reservoir sediment:

- Is there a sediment wedge evident in the longitudinal profile of the reservoir? A comparison of predam and current longitudinal profiles is an ideal way to characterize the longitudinal sediment distribution. However, predam profile data are often not available for small dams. However, it may be possible to infer or estimate the predam profile from the downstream and upstream channel profiles.

- Is a reservoir delta present in the longitudinal profile, from dive inspections, thickness probes or drill holes? A delta is typically composed of coarse sediment and may not be present in a stream that does not transport significant amounts of

sand or gravel or in narrow reservoirs with considerable drawdown. If the presence of a delta is uncertain, note that it cannot be determined at this stage.

- What is the ratio of the reservoir delta length to the original reservoir length? If the delta deposit has not yet reached the dam, then there may be opportunities to induce lateral erosion of the exposed sediments during reservoir drawdown.

- Amount or locations of or potential for finding debris during dam removal (beaver dams, wood, manmade)

Step 2c: Characterize the reservoir sediment particle sizes

- What is the particle size gradation of the reservoir sediment?
    - Delta sediment (typically sand, gravel, and cobble sized-sediment)
    - Lake bed deposit (typically silt and clay sized sediment)
    - Upstream river bar deposit

Potential data collection activities

Discuss how to determine the level of data collection necessary

- Reservoir sediment size
    - Probing survey
    - dive inspections of the reservoir sediment
    - draining or lowering of the reservoir pool.
    - core sampling of reservoir sediment from drill rig (large reservoirs)
    - hand cores of reservoir sediment (small to medium reservoirs with non-cohesive sediment, typically limited to depths of 5 to 10 ft)
    - laboratory testing for grain size and contaminants (see step 3)
    - dual frequency soundings of the reservoir sediment
    - make sure to look both within the normal pool and along the reservoir margins and upstream river channel
- Reservoir sediment volume
    - topographic ground survey if reservoir is shallow or can be drained
    - bathymetric boat survey of existing reservoir bottom and compare to pre-dam topographic maps
    - drill hole coring through the reservoir sediment (define, add photo)
    - look for tree stumps within the normal pool that may provide an indication of the pre-dam reservoir bottom
    - look for vegetation that may provide an indication of post-dam growth on reservoir sediment deposits;
- Historical and pre-dam aerial photographs and topographic maps
- Stream gage records

Check for the possible presence of contaminants (reference step 3a).

Step 3: Contaminant Assessment

Step 3a: Contaminant watershed investigation for "Due diligence"

The level of the watershed investigation depends on the size of the reservoir and the degree of historical disturbance.

- Were there any historical land use activities (e.g. industrial, agricultural, urban, etc), in the watershed upstream from the dam, that would have potentially contributed to contaminants within the reservoir? (Literature review, interviews, etc)?
- What are the most likely contaminants that might be discovered?
- Over what period of time has reservoir sedimentation occurred and how old is reservoir?
- Have the bottom sediments been flushed or sluiced from the reservoir?
- Is there a present upstream source of contaminants?
- What is the industrial history of the watershed?
- Were there major floods that could have contributed contaminants to the reservoir impoundment from upstream sources?

Compile information and continue to step 3b.

Step 3b: Determine if contaminant testing is needed

- Use local regulations where required to determine action level needed
- In lieu of local regulations, use the following guidance
    - If there is no cause for concern from the due diligence reconnaissance in step 3a AND the reservoir volume contains less than10 percent silt and clay, then no contaminant testing is necessary and proceed directly to step 4
    - If there is cause for concern that contaminants may be present or the silt and clay volume is greater than 10 percent, then continue to step 3c

<u>Sand and Gravel Contaminant Examples</u>

Contaminants are typically associated with clay and silt-sized sediment particles. However, there are examples where contaminants have been associated with sand and gravel-sized sediments. The likelihood of contaminated reservoir sediments is primarily determined from the watershed investigation (step 3a).

Examples of highly contaminated sediments with particle sizes larger than silt:

Comment [BOR3]: Use an applied example and show how it would fit into flow chart

- "Stamp sands": A copper ore processing technique used in the late 1800s produced copper-rich sand-sized particles that were usually discharged into river valleys (500 million tons in Michigan's Upper Peninsula alone). These stamp sands contain up to 5,000 mg/Kg total copper, well above commonly used sediment quality criteria (~ 150 mg/Kg).

- Organic microfilm on gravel: Elevated concentrations (> 20 mg/Kg) of PCBs have been found in coarse sands and gravels in the Housatonic River in Massachusetts, presumably sequestered in organic microfilms on the surface of the particles. These concentrations are well above commonly used sediment quality criteria (~ 0.7 mg/Kg).

Step 3c: Screening level sampling

- Implement a sampling plan to evaluate reservoir sediment contamination along with upstream and downstream channel sediments to provide present background conditions.
    - The laboratory analysis should test for arsenic, cadmium, chromium, copper, lead, mercury, nickel, zinc, PAHs, PCBs, TPH (total petroleum hydrocarbons), and total organic carbon plus any other constituents of concern identified from the historical land use assessment; optional testing of VOCs and dissolved organic carbon where necessary.
    - If reservoir sediment is less than 10,000 cubic yards of fine-grained sediment, than collect 2 cores in the reservoir, 1 core in the downstream river channel, and consider an additional core from the upstream channel.
    - If reservoir sediment is greater than 10,000 cubic yards of fine-grained sediment, develop a customized sampling plan to meet local regulations

If any contaminants are above background sediment levels or local sediment quality standards, proceed directly to step 3d.

If no contaminants are above background sediment levels or local sediment regulations, then proceed to step 4.

Data Collection Tips

- See Appendix B for guidance on determining sediment sampling locations for contaminant testing

Step 3d: Definitive survey

- Re-examine spatial stratigraphy maps or collect more detailed reservoir sedimentation data if needed to determine where to collect additional samples.
- Collect additional samples and do same chemical analysis in step 3c, but at new locations
    - For less than 10,000 cubic yards of fine sediment, sample according to local regulations or at least sample and evaluate 1 core per 1,000 cubic yards of fine-grained sediment.
    - For greater than 10,000 cubic yards of fine sediment, develop a customized sampling plan to meet local regulations

Compile information and continue to step 4.

SIGNIFICANCE OF RESERVOIR SEDIMENT VOLUME

Step 4: Determine the Relative Sediment Volume

Need intro describing scaling concept
Describe why coarse is broken out separately from analysis of fine sediment impacts
Use slide 32-33 from ppt
Add figures of project sites to show range

Step 4a: Determine the significance of the coarse reservoir sedimentation volume (sand, gravel, cobble)

The significance of the reservoir sediment volume is based on the ability of the river to transport the deposit volume. That is, the reservoir sediment volume is compared to the calculated median annual sediment load. The sediment transport capacity of the downstream channel will be computed for certain discharge frequencies to classify the significance of the coarse reservoir sediment mass:

- Median discharge at time of dam removal (upper limit for negligible mass),
- 2-year flood hydrograph (upper limit for small mass),
- 10-year flood hydrograph (upper limit for medium mass), and
- 50-year flood hydrograph (upper limit for large mass and lower limit for very large mass).

The sediment transport capacity does not have to be computed for all of the above discharge frequencies, only the frequencies that bracket the coarse reservoir sediment mass. Guidance to compute the sediment transport capacity is provided in Appendix A. The first step is to estimate (using best judgment) the significance of the coarse reservoir sediment mass: Negligible, small, medium, large, or very large. Don't worry if the initial guess is wrong, because the procedure described in Appendix A will eventually determine the appropriate significance classification.

For coarse sediment, compare the reservoir sedimentation mass of sand and gravel to the downstream sediment transport capacity[1]:

- Reservoir sediment mass is less than the transport capacity of the median discharge during the estimated month or season of dam removal **[Negligible coarse sediment mass]**

[1] Sediment transport capacity calculated at a downstream river cross section that represents capacity to move sediment through the downstream reach.

- Reservoir sediment mass is greater than the transport capacity of the median discharge during the estimated month or season of dam removal, but less than 2-year flood hydrograph **[Small coarse sediment mass];** if no dam removal timing has been determined, consider a range of months in the computation
- Reservoir sediment mass is between the transport capacity of the 2-year and 10-year flood hydrographs **[Medium coarse sediment mass]**
- Reservoir sediment mass is greater than the transport capacity of the 10-year flood hydrograph **[Large coarse sediment mass]**

Data Collection

- Verify reservoir sediment sizes and volume
- Compile or estimate stream flow values needed for computation (see Appendix A)

Analysis Tips

- Guidance on performing the coarse sediment scaling computation is provided in Appendix A.

Step 4b: Determine the significance of the fine reservoir sedimentation volume (silt and clay)

For fine (silt and clay) reservoir sediment, determine the relative sediment volume using one of two methods, depending on whether suspended sediment data are readily available.

If no suspended sediment load data are available, perform the following analysis.

- Compute the ratio of the original reservoir storage capacity (when the reservoir was built) to the mean annual discharge inflow.
    - If the ratio is less than or equal to 0.001 (or 0.1%) and the proportion of silt and clay in the total reservoir volume is less than 5 %, then the reservoir has a **negligible fine sediment mass**
- Compute the average annual fine sediment load (see analysis steps below)
    - If the average annual fine sediment load is less than or equal to the average one-year sediment supply, then the reservoir has a s**mall fine sediment mass;**
    - If the average annual fine sediment load is between the 1 and 5-year average fine sediment load, then the reservoir has a m**edium fine sediment mass**
    - If the average annual fine sediment load greater than 5–year average fine sediment load, then the reservoir has a **large fine sediment mass**

Where do we compute one-year, 1 to 5-year supplies?

Data Collection

- Verify reservoir sediment sizes and volume

- Original reservoir storage capacity
- Mean annual inflow

Analysis tips: move to appendix

1. Determine the trap efficiency of the reservoir using the Brune or Churchill trap efficiency curve (see Appendix D)
2. Compute the total fine sediment load (Q_s) over the period of reservoir sedimentation by dividing the fine reservoir sediment volume (V_{fine}) by the trap efficiency of the reservoir

$$\sum Q_s = \frac{V_{fine}}{Trap\_Efficiency} = \text{Total fine sediment load over the period of sedimentation}$$

3. Determine the total years to fill (T) based on the number of years where sediment trapping occurred (e.g. no flushing, excavation, or other removal); include all years regardless of flow magnitude (e.g. dry and wet years);
    a. Describe typical filling type examples
    b. If the reservoir is still filling with sediment, then estimate the total years of sedimentation as the age of the reservoir
    c. If the time period of sedimentation is unknown and the reservoir filled with sediment long ago, then estimate the total years of sediment conservatively as 2 years
4. Compute the average annual fine sediment load (Q_s avg) by dividing the total sediment load (Q_s) by the total years to fill (T)

$$\overline{Q_s} = \frac{\sum Q_s}{T} = \text{Average annual fine sediment load}$$

If fine suspended sediment load data are available, compare the fine reservoir sediment mass (clay and silt) to the fine sediment loads of the median discharge at dam removal, 2-year flood, and 10-year flood.

Comment [BOR4]: Clarify volume vs mass throughout document

- If the reservoir fine sediment mass is less than the fine sediment load of the median discharge during the estimated month or season of dam removal, then the reservoir has a **negligible fine sediment mass**
- If the reservoir sediment mass is greater than the fine sediment load of the median discharge during the estimated month or season of dam removal, but less than the sediment load of the 2-year flood hydrograph, then the reservoir has a **small fine sediment mass. I**f no dam removal timing has been determined, consider a range of months in the computation
- If the reservoir sediment mass is greater than the fine sediment load of the 2-year flood hydrograph, then the reservoir has a **medium fine sediment mass**
- If the reservoir sediment mass is greater than the fine sediment load of the 10-year flood hydrograph, then the reservoir has a **large fine sediment mass**

SEDIMENT AND DAM REMOVAL ALTERNATIVES

Step 5: Selection of Dam Removal and Sediment Management Plan Alternatives

Put in explanation of purpose of this step

i. Initially, assume rapid and complete dam removal with reservoir sediment eroded by available stream flows and transported into the downstream channel.
ii. Determine if the initial dam removal and sediment management plan needs to be adjusted for local conditions (steps 5a to 5e).
iii. Go through analysis guidance steps
iv. Are the impacts tolerable?
v. During additional iterations (if needed), consider alternative dam removal and sediment management alternatives that will reduce the volume and rate of sediment eroded and transported downstream (e.g., phased dam removal, sediment excavation, partial dam removal, etc) or necessary mitigation measures;
vi. When timing is flexible, but impact confidence is low or risks are high, consider if a staged dam removal, tied with an adaptive management plan, is feasible

Alternative Dam Removal and Sediment Management Plans (propose moving this into step 5 detailed discussion)

Dam removal projects can often include a diverse set of stakeholders that may not have similar viewpoints on the benefits and risks of the project, how dam removal and sediment management should be accomplished, or the necessary mitigation measures. In some cases the dam removal and sediment management must be adaptively managed for uncertainty which introduces challenges in permitting and implementation. In other situations, the presence of contaminants may dictate the selected dam removal and sediment management alternative. This chapter briefly describes typically considered dam removal and sediment management alternatives that can be considered when applying the sediment analysis guidelines. Each dam removal case is likely to have some variation on these concepts to address localized characteristics and concerns.

Dam Removal Alternatives

How much of the infrastructure will be removed from the historical river and floodplain, how the dam will be structurally removed, and over what time period. When someone mentions the words “dam removal”, we often envision the complete removal of all infrastructures associated with the dam. However, there may be valid reasons why a dam is only partially removed, either laterally or vertically. A portion of the dam and associated infrastructure may be left in place if it will still be utilized in the future

operation of the project, it is of historical significance, or if the cost of removal does not exceed the benefit in terms of project objectives. In some cases, a lateral portion of the dam may be left in place to limit flood flows or erosion of downstream infrastructure or property. Typically, the dam is removed down to the elevation of the pre-dam river bed. However, in a few cases only the upper portion of a dam is removed. The remaining portion of the dam may be left in place as a sill to prevent headcutting, limit release of stored sediment, or provide a barrier to prevent migration of an aquatic species.

Dam decommissioning alternatives might include the discontinued use of a hydroelectric powerplant, partial removal of the dam, or complete removal of the dam and all associated structures (e.g., spillways, outlets, powerplants, switchyards, etc.). Partial removal of a dam could be planned in many different ways to achieve different purposes. For example, the portion of the dam that blocks the river channel and flood plains could be removed, while the abutments and other structures are left in place for historic preservation and to reduce removal costs. Any remaining structures would have to be left in a safe condition and may require periodic maintenance. In the case where a dam spans a valley width that is significantly wider than the river channel, a relatively narrow portion of the dam could be removed so that the remaining dam would help retain a significant portion of the reservoir sediments. A partial dam removal could also mean that the upper portion of the dam is removed, while the lower portion is left in place to retain reservoir sediments deposited below that elevation. This alternative might also help to reduce or eliminate any dam safety concerns by reducing the size of the reservoir, but fish passage facilities might still need to be provided.

The type of material used to construct a dam (concrete, masonry, rockfill, or earth) is important for determining how much of the dam to remove, the volume of material for disposal, and the removal process itself (ASCE, 1997). In addition, there are several other engineering considerations that influence the amount and rate of sediment erosion, transport, and deposition.

The rate of dam removal and reservoir drawdown has a strong influence on the rate that sediments are eroded and transported to the downstream river channel. The effects from releasing a large volume of reservoir sediment into the downstream channel can be reduced by slowing the rate of reservoir drawdown. This might be accomplished by progressively removing layers of the dam over a period of weeks, months, or years, depending on the size of the dam and the volume of the reservoir sediments. The rate of reservoir drawdown needs to be slow enough to avoid a flood wave of reservoir water spilling into the downstream river channel. Also, the rate needs to be slow enough to avoid inducing any potential landslides along the reservoir margins or a slide failure of any earthen dams.

The ability to drawdown the reservoir pool depends on how flows can be released through, over, or around the dam. If the dam has a low-level, high-capacity outlet works or diversion tunnel, the reservoir could be emptied at a prescribed rate and the dam could be removed under dry conditions. However, if the width of the outlet works is narrow

relative to the reservoir sediment width, then a substantial portion of the sediments would remain in the reservoir until the dam is
removed. A bypass channel could be constructed around the dam, but it would need the ability to at least partially drain the reservoir. For concrete dams, it may be acceptable to release flows over the dam or through notches cut into the dam (ASCE, 1997).

Dam removal and reservoir drawdown plans have to prepare for the possibility of floodflows occurring during dam removal. The occurrence of a flood may simply mean the temporary halt of dam removal and reservoir drawdown activities. However, an overtopping flood could cause a failure of the remaining structure and a downstream flood wave that would be many times larger than the reservoir inflow. If the remaining structure can withstand overtopping flows, then floods may help to erode and redistribute delta sediments throughout the reservoir. In a wide reservoir, a floodflow may help to leave the reservoir sediment in a more stable condition after dam removal.

Sediment Management Alternatives

Reservoir sediment can be managed in a variety of ways depending on where commended needs to consider both physical method and the timing (low flow, coincident with flood, controlled or uncontrolled)

a. River erosion of reservoir sediments
b. Bypass river channel around reservoir sediments
c. Complete or partial excavation of sediments
    i. Hydraulic dredging
    ii. Mechanical dredging
    iii. Dry excavation
d. Complete or partial stabilization of sediments (temporary or permanent)
e. Staged release of reservoir sediment
f. Pilot channel to initiate erosion processes
g. Excavation of fine sediments and river erosion of coarse sediments
h. Design and build downstream deposition environments (more information will be needed to fully describe this option)
i. Adaptive management plan to reduce uncertainty by utilizing predictions, real-time monitoring data, and adjustments to the implementation plan based on monitoring results
j. Use of a cofferdam that is allowed to breach/overtop at higher flow

From river restoration chapter 8:

The development of alternative sediment management plans for dam decommissioning requires concurrent consideration of engineering and environmental issues. Sediment management alternatives can be grouped into four general categories (ASCE, 1997):

No action. Leave the existing reservoir sediments in place. If the reservoir-sediment storage capacity is not already full, then either allow future sedimentation to continue or reduce the sediment trap efficiency to enhance the life of the reservoir.

River erosion. Allow the river to erode sediments from the reservoir through natural processes.

Mechanical removal. Remove sediment from the reservoir by hydraulic or mechanical dredging or conventional excavation for long-term storage at an appropriate disposal site.

Stabilization. Engineer a river channel through or around the reservoir sediments and provide erosion protection to stabilize the reservoir sediments over the long term.

A sediment management plan can also consist of a combination of these categories. For example, fine sediments could be mechanically removed from the downstream portion of the reservoir to reduce the impacts on water quality. At the same time, the river could be allowed to erode coarse sediments from the reservoir delta to resupply gravel for fish spawning in the downstream river channel.

I don't' get the decommissioning option below, if it is continued to be operated how can it be decommissioned?

Table 8.2. Relationship between dam decommissioning and sediment management alternatives (modified from ASCE, 1997)

Sediment management alternative	**Dam decommissioning alternatives**		
	Continued operation	Partial dam removal	**Full dam removal**
No action	• Reservoir sedimentation continues at existing rates, • Inflowing sediment loads are reduced through watershed conservation practices, or • Reservoir operations are modified to reduce sediment trap efficiency.	• Only applicable if most of the dam is left in place. • The reservoir sediment trap efficiency would be reduced. • Some sediment may be eroded from the reservoir.	• Not applicable.
River erosion	• Sluice gates are installed or modified to flush sediment from the reservoir. • Reservoir drawdown to help flush sediment.	• Partial erosion of sediment from the reservoir into the downstream river channel. • Potential erosion of the remaining sediment by sluicing and reservoir drawdown.	• Erosion of sediment from the reservoir into the downstream river channel. Erosion rates depend on the rate of dam removal and reservoir inflow. The amount of erosion depends on the ratio of reservoir width to river width.
Mechanical removal	• Sediment removed from shallow depths by dredging or by conventional excavation after reservoir drawdown.	• Sediment removed from shallow depths before reservoir drawdown. • Sediment removed from deeper depths during reservoir drawdown.	• Sediment removed from shallow depths before reservoir drawdown. • Sediment removed from deeper depths during reservoir drawdown.

Stabilization	• The 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. • Construction of a river channel through or around the reservoir sediments.	• Construction of a river channel through or around the existing reservoir sediments. • Relocate a portion of the sediments to areas within the reservoir area that will not be subject to high-velocity riverflow .

Step 5a: Determine if the presence of contaminants requires a modification of the sediment management plan

Put in explanation of the purpose of this step

- Determine what happens to contaminants associated with the fine sediment when remobilized into system.
    - Determine the concentration of contaminants within the reservoir sediments and if sediment erosion would result in chronic (long-term) or acute (rapid) effects
- Determine what happens to contaminants associated with the fine sediment that are not mobilized and remain in the reservoir
- Potential evaluation tools
    - Refer to Appendix C for sample decision charts to assist with determining if impacts are tolerable
- Adjust dam removal and sediment management plan
    - Excavate or stabilize <u>all</u> sediment?
        - If yes, modify the sediment management plan and determine the future reservoir topography, then proceed with the dam removal planning.
    - Excavate or stabilize the contaminated reservoir sediments and allow the remainder of the sediments to erode or remain in place.
        - ***Return to step 4 and update the reservoir sediment volume potentially available for erosion.***
    - Allow contaminated sediment to erode and be transported downstream with mitigation measures as necessary. ***Proceed to step 5b***.

Step 5b: Evaluate need for alternative dam removal and sediment management plans based on the relative sediment volume

- If reservoir sediment mass is greater than the transport capacity of the 50-year flood hydrograph (from step 4), reformulate initial dam removal and sediment management alternative to include such things as stage dam removal, partial dam removal, partial sediment stabilization or excavation (see Chapter 2)

Add in volume and contamination of sediment to this step?

Step 5c: Predict the potential for head cut erosion lower than the pre-dam river bed to progress upstream through the reservoir sediment deposits

Predict the potential for downstream channel degradation to migrate upstream of the dam and reservoir after dam removal. If there is a moderate to high probability for upstream degradation, then consider including some sort of grade control structure in the dam removal and sediment management plan.

- Has the stream channel degraded downstream from the dam?
- Yes.
    - Was the degradation caused by a base-level lowering downstream of the dam rather than by upstream reservoir sedimentation? **If so, head cut erosion may proceed upstream through and potentially beyond the reservoir after dam removal. There is a moderate to high degradation impact probability. Unless there is an upstream control to limit head-cut migration, consider revising the dam removal alternative to create a grade control structure that prevents upstream degradation. Provide fish passage as necessary.**
    - Was the degradation caused by upstream reservoir sedimentation? **If so, erosion of reservoir sediment may re-deposit along the downstream channel and prevent head-cut erosion from progressing upstream from the reservoir. There is a low to moderate degradation impact probability. Simulate this process in a one or two-dimensional model]**.
    - Was the degradation caused by local scour downstream from the dam?
        - If the eroding reservoir sediments can fill the local scour, then there is a low to moderate degradation impact probability. Simulate this process in a one or two-dimensional model.
        - If there isn't enough coarse reservoir sediment to deposit in the downstream reach of local scour, then head-cut erosion may proceed upstream beyond the reservoir after dam removal. There is a moderate to high degradation impact probability. Unless there is an upstream control to limit head-cut migration, then revise dam removal alternative to create a grade control structure in the model that prevents upstream degradation. Provide fish passage as necessary.
- No **There is a low head-cut probability upstream from the reservoir below the original (pre-dam) river bed**

Step 5d: Determine if there are erosion resistant materials within the reservoir

Erosion resistant materials within the reservoir could create fish or boat passage problems after dam removal and prevent the erosion of reservoir sediments. Determine if these

materials are present with a probing survey (Step 2c) and the need for their removal or the installation of fish passage facilities.

- Is there non-native erosion-resistant material within the reservoir (large size particles or debris, logs, old structures) that could impede fish or boat passage?
    - If no, continue to step 5e
    - If yes
        - Would this material likely erode during a 2-year flood following dam removal? **If yes, determine the flow rate required for incipient motion and when such flow is likely to occur. If impacts cannot be tolerated for that period of time, consider the need for mechanical removal of the erosion resistant material.**
        - Would this material likely remain within the reservoir area after dam removal over the long term? **If yes and impacts cannot be tolerated, modify the dam removal plan to include the removal of these materials.**

Step 5e: Evaluate presence of species (threatened or endangered) that are sensitive to sediment

Provide examples of potential impacts or benefits

- If there are sensitive species (threatened or endangered) present downstream of the dam that cannot tolerate sediment impacts without dire consequence to the species primary production or community composition, then develop a sediment management plan to minimize sediment impacts.
    - If possible, considering removing the dam at a time when the species are not susceptible to the impacts.
    - Consider if excavation or stabilization of the reservoir sediment is necessary
    - If possible, relocate the species in question (see Appendix C, Step C2)

Step 5f: removal of multiple dams or impact to downstream reservoirs

SEDIMENT ANALYSIS AND MODELING

Step 6: Reservoir and Downstream Effects Analysis

Objectives of Step 6
Advice on the scope of analysis and modeling necessary to answer the following key questions under step 6 are listed below:

- What portion of the reservoir sediment is expected to be eroded past the dam, and at what rate over the short and long term?
- What will be the future landscape topography of the reservoir area after dam removal and how will this landscape be influenced by vegetation?
- What will be the fate of the eroded reservoir sediments after they enter the downstream river channel?

Outline the major elements of Step 6.

- Determine the level of risk for coarse sediment
- Determine the level of risk for fine sediment
- Identify analysis and modeling tasks

Risk Level

The level of sediment analysis and modeling applied should correspond to the level of risk. The first part of step 6 is to determine the level of risk. Analysis and modeling tasks are recommended based on the level of risk.

Risk could be calculated by complex numerical analysis, but a more qualitative approach is presented in this guideline. The risk is computed by taking the product of the probability of sediment impact and the consequence of the impact. The risk may be different for the release of coarse and fine sediment, so additional levels of analyses may be necessary.

Qualitative Risk Calculator	Consequence (potential resource impact)		
Probability (Fine or Coarse sediment)	Low	Medium	High
Small	Low	Low	Medium
Medium	Low	Medium	High
Large	Medium	High	High +

For this guideline, the probability of sediment impact is equivalent to the relative reservoir sediment volume (computed in Step 4 earlier in guideline). The relative reservoir sediment volume should be determined separately for coarse and fine sediment. When initially going through the guideline at a planning level, there may be large uncertainty in the relative reservoir sediment volume. This uncertainty should be reduced and the relative reservoir sediment volume refined when going through the guidelines during the analysis and implementation phases.

Potential Consequences

A list of potential sediment-related consequences should be generated for the project. Each potential consequence should be linked to coarse sediment, fine sediment, or both. An example list of resources and potential sediment impacts from a release of reservoir sediment is provided below:

- Infrastructure, property, and water use
  - Burial of intakes or water diversion structures (coarse sediment effect)
  - Stream bank erosion and channel migration affecting such things as property, levees, and bridges (coarse sediment effect)
  - Flooding increase affecting such things as levees, bridges, and property (coarse sediment effect)
  - Downstream reservoir sedimentation (coarse and fine sediment effect)
  - Increased suspended sediment concentration and turbidity (fine sediment effect)
  - Release of contaminants during reservoir sediment erosion (fine sediment effect)
- Species
  - Habitat substrate (fine sediment and coarse effect)
  - Deposition in pool habitat (fine sediment and coarse effect)
  - Increased suspended sediment concentration and turbidity (fine sediment effect)
  - Check 2008 notes water quality
- Reservoir lands
  - Reservoir shoreline landslides (related to rate of reservoir drawdown)
  - Reduced water level for wells and water intakes associated with the reservoir (related to extent of reservoir drawdown)
  - Re-vegetation and suitability of sediment as substrate (coarse and fine sediment)
- Cultural resources
  - Possible alteration of riverine landscapes that have important cultural properties (coarse and fine sediment)

For example, the release of an excessive amount of coarse sediment could aggrade the river bed and increase flood stage and the potential for stream bank erosion. The release of fine sediment primarily affects water quality for the aquatic environment and

downstream water users. The consequences of an impact depend on the potential effects, regulations, and the perception of stakeholders to resources of concern. Public and regulatory perception of the types and magnitude of potential sediment impacts may be greater than the actual impacts. Public education and outreach on hydraulic and sediment processes may be a useful way to help the public understand what the actual sediment effects may be and a collaborative way of determining the level of potential consequences to resources and stakeholders. For example, a medium relative reservoir sediment volume (and medium probability) would have a high level of risk if the consequence(s) were high. Conversely, a medium relative reservoir sediment volume would have a low level of risk if the consequence(s) were low.

For a given dam removal project, there may be a wide range of potential consequences of concern that could range from low to high. For determining the level of data collection, analysis, and modeling, it is recommended to take the highest risk associated with coarse and fine sediment separately. However, it is important to limit the potential consequences to what may actually occur based on the available reservoir volume and particle size gradation (fine versus coarse percentages). For example, Savage Rapids Reservoir near Grants Pass, Oregon had 98% coarse sediment stored in the reservoir with only 2% fine sediment. There was initially concern about the potential for water quality impacts and release of contaminants. However, for this example, the sediment analysis emphasis was focused on coarse sediment because no contaminants were found above background levels and the fine sediment volume was too small to cause any significant water quality impacts. The types of data collection, analysis, and modeling needed for a high level of risk from coarse reservoir sediment would be different than from fine sediment.

The potential concerns of stakeholders needs to be identified to help determine the level of consequences from the release of reservoir sediment upon dam removal. A qualitative judgment may have to be used to estimate the level of consequence. The consequence should consider the increased effects from released reservoir sediment relative to existing conditions, including periods of low and high sediment loads.

List and group potential resource consequences into low, medium, and high categories so that, when combined with the probability of impact, the risk can be estimated. If the consequence to any of the resources of concern is considered high, then the risk will be either medium or high, depending on the relative reservoir sediment volume.

Examples of low consequence are where there is no infrastructure or property that could be impacted by the release of reservoir sediment, such as in a canyon reach of river. In addition, there are no threatened or endangered aquatic species that are sensitive to sediment and present at the time and location of impacts. Other areas of low consequence might include natural resources that would be perceived to benefit from changes due to released sediment, such as release of spawning gravels, recovery of habitat beneath the reservoir, or reconnection of the channel with adjacent wetlands and floodplains.

Medium consequence might include cases where sediment-related impacts would be localized or temporary and such impacts may require mitigation. A medium consequence might also include cases where the consequence is not necessarily low or high.

Examples of high consequences would include streambed aggradation, leading to flooding or erosion of property or infrastructure. Increased sediment concentrations would make it very difficult or impossible for water users to obtain water for beneficial uses. Threatened or endangered species would be irreversibly harmed.

Probability of Sediment Related Effects

For each consequence, the following three questions should be answered. More discussion is provided below these questions:

- Where is the potential concern located relative to the dam (distance downstream from dam)?
- When are the concerns occurring (during dam removal, seasonal, all year).
- Are they short term (during and immediately after dam removal) or long term concerns

Sediment-related effects tend to diminish with distance downstream because of tributary inflows and because coarse sediment waves attenuate with distance downstream. For example, infrastructure 1 mile below the dam would be at a higher risk for greater sediment deposition than a project 10 miles downstream of the dam. However, low gradient stream reaches, lakes, and estuaries can be expected to act as sediment traps.

Table 2. The relationship of probability of sediment effects with time and distance downstream.

Probability Table	**Probability of impact tends to decrease with time and distance downstream**		
Relative Reservoir Sedimentation Volume	**Short-term in the reservoir and the near reach below the dam**	**After additional time or additional distance downstream**	**After additional time or additional distance downstream**
Small →	Small →	Negligible	
Medium →	Medium →	Small →	Negligible
Large →	Large →	Medium →	Small →

The timing of dam removal with respect to low and high flow hydrologic seasons will make a difference on the magnitude and duration of sediment effects. The volume and rates of reservoir sediment erosion and downstream transport will be greater during periods of high flow than during periods of low flow. Therefore, the duration of sediment effects may be shorter when high flows occur following a dam removal. In

some cases, it may be possible to time dam removal to avoid or reduce consequences to seasonal concerns related to aquatic species or downstream water users.

The short and long-term sediment effects from dam removal can be very different. Many long-term sediment effects may be beneficial, while short-term effects may require mitigation. For example, sediment concentrations and turbidity may be temporarily high, but fish would have increased access to the upstream watershed. A water intake located in close proximity below the dam may experience a short-term increase in coarse sediment deposition, but the this sediment could be flushed and returned to pre-dam levels following the first few high flows. Alternatively, recreationalists and property owners along the reservoir shoreline will see a long-term change from lake conditions to river conditions. Water intakes or wells associated with the reservoir may require mitigation to compensate for a permanent reduction in water levels.

Discuss coarse and fine sediment analysis recommendations separately for each section
Consider separate sub headings for coarse sediment and fine sediment.

Low Risk Dam Removals

This part of the guideline describes the analyses associated with low risk dam removals for coarse sediment, fine sediment or both. If the risk is greater than low for either coarse or fine sediment, then also utilize the analysis tools recommended under the medium or high risk categories. The possible combinations of probability and consequence that produce a low level of risk are presented in the table below.

	Consequences		
Probability	**Low**	**Medium**	**High**
Small	Low	Low	Medium
Medium	Low	Medium	High
Large	Medium	High	High +

For the low-risk case, either the volume of reservoir sediment to be released downstream is small enough or the consequence of sediment release is low enough such that the overall risk to resources is low. This means that dam removal and reservoir sediment release is not expected to cause large (significant) consequences to infrastructure, property, and water use, aquatic species, cultural resources, and recreation.

For a low risk dam removal, application of three analysis tools is recommended. The information provided from these analysis tools can then be compared with potential consequences to resources of concern. For more information on these analysis tools, please see the following sections presented later in this chapter:

- Conceptual Model. Using readily available data and professional experience, the conceptual model will qualitatively describe what will happen to the reservoir sediments upon dam removal including estimates of the portion of the sediment

that will erode, downstream transport mechanisms, and depositional areas over the short and long term.

- Total Stream Power Analysis. The total stream power analysis will help determine the downstream channel reaches where sediment released from the reservoir is likely to be transported or deposited.

- Simple Mass Balance Computations. Simple mass balance computations are recommended to relate the reservoir sediment volume to downstream channel features such as sand or gravel bars or the average thickness of sediment deposition on the channel bed.

Medium Risk Dam Removals

This part of the guideline describes the analyses associated with medium risk dam removals for coarse sediment, fine sediment or both. If the risk is different than medium for either coarse or fine sediment, then also utilize the analysis tools recommended under the low or high risk categories. The possible combinations of probability and consequence that produce a medium level of risk are presented in the table below.

	Consequences		
Probability	**Low**	**Medium**	**High**
Small	Low	Low	Medium
Medium	Low	Medium	High
Large	Medium	High	High +

For the medium-risk case, the relative reservoir sediment volume could be small combined with a high consequence, medium combined with a medium consequence, or large combined with a low consequence. For the case of a relatively small reservoir sediment volume, the risk could be considered medium if the potential consequences are interpreted as high. For example, if a downstream pumping plant was present that may have problems with even a small increase in sediment load; this might be considered a medium risk. On the other hand, for the case of a large sediment volume, the risk could be considered medium rather than high if the potential consequences are low.

For a medium risk dam removal, application of some analysis tools are recommended in addition to those recommend for a low risk dam removal. The application of these additional analysis tools will depend on local circumstances. The information provided from all analysis tools can then be compared with potential consequences to resources of concern. For more information on these analysis tools, please see the following sections presented later in this chapter:

- Conceptual Model. Using readily available data and field measurements and professional experience, the conceptual model will qualitatively describe what will happen to the reservoir sediments upon dam removal including estimates of the portion of the sediment that will erode, downstream transport mechanisms, and depositional areas over the short and long term.

- Total Stream Power Analysis. The total stream power analysis will help determine the downstream channel reaches where sediment released from the reservoir is likely to be transported or deposited.

- Simple Mass Balance Computations. Simple mass balance computations are recommended to relate the reservoir sediment volume to downstream channel features such as sand or gravel bars or the average thickness of sediment deposition on the channel bed.

Additional analysis tools are needed for a medium risk dam removal. There are several analysis tools to choose from, which are listed below. The selection of the additional analysis tools should be based on their ability to help answer resource management questions.

- Geomorphic Analysis. For medium risk dam removals, a geomorphic analysis is recommended based on readily available data and field inspection. Available data may include historic aerial photographs, geologic and soil maps, topographic maps and historical photographs and accounts. This analysis will describe the physical setting of the dam, reservoir, and river channel and help define the areas where more detailed sediment investigations are needed. This may include a description of geologic controls, significant water and sediment sources, and characterization of the river and reservoir sediment. For significant reservoir drawdown and steep reservoir shoreline slopes, the potential for landslides during reservoir drawdown should be investigated. Historical analysis of the river channel will identify trends and allow for estimates of future channel evolution trends following dam removal.

- Sediment wave model. The sediment wave model is fairly simple to use and provides estimates of coarse sediment deposition thickness that tend to decrease with distance downstream from the dam and with time. Data requirements for this model include the initial reservoir sediment thickness, sediment porosity, longitudinal slope of the downstream river channel, and the transport rates of the reservoir sediment and downstream channel bed material. This model utilizes the average longitudinal river slope rather than detailed cross sections.

- Reservoir routing model. If the increments of reservoir drawdown could potentially case a small flood wave to be released downstream and result in a rapid reservoir drawdown, then a level-pool routing model should be used to predict the rate of reservoir drawdown and discharge hydrograph released to the downstream channel. Data requirements include a table of reservoir surface area

versus elevation, the geometric description of the dam opening, and the reservoir inflow discharge hydrograph, which is normally assumed to be a constant and steady value.

- 1D hydraulics and sediment transport capacity model.
- 2D hydraulics model and sediment transport capacity model. for complex or meandering channels
- Physical model of reservoir or river channel.
- Field test in reservoir or river channel.

Data Collection Plans

High Risk Dam Removals

List of assumptions
List of analyses
Conceptual model
Data Collection Plans

Geomorphic Analysis. For high risk dam removals, a geomorphic analysis is recommended based on available data and field data collection.

	Fine Sediment	Coarse Sediment	Risk Level	Outputs
Conceptual model ()	X	X	All	
Simple mass balance Computations	X	X	All	
Geomorphic Analysis (major reach breaks, trends)	X	X	medium to high	
Sediment wave model		X	Medium to High	

Mass balance model for wide reservoirs and staged removal	X	X	high	Reservoir sediment release of coarse and fine sediment and resulting reservoir topography over time
Total Stream Power		X	All	
1D hydraulics model			medium to high	
Reservoir routing model	X		medium to high	
1D sediment transport capacity model		X	Medium	
1D sediment erosion and deposition model	X	X	High	
2D hydraulics model (steady flow & transport capacity)		X	Medium/High	
2D sediment erosion and deposition model	X	X	High	
Bank erosion model	X	X	High	
Vegetation growth and mortality model	X	X	High	
Physical model of reservoir or river channel		X	medium to high	
Field test in reservoir or river channel	X	X	medium to high	

Analysis Tools

Conceptual Model

A conceptual model should have already been developed in step 4c for how much of the reservoir sediment is expected to erode on dam removal. The conceptual model now needs to be expanded to qualitatively describe the rate and timing of reservoir sediment erosion and downstream fate of the released sediments. This includes a description of how sediments will be transported through the downstream channel over the short term and where the sediments might ultimately deposit over the long term.

Reservoir Processes

- Describe the sediment volume, gradation, and size distribution of reservoir sediment– step 2
- Describe the presence of woody debris in the reservoir sediment (reference reach, historical information, drilling and probing data) – step 2
- Describe the potential for old structures or debris buried in the reservoir sediment that could potentially limit headcut or reservoir bank erosion
- Compare the total volume to the annual sediment load? (relative sediment volume) – step 4 a and b (?)
- Determine if the reservoir is no longer accumulating reservoir sediment (estimate sediment trap efficiency from the ratio of reservoir water storage volume to mean annual stream flow)
- Describe how the reservoir sediment will erode upon dam removal, including the quantity and rate of erosion.

Downstream River Processes

- Determine if the hydrology upstream and downstream of the reservoir is essentially the same. In other words, determine if reservoir operations have a significant effect on downstream river flow
- Describe the morphology and geology of the downstream channel and floodplain
    - Existing bed-material in downstream channel
    - Estimate the relative sediment transport capacity with distance downstream (total stream power analysis)
    - Identify significant downstream tributaries and their relative contribution of water and sediment
    - Characterize distinct reaches of the downstream channel (canyon, wide alluvial valley)
    - Describe the potential depositional environments for sediment (e.g. pools, bars, side channels, floodplains)
- Estimate portion of reservoir sediment expected to move as bed-material load versus wash load
- Describe what happens to the released bed-material load including potential consequences to resources (mass balance computation)
    - Identify potential areas of deposition of coarse reservoir sediment
    - Identify potential consequences of coarse sediment deposition
    - Estimate how long coarse sediment deposits are expected to persist

- Describe what happens to the released fine sediment (wash load) including potential consequences to resources (mass balance computation)
    - Identify potential consequences of increased wash load and concentration
    - Estimate additive effects of suspended sand loads
    - Describe if deposition is expected on the floodplain
- Identify and describe the ultimate downstream depositional environments (e.g. low gradient river reach, reservoir, lake, or estuary)

Reservoir Processes

- Describe the sediment volume, gradation, and size distribution of reservoir sediment– step 2

The description of the reservoir sediment volume, spatial distribution, and size gradation should identify the quantities of coarse and fine sediment and their locations within the reservoir.

An existing longitudinal profile of the top and bottom of reservoir sediment, along with the upstream and downstream river profiles, would help describe the thickness of the reservoir sediment, which can be related to the total reservoir sediment volume. The existing longitudinal river profile should extend far enough downstream from the dam (length equivalent to 10 to 20 channel width) to document the extent of any local scour downstream of the dam. Local scour is different than general channel degradation. Local scour often created by the hydraulic drop over dams. A flatter channel slope immediately downstream from the dam may be an indication of local scour. Upon dam removal, released reservoir sediment can be expected to fill in areas of local scour and reestablish the predam channel grade. General channel degradation can occur when the upstream sediment supply to the downstream channel has be significantly reduced or eliminated. This typically occurs downstream from large reservoirs rather than reservoirs with relatively small sediment volumes. For the case where general channel degradation has already occurred downstream of a dam to be removed, then grade control at or near the dam site may be necessary after dam removal (see step 5).

The longitudinal profile should also extend far enough upstream to capture sedimentation within riverine areas beyond the full reservoir pool. The upstream river profile should identify the change in slope upstream of the reservoir where the river slope is no longer affected by reservoir sedimentation.

In the absence of a predam contour map, attempt to estimate the predam channel slope by extrapolation of the existing upstream and downstream river profile slopes into the reservoir area. Be careful to avoid extrapolating the river profile slopes that are affected by reservoir sedimentation or local scour below the dam. For example, the delta may extend upstream of the reservoir, but at about one-half of the predam channel slope (Strand and Pemberton, 1982; Randle, et al., 2006). On Lake Mills on the Elwha River, the delta extended about 1 mile upstream of the reservoir pool into a canyon creating sediment deposits several tens of feet thick above the reservoir pool stage (insert figure of

canyon sedimentation). The predam-river profile, combined with the current reservoir sediment profile, will provide an estimate of the reservoir sediment thickness, which can be compared against probing or drill-hole data.

The predam-river profile will provide a good estimate of the profile eventually achieved after complete dam removal and erosion of the reservoir sediment. The predam profile immediately downstream of the dam may be higher than the existing channel profile in areas affected by local scour.

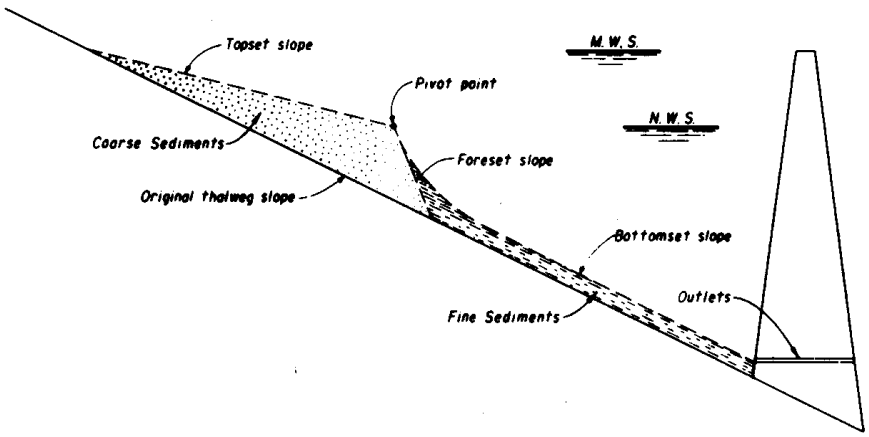

Figure 3. Example river and reservoir profiles. Label upstream channel break between river and delta profiles. Show local scour downstream from dam. Show predam channel profile.

- Describe the presence of woody debris in the reservoir sediment (reference reach, historical information, drilling and probing data) – step 2
- Describe the potential for old structures or debris buried in the reservoir sediment that could potentially limit headcut or reservoir bank erosion

The presence of woody debris and litterfall in reservoir sediment deposits needs to be considered because it can affect the rate and extent of reservoir sediment erosion along with an increased supply of woody debris and litterfall to the downstream channel. During drawdown, exposed log jams or large pieces of wood can deflect the flow and alter lateral erosion processes. In many cases, old timber crib dams or debris may exist that could limit the extent of headcut migration or lateral erosion and need to be removed if the predam channel is to be restored. For example, a large timber crib dam was found just upstream of Gold Ray Dam on the Rogue River in Oregon and had to be removed in conjunction with removal of the main dam. The supply of woody debris to the downstream channel may increase as a result of dam removal. Large wood released may help restore fluvial processes and form log jams, surfaces for vegetation to grow on, and improve aquatic habitat. Small woody debris and any accompanying litterfall could also pose challenges to operate and maintain water diversions and treatment facilities.

- Determine if the reservoir is no longer accumulating reservoir sediment (estimate sediment trap efficiency from the ratio of reservoir water storage volume to mean annual stream flow)

All reservoirs formed by dams on natural water courses trap some sediment over time. For many small reservoir sediment volumes, the reservoir likely filled to its sediment storage capacity within the first few years of operation. Once the sediment storage capacity has been filled, sediments are transported through the reservoir to the downstream channel. The trap efficiency approaches zero for fine sediment first and eventually for coarse sediment. If the reservoir has already reached its sediment storage capacity, then the sediment volume would not change with time. However, if the reservoir is still accumulating sediment, the sediment volume at the time of actual dam removal (in the future) should be updated and downstream impacts re-evaluated.

The physical shape and size of the reservoir, upstream sediment supply, and hydrology affect how fast the reservoir fills with sediment. The ability of the reservoir to continue to trap fine sediment can be estimated from the Brune trap efficiency method (see Appendix D). The longitudinal profiles of the existing reservoir sediment and predam channel provide a good indication of whether the reservoir is still trapping coarse sediment. If the delta profile extends downstream to the dam, then the reservoir has likely reached its sediment storage capacity. If the depth of water and sediment size in the reservoir is similar to the upstream or downstream channel, it is also a sign that the reservoir has filled to capacity with sediment. Another tool is to compare the original storage capacity with the existing capacity. If the majority of storage capacity has been lost, the reservoir may be filled with sediment. Alternatively, if a significant portion of the storage capacity is still available, the reservoir is still trapping coarse sediment.

Compare the total sediment volume to the annual sediment load to determine how many years of sediment accumulation are in the reservoir.

- Describe how the reservoir sediment will erode upon dam removal, including the quantity and rate of erosion.
    - Estimate the reservoir sediment volume expected to erode – step 4c
    - Make an assumption about the rate and extent of dam removal (step 5)
    - Describe how the head-cut erosion will progress upstream through the reservoir sediment including upstream and beyond the full pool elevation of the reservoir if applicable.
    - Estimate the rate of sediment erosion following dam removal
    - Estimate the recovery time in the reservoir for a stable landscape and vegetation growth

For most small reservoir sediment volumes, the dam would be completely removed and nearly all of the reservoir sediment can be expected to erode. However, there may be cases where some of the dam is left in place and this may limit the amount of reservoir

sediment erosion, especially if the dam in not removed all the way down to the predam river bed. Alternatively, if portions of the dam were left in place along the left or right abutments, then some reservoir sediment near the dam may not be subjected to lateral erosion. For reservoir sediment deposits that are much wider than the river channel, the lateral extent of reservoir erosion may be limited to a few channel widths. If the reservoir sediment is cohesive or becomes quickly vegetated after dam removal, this may also reduce the extent and rate of lateral erosion.

Step 4c: Consider the reservoir sedimentation volume that can be eroded

To estimate if all of the reservoir sediment volume is likely to erode, the following steps and rules of thumb can be applied. If there is a reason to expect that a significant portion of the reservoir sediment volume will not erode, the relative reservoir sediment volume should be reconsidered to determine if it is reasonable to adjust it before proceeding to step 5. Key questions to be answered are listed below:

- What portion of the reservoir sediment is expected to be eroded past the dam over the short and long terms?
- What will be the future stability of the remaining reservoir sediments?

Comment [BOR5]: *Joe notes: These 2 questions are confusing – and the following bullets are not questions – make consistent?*

- Develop a conceptual model of the reservoir sediment erosion processes.
    - Initially, the erosion channel width through the reservoir sediments would be a function of the stream-flow discharge.
    - Subsequently, the reservoir erosion width will tend to increase with each passing flood, of a larger magnitude, and as one or more erosion channels begins to migrate laterally and create a new floodplain within the eroded reservoir sediments.
    - Refer to Doyle et al. (reference) for an example conceptual model for non-cohesive sediment.
    - The maximum erosion width can be estimated based on some rules of thumb provided below.
- Determine the ratio of reservoir width to stream channel width[2]
    - If the reservoir width is greater than 3 times the active channel width, then the amount of sediment erosion may be limited to the volume contained within 3 active channel widths. The erosion width needs to be centered along the expected erosion channel alignment, which may likely be the centerline of the pre-dam thalweg). **[Re-evaluate significance of the reservoir sediment volume in Step 5a and 5b and whether this has an impact on contaminated areas that may have been initially expected to erode]**.
- Estimate reservoir sediment stability following dam removal

[2] Measure the active channel width of the stream in a wide alluvial reach that has essentially the same discharge as the reservoir reach (e.g. no significant tributaries, runoff contribution, or diversions).

- If ratio of the reservoir width is less than or equal to 3 stream channel widths, then assume for analysis purposes that all the reservoir sediment will be available for erosion and transport to the downstream channel. Maintain same relative sediment size determined in Step 5a and 5b
    - Return to pre-dam topography, which can be considered a **stable reservoir topography**
- If the reservoir width is greater than 3 stream channel widths and the reservoir sediment thickness is less than 3 stream hydraulic depths (typical channel flow area divided by the top width), then the reservoir topography likely will be consistent with the natural landscape and a **stable reservoir topography**
- If a narrow channel incises through reservoir sediment, then a potentially large portion of the reservoir sediment volume would be left behind after dam removal
    - If the reservoir sediment thickness is less than three hydraulic depths and the width is greater than 3 hydraulic widths, then the reservoir sediment left behind likely form stable terraces **[stable reservoir topography]**
    - If the reservoir sediment thickness is greater than 3 hydraulic depths, then the reservoir sediment left behind likely will be in an unstable condition **[unstable reservoir topography]**
- If an incised river channel erodes along the reservoir margin and becomes stuck on an erosion-resistant layer, then a prolonged period of reservoir sediment erosion may occur **[unstable reservoir topography]**
- If head-cut erosion through the reservoir sediments encounters an erosion resistant clay layer, the period of reservoir sediment erosion will be prolonged**[unstable reservoir topography]**

- If not all reservoir sediment erodes, will the reservoir sediment topography be stabilized by vegetation within the timeframe of predicted reservoir sediment erosion?
    - No (increases risk of unstable reservoir topography)
    - Yes (increases potential for stable reservoir topography), *consider whether there is a need to prevent exotic vegetation and/or actively promote native vegetation growth*

Special Cases to Consider:

- Erosion channels along delta margins
- Bank erosion from wave action
- Mass wasting and slope failures caused by rapidly changing pool levels
- Active erosion of predominantly clay banks
- Lateral migration and down-cutting of along reservoir tributaries

Downstream River Processes

- Determine if the hydrology upstream and downstream of the reservoir is essentially the same. In other words, determine if reservoir operations have a significant effect on downstream river flow
- Describe the morphology and geology of the downstream channel and floodplain
    - Existing bed-material in downstream channel
    - Estimate the relative sediment transport capacity with distance downstream (total stream power analysis)
    - Identify significant downstream tributaries and their relative contribution of water and sediment
    - Characterize distinct reaches of the downstream channel (canyon, wide alluvial valley)
    - Describe the potential depositional environments for sediment (e.g. pools, bars, side channels, floodplains)
- Estimate portion of reservoir sediment expected to move as bed-material load versus wash load
- Describe what happens to the released bed-material load including potential consequences to resources (mass balance computation)
    - Identify potential areas of deposition of coarse reservoir sediment
    - Identify potential consequences of coarse sediment deposition
    - Estimate how long coarse sediment deposits are expected to persist
- Describe what happens to the released fine sediment (wash load) including potential consequences to resources (mass balance computation)
    - Identify potential consequences of increased wash load and concentration
    - Estimate additive effects of suspended sand loads
    - Describe if deposition is expected on the floodplain
- Identify and describe the ultimate downstream depositional environments (e.g. low gradient river reach, reservoir, lake, or estuary)

Downstream Channel Predictions

- Estimate the deposition thickness, extent, and duration
- Estimate the bed-material grain size change
- Predict if there is any expected morphology change
    - Gather historical aerial photography, maps, pre-dam photographs, field observations, historical survey comparisons
    - Where is sediment likely to be deposited downstream (e.g., pools, flood plains, bars, downstream reservoirs, lakes, or estuaries)?
    - Is morphology expected to be altered either short-term or long-term as a result of dam removal? (e.g. meandering to braided, widen, etc)

Coarse reservoir sediment:

How does sediment transport capacity change with distance downstream?

- Where is the dam located within the watershed?
- To what extent has the natural watershed hydrology at the dam site been altered by upstream development, including dams and reservoirs? In other words, are stream flows at the dam site less than, greater than, or about the same as natural conditions? Will the hydrology change significantly as a result of dam removal?
- To what extent has the natural sediment load at the dam site been altered by upstream development, including dams and reservoirs? In other words, are sediment loads at the dam site less than, greater than, or about the same as natural conditions?
- Where are significant tributaries downstream from the dam and what are their relative water and sediment contributions?
- What is the longitudinal slope of the downstream river channel relative to the upstream channel? Is the channel slope becoming more mild, steeper, or about the same?
- Is the downstream channel morphology (e.g. narrow, meandering, wide, straight, braided, white water rapids or riffles and pools)?
- What material comprises the stream bed and banks (e.g. bedrock, boulders, cobbles, gravel, sand, silt, clay, rip rap, concrete)?
- Is there extensive riparian vegetation along both or either stream bank?
- Are the stream banks stable or actively eroding? If there is active stream bank erosion, describe the locations?
- Is the grain size of the reservoir sediment finer than the downstream bed-material or about the same size?
    - If the reservoir sediment grain size is finer than the downstream bed material, then the reservoir sediment particles can be expected to transport at a faster rate than the downstream bed material.
    - If the reservoir sediment grain size is about the same size as the downstream bed material, then the reservoir sediment particles can be expected to transport at about the same rate than the downstream bed material.
- Is the dam likely to be removed during periods of low or high stream flow?
    - If

Generally describe what happens to coarse sediment eroded and released from the reservoir to the downstream channel.

Series of questions related to downstream storage areas

Fine reservoir sediment:

-

For example, . . .

- Use some simple mass balance computations and a total stream power analysis to help guide the conceptual model.

Relate back to resource concerns

- downstream fine sediment concentration,
- downstream dispersion and dilution by tributaries, and
- downstream deposition locations.

Total Stream Power Analysis

- **Compute and plot total stream power for a frequent flood peak (e.g. 2-year flood peak) versus channel distance to account for varying reach slopes and tributary streams.**

Data Collection Needs:

- Verify the reservoir sediment volume and particle size distribution, perhaps by wading, diving or snorkeling, and sediment coring to the pre-dam river bed.
- Estimate the portion of reservoir sediment that is sand, gravel, and cobble.
- Estimate the D_{90} of the reservoir sediment.
- Estimate the bankfull depth in a likely depositional reach of the downstream river channel using survey.
- Estimate bankfull channel width using surveys or current rectified aerial photography of the downstream active river channel.
- Measure the surface area and length of the downstream active river channel.
- Determine the channel slopes from topographic maps or TIN models
- Determine the flood frequency at key locations along the main channel

Simple Mass Balance Computations

Put the sediment volume in perspective. Calculate the length of reservoir sediment volume spread evenly over the downstream active channel in a likely depositional reach assuming a uniform sediment thickness:

- For a gravel or cobble-bed stream, assume sand is transported downstream in suspension and gravel and cobble would be spread out in a uniform thickness over the downstream river channel as a single layer thickness equal to the D_{90} of the reservoir sediment. To compute the longitudinal extent of deposition, first compute the depositional area by dividing the reservoir gravel and cobble volume by the D_{90} of the total reservoir sediment. Then divide the sediment area by the bankfull channel width to determine the length of deposition along the downstream channel. Also compute how this length compares to the bankfull channel width (e.g. Length/bankfull width). How does the reservoir sediment volume compare to a typical gravel bar?

- For a sand-bed stream, assume a uniform sediment thickness is equal to 10 percent of the bankfull channel depth. Also compute how this length compares to channel width (e.g. Length/bankfull width). How does the reservoir sediment volume compare to a typical sand bar?

Example: If Elwha reservoir fine and coarse sediment were vertically stacked on the downstream riverbed (8 km long and 60 m wide):44 m (145 feet) high

Simple (Low Risk) Suspended Sediment Concentration and Turbidity

- Assume that fine sediment quickly erodes as the reservoir is drawn down and that it is transported downstream.
- Compute an average fine sediment concentration from the fine sediment mass (from reservoir sediment samples) divided by the sum of reservoir water volume and the mean daily inflow volume. The fine sediment mass can be computed from cores of reservoir sediment.
- Predict where the fine sediment will eventually deposit (e.g. ocean, lake, downstream pools, etc).

- Are the fine sediments cohesive (plasticity index > 20)?
  - No
    - Assume that fine sediment quickly erodes as the reservoir is drawn down.
    - Compute an average fine sediment concentration from the fine sediment mass (from reservoir sediment samples) divided by the sum of the reservoir water volume and mean-daily inflow volume. The fine sediment mass can be computed from cores of reservoir sediment.
  - Yes
    - Assume fine sediment erosion occurs over an extended period beyond period of reservoir drawdown) due to the slow progression of head-cut erosion.
    - Using best judgment, estimate duration of reservoir sediment erosion (days, weeks, months, years); consider similar case studies
    - Estimate the average rate of head-cut erosion.
    - Estimate a range of fine sediment concentrations corresponding to the average erosion rates assuming a range of flow conditions.

Analysis Tips:

- The plasticity index (PI) represents the range in water contents over which a soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit (PI = LL - PL). Soils with a high PI tend to be clay, those with a lower PI tend to be silt, and those with a PI of 0 tend to have little or no silt or clay.

how do you get LL and PL?

Data Collection Plans

Coarse sediment

Fine sediment

Reservoir Sediment Erosion Predictions

Move somewhere else

In many cases, the same model may be used to simulate reservoir and downstream processes. In large complex cases, separate reservoir and downstream models may be needed, including a combination of physical and numerical models. More information on modeling techniques for dam removals can be found in the ASCE Monograph on Sediment Dynamics upon Dam Removal (2010 in progress).

Consider a reservoir drawdown field experiment to help understand the reservoir sediment erosion processes and refine the sediment management plan.

Downstream Channel Predictions

- Predict the deposition thickness, extent, and duration
- Predict the bed-material grain size change
- Predict morphology change that may not be accounted for in numerical modeling
    - Gather historical aerial photography, maps, pre-dam photographs, field observations, historical survey comparisons
    - Where is sediment likely to be deposited downstream (e.g., pools, flood plains, bars, downstream reservoirs, lakes, or estuaries)?
    - Is morphology expected to be altered either short-term or long-term as a result of dam removal? (e.g. meandering to braided, widen, etc)

Interpretation of analysis and model results

- Putting results in context with background sediment perturbations in system
- Short term vs long term perspective
- Handling convergence or divergence of results
- Note where sediment releases can provide benefits to system that may be currently starved (impacts may actually be good)

Tools Outline

- Describe what the model or analysis tool can predict
    - Reach scale or local scale
    - Short or long term predictions
- Describe what input data are needed
- Discussion (e.g. strengths and weaknesses)
    - (things to be aware of such as depth average velocity in pools)
    - Cohesive sediment
- Where to find models (references)

Tools Appendix

- **Conceptual model (simple mass balance)**
- **Geomorphic Analysis (major reach breaks, trends)**
- **Sediment wave model**
    - One example of an analytical sediment wave model can be found in Greimann, B., Randle, T. and Huang, J. (2006) or in the ASCE Monograph on Sediment Dynamics upon Dam Removal, Chapter 9: Movement of Sediment Accumulations (Greimann, 2009 in progress)
- **Mass balance model for wide reservoirs and staged removal**
- **Stream Power**
- **1D hydraulics model (water temperature)**
- **Reservoir routing model**
- **Water quality models (see report)**
- **Ground water model**
- **1D sediment transport capacity model**
- **1D sediment erosion and deposition model**
    - See Chapter 8 of ASCE Monograph[3]: Modeling and measuring bed adjustments for river restoration and dam removal – a step toward habitat modeling (Granata, Cheng, Zika, Gillenwater, and Tomsic, 2009 in progress)
    - See Chapter 10 of ASCE Monograph: Guidelines for Numerical Modeling of Dam Removals (Randle and Bountry, 2009 in progress)
    - See Chapter 11 of ASCE Monograph: Sedimentation Studies for Dam Removal Using HEC-6T (Thomas, 2009 in progress)
- **2D hydraulics model (steady flow & transport capacity)**
- **2D sediment erosion and deposition model**
- **Bank erosion model**
- **Vegetation growth and mortality model**
- **Physical model of reservoir or river channel**
- **Field test in reservoir or river channel**

[3] The new ASCE monograph on dam removal should be available in 2010.

Sediment Wave Model

apply a sediment wave (analytical) model to predict the sediment release hydrograph from the reservoir and the sediment deposition thickness on the downstream riverbed with time and distance downstream.

Data Collection Needs:

- Verify the reservoir sediment volume and size, perhaps by wading, diving or snorkeling and coring of sediment samples to the pre-dam river bed.
- Measure the D_{50} and D_{90} of the reservoir sediment.
- Measure longitudinal profiles of the reservoir sediment and downstream river channel.
- Determine the reservoir sediment thickness and slope of the downstream river channel.
- Compute total stream power to determine the reaches of potential transport and deposition and where channel survey data are needed.
- Measure the typical downstream channel width and slope where sediment transport capacity is of interest. This can be computed at a range of cross sections to evaluate the downstream variability.

1D Sediment Capacity Model

one-dimensional hydraulic model to compute the sediment transport capacity along the downstream river channel to provide predictions of the magnitude, duration, and extent of downstream sediment transport and deposition.

If more precise predictions are required to satisfy local stakeholders or regulatory agencies, apply a one or two-dimensional sediment transport model to predict the sediment release hydrograph from the reservoir and the deposition thickness on the downstream riverbed with time and distance downstream. The model should include the entire stream reach of concern. An appropriate downstream model boundary could include a lake, estuary, or major tributary. Simulate and track both the bed-material load and the wash load.

Data Collection Needs:

- Verify sediment volume with a dive inspection, coring of sediment to the predam reservoir bed or comparison of present condition and predam bathymetric maps if available.
- Measure cross sections through the reservoir.
- For each reservoir cross section, measure or estimate the sediment thickness.
- Measure the reservoir sediment thickness and grain size distribution throughout the length of the reservoir.

- Measure cross sections along the downstream channel making sure to include hydraulic controls (riffles, rapids, bridges, weirs, etc); consider surveying a longitudinal profile of river channel to provide more information on the river channel slope and help identify where cross-sections are needed

Analysis tips:

- Interpolate reservoir cross sections so the spacing is close enough to simulate head-cut erosion through the reservoir sediments (see ASCE Chapter 10).
- Do not allow the one-dimensional model to erode below the reservoir sediment.
- Interpolate downstream channel cross sections as necessary.
- For each cross section of the downstream channel, assume a minimal thickness (e.g. 0.1 ft) of the reservoir sediment size gradation rather than entering the existing river bed size gradation. This will prevent the numerical model from mixing reservoir sediment with a coarser streambed. Do not allow the model to erode the existing streambed.
- Estimate the stream flow hydrograph for the time period during and immediately following dam removal.

1D or 2D Sediment Transport Model

Apply a one or two-dimensional sediment transport model and consider constructing a scaled physical model to predict the reservoir sediment erosion versus time, new reservoir topography, and the downstream sediment transport and deposition along the downstream channel. Simulate and track both the bed-material load and the wash load. As in the case of the medium sediment mass, the model should include the entire stream reach of concern. An appropriate downstream model boundary could include a lake, estuary, or major tributary. If potential consequences are critical, consider applying both numerical and physical models.

Data Collection Needs:

- Verify sediment volume with a dive inspection, coring sediment to the predam riverbed or comparison of present condition and original bathymetric maps if available.
- Measure sediment surface bathymetry throughout the reservoir.
- Measure or estimate the reservoir sediment thickness throughout the reservoir bathymetry.
- Measure the sediment grain size distribution throughout the reservoir bathymetry.
- Measure the downstream channel and floodplain topography throughout the reach of concern.
- Estimate the potential stream flow hydrograph for the period during and following dam removal. Assume range of potential hydrographs to represent a range of hydrologies.

Modeling:

- Do not allow the model to erode below the base of the reservoir sediment.
- For the downstream model mesh, assume a minimal thickness of the reservoir sediment size gradation. This will prevent the numerical model from mixing reservoir sediment with a coarser streambed. Do not allow the model to erode the existing streambed.

UNCERTAINTY, MONITORING, AND ADAPTIVE MANAGEMENT

Step 7: Assess Prediction Confidence

Presenting results, dealing with uncertainty, adaptive managment

Estimate the confidence of each data category. Some possible categories are listed below (needs additional input).
Estimate the confidence of each data category:

- Reservoir sediment volume
  - Adequate data collection? (increased or reduced confidence)
  - Legacy thalweg? (increased confidence)
- Grain size distribution
  - Adequate data collection? (increased or reduced confidence)
- Contaminant sampling
  - Adequate sampling effort, spatial distribution, core length, analyte selection
- Reservoir sediment erodibility
  - Is there a substantial amount of silt and clay-sized sediments within the reservoir (> 30 percent)? **[Low to moderate to confidence on timing of erosion]**
  - Are the fine sediments cohesive? **[Low confidence on timing of erosion]**
  - If not acceptable to wait for erosion over potentially longer time period, consider need for reservoir sediment removal or stabilization *how is this related to confidence?*
- Stream flow hydrograph
  - Stream gage available on stream where dam is located? (increased or reduced confidence)
- Aggradation predictions
  - Is channel migration or significant planform changes expected from the conceptual model that is not accounted for in the modeling predictions (increased or reduced confidence)
  - Sediment pool deposition

Step 8: Present to decision makers and stakeholders and determine if predicted impacts can be tolerated or if other alternatives are needed

Compile the predicted sediment effects from step 6 and assess the impacts to resources of concern including aquatic organisms and habitat, property, water quality, infrastructure, diversion water needs, etc.

- If impacts can be tolerated, then proceed with dam removal planning.
- If impacts cannot be tolerated, then develop alternative dam removal or sediment management plans, or mitigation options to reduce impacts to tolerable levels, or do not remove the dam.
    - Consider alternatives to reduce the amount of reservoir sediment that is allowed to erode downstream.
    - Consider alternatives to slow the release of reservoir sediment.
    - Determine if more data collection or analysis are needed to increase the certainty of predictions or evaluate new alternatives.
    - Consider adding mitigation measures to the sediment management plan (e.g. water treatment plant capabilities, flood protection, etc)

Consider adding flow charts from water quality notes 2008

Step 9: Develop Monitoring and Adaptive Management Plan

1. Establish predictions of sediment erosion and transport rates and volumes
2. Develop a monitoring plan to determine if predictions are correct. If not, determine how the monitoring results differ from prediction effects in terms of location, timing, duration, and magnitude.
3. Consider a tiered monitoring plan (e.g., monitoring of reservoir sediment erosion can be used to trigger downstream monitoring)
4. Monitoring results can be used to approve increments of removal
5. Monitoring results can be used to anticipate water quality effects from subsequent increments of dam removal
6. Monitoring results can be used to anticipate bank erosion or flooding problems
7. Monitoring results need to be real-time to provide feedback for adaptive management decisions.

(Provide additional references to adaptive management material and case studies such as the Elwha and Glines Canyon Dam removals and other small dams if available)

Potential data collection:

- Time-lapse photography
- Stage recorders to evaluate stage-discharge relationships to detect signs of aggradation
- Repeat reservoir surveys
- Repeat river channel surveys

- Repeat sediment bed-material size gradation measurements
- Suspended sediment and bedload measurements
- Turbidity measurements
- Repeat aerial photography
- Bank erosion monitoring
- Sediment wave tracking (location and speed)

Insert from Matt Collins (March 2012)

I. BACKGROUND

A decade ago, as dam removal became an increasingly appealing option for dam owners and resource managers, there were numerous calls for increased monitoring of dam removal projects to better understand ecological effectiveness, reduce uncertainties about short and long-term impacts, increase the predictive capabilities of project planners and designers, and enable adaptive management (Aspen Institute, 2002; Babbitt, 2002; Doyle et al., 2003a; Hart et al., 2002). It was recognized that robust project monitoring is necessary to improve the practice of dam removal.

While many still note the relative paucity of quantitative effectiveness monitoring for dam removals, especially small dams (Bernhardt et al., 2007; Burroughs et al., 2009; Downs et al., 2009; Kibler et al., 2011), there has been progress in recent years particularly with respect to sediment monitoring (Burroughs et al., 2009; Cheng and Granata, 2007; Doyle et al., 2003b; Kibler et al., 2011; Major et al., 2008, 2010; Pearson et al., 2011). Despite these advances, the geomorphic responses of the upstream and downstream channels vary considerably by impoundment grain size distribution, reach gradients, valley morphology, regional physiography, surficial geology (e.g., glaciated versus non-glaciated), and climate. Thus it is necessary to monitor more sites to adequately represent the range of fluvial habitat variability across the nation so that practitioners can have useful analogs for planning and prediction.

Monitoring may also be warranted to support adaptive management at any given site. The fundamental motivation for using adaptive management is to reduce uncertainty. This occurs by promoting flexible decision making that can be adjusted as outcomes from previous management actions and other events become better understood (Williams et al, 2007). Monitoring data are a necessary component to measure river responses and whether management actions are working and meeting objectives. If objectives are not being met, then the focus would shift on determining why not and how existing actions should be modified or new actions implemented to achieve those objectives. For the Elwha River Restoration Project near Port Angles, Washington, monitoring tasks were designed to be conducted in a “real-time” operational mode for rapid decision making during the dam-removal process.

II. MONITORING PURPOSES AND SCOPES

The type of sediment monitoring, as well as the spatial and temporal scale over which it is conducted, will vary depending on the purpose for the monitoring and the questions guiding it. Monitoring is usually done to support permit compliance, specific adaptive management actions, verify implementation quality, and/or understand ecological effectiveness (citation to Roni). Generally speaking, permit compliance and ecological effectiveness sediment monitoring are end-members on the spectrums of spatial and temporal monitoring scales. Permit compliance and implementation monitoring is typically conducted over small spatial scales and short durations. Ecological effectiveness monitoring, on the other hand, usually requires larger spatial coverage and considerably longer durations. The spatial and temporal scales over which monitoring is done for adaptive management purposes will vary according to the needs identified in the applicable adaptive management plan.

Comment [TJR6]: Try to link the level of monitoring to risk. The permit monitoring will always be the minimum level required. Risk would relate to potential problems that could develop. Monitoring needs to be designed to detect the initial development of those problems in time to take corrective action (adaptive management).

Permit compliance sediment monitoring is usually concerned with documenting suspended sediment concentrations during project construction. The purpose of the monitoring is to assure that suspended sediment concentrations remain within a range specified in a permit governing work at the site, typically a state Section 401 (of the federal Clean Water Act) water quality certification. Turbidity is frequently the parameter monitored and it is often done continuously throughout the construction period at sites a relatively short distance downstream and upstream from the dam removal.

Implementation monitoring simply evaluates whether a project is carried out as designed and meets basic structural goals. It is also short-term. At dam removal sites, implementation monitoring is often achieved by the comparison of an as-built survey with the design plans.

Ecological effectiveness monitoring, in contrast, is concerned with functional success and documents the physical, biological, and geochemical response of the river to the removal. Understanding effectiveness very frequently requires monitoring over larger spatial scales, including control sites or control reaches, and the monitoring durations are usually considerably longer than compliance and implementation monitoring. Effectiveness monitoring is usually focused on parameters that will document whether the project was successful at achieving specific project objectives, for example passage of target fish species. However, some effectiveness monitoring evaluates a range of parameters to understand broad-scale ecological response. Effectiveness monitoring also enables impact analyses of specific dam removal techniques (e.g., sediment release) and better equips practitioners to improve construction methods and prediction tools. Thus, effectiveness monitoring advances the scientific basis for the practice of dam removal.

Monitoring to support adaptive management will vary in spatial and temporal scope according to the project's management objectives and priorities. These will ideally be described in an adaptive management plan. For example, for a small dam removal on the Patapsco River in Maryland, specific locations as much as 4 river miles downstream are being monitored for as long as two years to observe whether conditions over that time exceed pre-determined erosion or aggradation thresholds (NOAA, 2010). Monitoring can be applied to adaptively manage specific implementation actions such as approve

increments of removal or anticipate the sediment-related effects of subsequent dam removal increments.

III. MONITORING DESIGN CONSIDERATIONS

A. Monitoring Design

The monitoring design should be guided by the questions of interest for the site. These questions should be well defined and agreed upon by all of the interested parties before the monitoring program is planned. As noted above, the questions of interest will usually be associated with permit compliance, adaptive management, implementation quality, and project effectiveness. Simple questions may only require short-term monitoring of simple parameters at one or a few locations proximal to the dam. More complex questions may require long-term monitoring of parameters that require more sophisticated methods employed over larger spatial scales.

Comment [TJR7]: Relate monitoring activities to predictions. Avoid monitoring without predictions because it would be difficult to interpret the monitoring results.

From a practical perspective, monitoring designs are also driven by available project monitoring budgets which are frequently small or non-existent. Indeed, the relative lack of dam removal monitoring over the last decade or so, and the difficulty with getting a greater level of monitoring at a larger number of dam removal sites, is directly related to the challenge of securing funding for monitoring activities. For the purposes of this document, the recommended level of monitoring should correspond to the level of risk. Adaptive management will require some level of monitoring to implement the project.

After identifying clear guiding questions, the project team should identify the extent of the monitoring reach. It is important to establish this early in the planning process because the spatial scale that must be evaluated may dictate the parameters and methods that should be employed. For example, is the project team interested in the magnitude of aggradation within a comparatively short distance downstream or over a much longer reach?

With the exception of narrowly focused permit compliance monitoring and implementation monitoring, there is usually an interest to have sediment monitoring at dam removal sites reveal whether there are changes to the system brought about by the removal. A simple before and after monitoring design will accomplish this by sampling the parameters of interest before the impact (e.g., removal) and again after the impact. While the intention of a before and after monitoring design is to evaluate changes brought about by the impact, sometimes it is impossible to distinguish between changes caused by the impact and those brought about by other environmental conditions (Kibler et al., 2010). For that reason investigators usually prefer a monitoring design that not only compares before and after monitoring, but also monitoring of a control reach. Monitoring of a control reach will help distinguish between changes caused by the dam removal and those that may be caused by external factors (natural or otherwise) (Collins et al., 2007). Roni et al. (2005) and Kibler et al. (2010) provide reviews of both monitoring designs and a number of variants that can improve monitoring design rigor.

B. Parameters, Methods, and Reporting Standards

Project proponents, stakeholders, regulators, and researchers have a wide range of concerns about how sediment storage and release at dam removal sites will affect upstream and downstream channels and floodplains—and related effects on stream and floodplain biota as well as human uses. Most sediment concerns are related to a handful of physical processes: reservoir sediment erosion, downstream sediment transport, channel bed and floodplain aggradation and degradation, bank erosion, and channel morphology. The spatial extent and duration of these processes can be investigated through repeat monitoring activities:

- Reservoir surveys
- Channel cross-section surveys
- Channel longitudinal profile surveys
- Channel and floodplain digital elevation models
- Water stage recorders to detect bed aggradation or incision
- Photography stations including web cameras
- Orthophotography
- Bed material grain size distribution measurements
- Stratigraphic observations and measurements of sediment deposits
- Suspended sediment and bedload measurements
- Turbidity

Collins et al. (2007) describe traditional survey techniques for accomplishing channel cross-section and longitudinal profile surveys; repeat photograph stations; and bed material grain size distribution measurements on wadeable streams at dam removal sites. Harrelson et al. (1994) also provide detailed methods for stream channel surveys. Methodologies for some of the other parameters listed are reviewed generally in Kondolf and Piegay (2003).

Reporting standards...

C. Duration/Frequency

D. Challenges

IV. INTEGRATING MONITORING WITH PROGRAM PLANNING

Comment [m8]: I'd like to include here a brief discussion about the importance of consistent reporting standards for looking at data across sites, and from the perspective of another SOS effort Tim and I are involved with—developing a National Stream Morphology Database. However, if you two would prefer that not be included here, I am fine with that.

Comment [m9]: This is a short, straightforward section I just haven't written yet.

Comment [m10]: Here I would like to briefly describe common challenges ranging from field conditions and capturing events to problems with study design (identifying reference sections and/or reaches) and establishing significance of outcomes (e.g., Desiree Tullos' stuff).

Comment [m11]: Jennifer, this is a section I would like to include that follows the general theme of the presentation I gave at NCER in Baltimore last summer. That is, as important as it is to monitor dam removals, project monitoring must be integrated with the rest of a program if we want to increase the effectiveness of our projects. If monitoring results from individual projects never feed back into program planning and future project implementation, which they often don't, we'll get diminished value out of the monitoring dollars we spend. I will understand if you and Tim don't really feel a section like this belongs in your manual. I am just trying to beat this drum wherever I can!

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CASE STUDIES

Map of United States showing locations of case-study dams
Table of Case Studies

Dam Name	River	State	Nearest City	Dam Hydraulic Height	Ratio of Reservoir Width to Channel Width	Year Dam Removed	Relative Sediment Volume	Sediment Impact Risk	Reference Documents

SUMMARY

While the great majority of dams still provide a vital function to society, some of these dams may need to be removed for various reasons such as economics, dam safety and security, legal and financial liability, ecosystem restoration (including fish passage improvement), site restoration, and recreation use.

The sediment effects related to dam removal may be significant if any of the following conditions apply:

- The reservoir storage, below the normal operating pool, is at least 1 percent of the average annual inflow.
- The reservoir sediment volume is equivalent to a multi-year sediment supply from the upstream river channel, or several years would be required to transport the reservoir sediment volume through the downstream river channel.

- The reservoir sediments are contaminated at concentrations significantly above background levels.

Portions of the dam can be left in place for historic preservation, to reduce dam removal costs, and to help stabilize reservoir sediments. The rate of reservoir sediment erosion and release to the downstream river channel is primarily controlled by the rate of dam removal and reservoir drawdown and by the upstream hydrology. Although headcuts may erode the reservoir sediments during periods of low flow, sufficient flow is necessary to provide transport capacity of reservoir sediments. The rate of reservoir drawdown needs to be slow enough to avoid a flood wave of reservoir water spilling into the downstream river channel. Also, the rate needs to be slow enough to avoid inducing any potential landslides along the reservoir margins or a slide failure of any earthen dams. The ability to draw down the reservoir pool depends on how flows can be released through, over, or around the dam. If the dam has a low-level, high-capacity outlet works or diversion tunnel, then the reservoir could be emptied at a prescribed rate and the dam could be removed under dry conditions. Otherwise, a diversion channel may have to be constructed around the dam or an outlet may have to be constructed through the dam.

The basic types of sediment management alternatives associated with dam removal include no action, river erosion, mechanical removal, and stabilization. River erosion is typically the least expensive and most commonly employed alternative. However, mechanical removal or stabilization may be required if the reservoir sediments are contaminated. If the reservoir is many times wider than the upstream river channel, then a significant portion of the reservoir sediments will remain stable in the reservoir over the long term, even without stabilization techniques.

The rate and extent of reservoir sediment erosion, and the possible redistribution and storage within the reservoir, need to be predicted before sediment transport can be predicted through the downstream river channel. The primary predictive tools include

both numerical and physical modes. Physical models can provide accurate predictions if the model scales are properly selected and they can be used to calibrate numerical models. The numerical models tend to be more easily adaptable to simulate multiple management or hydrology scenarios. Most numerical sediment transport models are one dimensional and can simulate river conditions over many miles and over a time period of many decades. Two-dimensional models are also available, but their focus is normally limited to relatively short river lengths over periods of days or maybe weeks. A thorough understanding of the numerical model equations and limitations is necessary for proper application of the model to a dam removal problem. In addition, thorough understanding of the geomorphic, hydraulic, and sediment transport processes of the river is necessary for proper model application and interpretation of the results.

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Appendix B: Guidelines Development

The guidelines were developed through a combination of technical workgroups, individual efforts, and feedback from technical venues. Much of the development of the core guideline ideas occurred at two workshops, held in Portland, Oregon in 2008 and in State College, Pennsylvania in 2009. Throughout development, the latest draft of the guidelines were presented at technical conferences including the 2010 Federal Interagency Sedimentation Conference in Las Vegas, Nevada, the 2011 USSD Society of Dams.

The first draft of the guidelines were based on input from participants at a three-day workshop sponsored by the Subcommittee on Sedimentation held October 14-16, 2008. The 2008 workshop was jointly organized by the Bureau of Reclamation and the U.S. Geological Survey. The U.S. Geological survey hosted the workshop in Portland, Oregon and a field trip to the Marmot Dam Removal Project on the Sandy River, Oregon. Rose Wallick, Chauncey Anderson, Jon Major, Kurt Spicer, and Heather Bragg are acknowledged for their effort in organizing the workshop and field trip. Participants were broken up into three technical groups to work on development of a guideline methodology. Acknowledgements go to the leaders of the technical teams who summarized the ideas into the first draft components of the guidelines. The reservoir erosion and sedimentation group was led by Peter Downs of Stillwater Sciences, the downstream river sediment transport and deposition group was led by Will Graf of the University of South Carolina, and the water quality group was led by Chauncey Anderson of the U.S. Geological Survey. All of the participants in the 2008 workshop who are acknowledged for contributing to the guidelines are listed in Table X.

After the first workshop, a core group of participants condensed the ideas from the three technical groups into one draft. The guidelines were then tested with historical and in progress dam removal case studies at a second workshop held October 2009 in State College, Pennsylvania. The Pennsylvania Fish and Boat Commission hosted the second workshop and Scott Carney is acknowledged for his efforts in organizing the workshop venue and a field visit to two local dam removal projects. Workshop participants provided a range of dam removal projects for testing that varied in sediment mass and location within the United States. A list

Table 3. List of workshop participants in October 2008 at Portland, Oregon.

Participant	Affiliation
David Admiral	American Society of Civil Engineers, West Consultants
Chauncey Anderson	U.S. Geological Survey
Dick Bauman	Bureau of Reclamation
Jerry Bernard	National Resources Conservation Service
Jennifer Bountry	Bureau of Reclamation
Jeff Bradley	American Society of Civil Engineers, West Consultants
Curt Brown	Bureau of Reclamation
R. Scott Carney	Pennsylvania Fish and Boat Commission
Dan Cenderelli	U.S. Forest Service
Brian Cluer	National Marine Fishery Service
Mathias Collins	National Marine Fishery Service
Yantao Cui	Stillwater Science
Pete Downs	Stillwater Science
John Esler	Portland General Electric
Stanford Gibson	U.S. Army Corps of Engineers
Doug Glysson	U.S. Geological Survey
Chris Goodell	West Consultants
Will Graf	University of South Carolina
Gordon Grant	U.S. Forest Service
Blair Greimann	Bureau of Reclamation
Craig Hickey	University of Mississippi
Bill Jackson	National Park Service
Yafei Jia	University of Mississippi
Cassie Klumpp	Bureau of Reclamation
Karl Lee	U.S. Geological Survey
Mary Ann Madej	U.S. Geological Survey
Christopher Magirl	U.S. Geological Survey
Jon Major	U.S. Geological Survey
James MacBroom	Milone and MacBroom
Marty Melchior	Interfluve
Charles Podolk	National Center for Earth-Surface Dynamics
Cynthia Rachol	U.S. Geological Survey

Participant	Affiliation
Tim Randle	Bureau of Reclamation
Joe Rathbun	Michigan Department of Environmental Quality
John Remus	U.S. Army Corps of Engineers
Stephen Scott	U.S. Army Corps of Engineers
Mike Shannon	Agricultural Research Service
Gary Smillie	National Park Service
Tim Straub	U.S. Geological Survey
Desiree Tullos	Oregon State University
Rose Wallick	U.S. Geological Survey
Marcin Whitman	California Department of Fish and Game
Andrew Wilcox	University of Montana
Laura Wildman	American Rivers
Brian Winter	National Park Service

Table 4. List of test cases used in October 2009 workshop at State College, Pennsylvania.

Dam Name	Author(s)
Anaconda Dam	Laura Wildman
Ballou Dam	Brian Graber
Billington Dam	Jim McBroom
Brewster Creek Dam	Tim Straub
Carbonton Dam	Jim McBroom
Chiloquin Dam	Travis Bauer/Desiree Tullos
Condit	Mike Burke
Edwards	Laura Wildman
Freight Street Dam	Laura Wildman
Glines Canyon & Elwha Dams	Tim Randle
Gold Hill Dam	Jennifer Bountry
Great Works Dam	Jim McBroom
Hemlock Dam	Chris Magirl, Bengt Coffin, Pat Connolly, Blair Greimann
Hoffman Dam	Tim Straub
Indian Lake Dam	Sara Strassman/Laura Wildman
Kamarath Dam	Brian Graber
Marmot Dam	Yantao Cui and Chuck Podolk
Matilija Dam	Randle / Blair Greimann
McCoy Dam	Scott Carney
McGowan Dam	Marcin Wittman
McPherrin Dam	Marcin Wittman
Merrimack Village Dam	Matt Collins
Milltown	Andrew Wilcox
Norwalk Mill Pond Dam	Jim McBroom
Pizzini Dam	Laura Wildman
Rasmussen Lake Dam	Tim Straub
Raymond	Laura Wildman
Reedsville Mill Dam	Scott Carney
San Clemente Dam	Mike Burke
Savage Rapids Dam	Jennifer Bountry/Desiree Tullos
Sawmill Dam	Marty Melchior
Simkins Dam	Marty Melchior
State Hospital Dam	Marty Melchior
T&H Dam	Jim McBroom
Zemko	Laura Wildman

Appendix C: Reservoir Sediment Surveys

Appendix D: Sediment Transport Capacity Computations

Note what step this supports

Written by Tim Randle and Blair Greimann

Sediment transport capacity needs to be computed to determine the significance of the coarse sediment mass contained within the reservoir. In these guidelines, the significance of the coarse reservoir sediment mass is defined as negligible, small, medium, large, or very large and the classification is based on the sediment transport capacity at discharges of a certain frequency.

Sediment transport capacity needs to be computed for the downstream channel to evaluate the potential to move the coarse reservoir sediment downstream from the reservoir. The following data are required for the sediment transport computations:

- Streamflow discharge
- Channel hydraulic data
- Coarse reservoir sediment unit weight and particle size gradation
- Selection of a predictive sediment transport equation

Streamflow discharge

If available, streamflow data from a stream gage in the downstream channel reach is the best source of discharge data. If streamflow gage data are not available, then discharge for the downstream channel reach will have to be estimated from a stream gage in the watershed or from a gage in a nearby watershed with similar characteristics.

$$Q_d = Q_g \left(\frac{A_d}{A_g} \right)^p$$

Where,
Q_d = discharge at dam site,
Q_g = discharge at stream gage,
A_d = drainage area above dam site,
A_d = drainage area above stream gage, and
p = exponent power, typically 0.5 (add reference)

Another option is to estimate discharge from a regional regressions. Regional regressionsfor the United States can be found at the following USGS website: http://water.usgs.gov/osw/programs/nss/summary.html

The regional regressions also may provide guidance on the appropriate exponent (p) to use for extrapolating discharge from a nearby stream gage. The regional regressions also include affects of elevation and average annual precipitation.

Channel hydraulic data

Channel hydraulic data are needed to represent the hydraulic capacity of the downstream channel to transport sediment. The required hydraulic data are listed below:

- Cross-sectional channel shape from which to compute the following variables as a function of the water depth, y:
  - Cross-sectional area (A),
  - Wetted channel width (T),
  - Wetted perimeter (P), and
  - Hydraulic radius ($R = A/P$)
- Channel roughness (Manning's n coefficient)
- Longitudinal energy slope (S_e) for the cross section of interest

The best source of hydraulic data are from a one-dimensional hydraulic model that is based on measured channel cross sections and calibrated to measured water surface elevations. At least one cross section must be chosen from the hydraulic model to represent the downstream channel. Selection of a typical river cross section that represents average friction slope and transport capacity is recommended. Selection of a riffle cross section is not recommended in pool-riffle river systems because it is likely to over-estimate the typical sediment transport capacity. Conversely, the same recommendation is true for a section with backwater or eddies present or locations with localized influences near bridges or other man-made in-stream structures.

If a one-dimensional model is not available, then Manning's equation can be used to compute normal depth at a measured cross section. As a minimum, the channel width and maximum depth should be measured and channel geometry assumed (e.g. rectangular, trapezoidal, and triangular).

$$Q = \frac{c}{n} A \, R^{2/3} \, S_o^{1/2}$$

where

c = 1.486 for English units and 1.0 for S.I. units and

S_o = average longitudinal bottom slope of the channel.

For normal depth, the average bottom slope is assumed to be equal to average friction slope, S_f. By iteration, Manning's equation can be used to compute the cross-section flow depth for a given discharge, longitudinal slope, and channel roughness.

$$\frac{A^{5/3}}{P^{2/3}} = \frac{n\,Q}{c\,S_o^{1/2}}$$

Coarse reservoir sediment unit weight and particle size gradation

The coarse sediment mass is computed by multiplying the sediment volume by the unit weight (dry weight or mass per unit volume). The best source for obtaining the unit weight of reservoir sediment is by direct field measurement (ASTM D4823 - 95(2008) Standard Guide for Core Sampling Submerged, Unconsolidated Sediments, http://www.astm.org/Standards/D4823.htm). As an alternative, the unit weight can be assumed. Morris and Fan (1998) reported unit weights for various sizes of reservoir sediments for cases where the sediment is always submerged and the sediment exposed above the water (Table 5).

Table 5. Reservoir sediment unit weights reported by Morris and Fan (1988).

Dominant grain size	Always submerged	Exposed above water
Clay	40 to 60 lbs/ft^3	60 to 80 lbs/ft^3
Silt	55 to 75 lbs/ft^3	75 to 85 lbs/ft^3
Clay-silt mixture	40 to 65 lbs/ft^3	65 to 85 lbs/ft^3
Sand-silt mixture	75 to 95 lbs/ft^3	95 to 110 lbs/ft^3
Clay-silt-sand mixture	50 to 80 lbs/ft^3	80 to 100 lbs/ft^3
Sand	85 to 100 lbs/ft^3	85 to 100 lbs/ft^3
Gravel	85 to 125 lbs/ft^3	85 to 125 lbs/ft^3
Sand-gravel mixture	95 to 130 lbs/ft^3	95 to 130 lbs/ft^3

Laura and Pemberton (1982) and Bureau of Reclamation (2006) reported initial unit weights for clay, silt, and sand-sized reservoir sediment under different reservoir conditions (Table 6). The unit weights of clay and silt would be expected to increase over time as the sediments compact. Clay would be expected to compact the most. For older reservoirs, the unit weights for river conditions can be assumed.

Table 6. Initial unit weights of reservoir sediment reported by Lara and Pemberton (1982).

Reservoir Condition	Clay	Silt	Sand
Reservoir always full	26 lbs/ft^3	70 lbs/ft^3	97 lbs/ft^3
Reservoir periodically drawn down	35 lbs/ft^3	71 lbs/ft^3	97 lbs/ft^3
Reservoir normally empty	40 lbs/ft^3	72 lbs/ft^3	97 lbs/ft^3
River conditions	60 lbs/ft^3	73 lbs/ft^3	97 lbs/ft^3

The bed-material size gradation of the downstream channel is often coarser than the coarse reservoir sediment. When a thin layer of reservoir sediment is assumed to cover the downstream channel, the capacity to transport the reservoir sediment through the downstream channel can be computed. The transport capacity to move the existing bed-material sizes of the downstream river channel may be much less than the reservoir sediment and, therefore, is not a good indicator for the reservoir sediment mass.

Most sediment transport equations predict transport capacity for each grain size. Therefore, the coarse reservoir sediment mass should also be computed for each grain size.

Selection of a predictive sediment transport equation

Many sediment transport functions are available, each one specified for a certain range of sediment size and flow conditions (add reference). Computed results based on different transport equations can differ significantly from each other and from actual measurements. No universal equation exists which can be applied with accuracy to all sediment and flow conditions. Many predictive sediment transport equations have been programmed to facilitate their use (add example). Many federal agencies and universities have developed computer programs to compute sediment transport. For example, the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers have developed computer programs to compute sediment transport.

The choice of a predictive sediment transport equation depends primarily on the sediment particle grain size and on the experience of the user. Some predictive sediment transport equations that are often used for sand-sized sediment are listed below:

- Engelund and Hansen (1972),
- Ackers and White (1973),
- Yang (1973),
- Yang (1979),

Some predictive sediment transport equations that are often used for gravel-sized sediment are listed below:

- Wilcock and Crowe (2003),
- Parker (1990),
- Meyer-Peter and Müller (1948)
- Yang (1984)

Some predictive sediment transport equations that are often used for rivers with both sand and gravel-sized sediment are listed below:

- Parker (1990)
- Wilcock and Crowe (2003)
- Wu (2004)

*Note: Additional guidance will be provided on transport equation use in subsequent versions

Sediment Transport Capacity Computation Steps

*Work in project examples for each category either here or in main body of text

The sediment transport capacity of the downstream channel will be computed for certain discharge frequencies to classify the significance of the coarse reservoir sediment mass:

- Median discharge at time of dam removal (upper limit for negligible mass),
- 2-year flood hydrograph (upper limit for small mass),
- 10-year flood hydrograph (upper limit for medium mass), and
- 50-year flood hydrograph (upper limit for large mass and lower limit for very large mass).

The sediment transport capacity does not have to be computed for all of the above discharge frequencies, only the frequencies that bracket the coarse reservoir sediment mass. The first step is to estimate (using best judgment) the significance of the coarse reservoir sediment mass: Negligible, small, medium, large, or very large. Don't worry if the initial guess is wrong, because the following procedure will eventually determine the appropriate significance classification.

Negligible coarse sediment mass:

- Estimate the most likely season or month of dam removal.
- From the available streamflow data, compute the median discharge during the estimated time of dam removal.
- Determine the hydraulic properties for the median discharge at the cross section representing the downstream channel.
- Calculate the sediment transport capacity rate (for each grain size) at the median discharge. Multiply this transport capacity rate by one day to compute the sediment transport capacity mass.
- Compare the transport capacity mass with the coarse reservoir sediment mass for each grain size.
    - If the reservoir sediment mass is less than or equal to the transport capacity mass for each grain size, then the significance is negligible and no other transport capacity calculations are required. If the transport capacity mass is less than the reservoir mass in just a few of the coarsest grain sizes and if the reservoir mass that cannot be transported is less than 10 percent of the total reservoir mass, then the significance can still be considered negligible.
    - If the reservoir sediment mass is greater than the transport capacity mass, then the significance is at least small. The transport capacity of the 2-year flood needs to be computed to determine if the significance is small or large.

Small coarse sediment mass:

- From the available streamflow data or regional curve, determine the 2-year flood peak.
- Sort the available flood peak data and find the date where a flood peak occurred that is close in magnitude to the 2-year flood peak. Continue with the following steps:
    - Compute the ratio of the 2-year flood peak to the actual flood peak.

  - Find the measured hydrograph data (e.g., daily, hourly, 15 minute) associated with an actual flood, which is close to the 2-year flood peak. The hydrograph data should include the discharge values greater than the base flow just prior to and just after the 2-year flood. Do not use the instantaneous flood peak discharge because the duration may be too short and the transport capacity rate at this discharge may over estimate the transport capacity of the entire hydrograph. It is recommended to use hourly or 15-minute hydrograph data, if available, to provide an estimate of sediment transport.
  - Multiply the measured discharge hydrograph values by the ratio of the 2-year flood peak to the actual flood peak.
- Determine the hydraulic properties for each discharge of the 2-year flood hydrograph at the cross section representing the downstream channel.
- Using a suitable predictive equation, calculate the sediment transport capacity rate for each discharge of the 2-year flood hydrograph and multiply these transport capacity rates by the hydrograph time step. Sum the transport capacity mass for each discharge of the hydrograph to compute the transport capacity mass for the entire hydrograph.
- Compare the 2-year flood transport capacity mass with the coarse reservoir sediment mass for each grain size.
  - If the reservoir sediment mass is less than or equal to the 2-year flood transport capacity mass for each grain size, then the significance is small. The coarse sediment transport capacity for the median discharge may need to be computed to determine if the coarse sediment mass is negligible.
  - If the reservoir sediment mass is greater than the 2-year flood transport capacity mass, then the significance is at least medium. The transport capacity of the 10-year flood needs to be computed to determine if the significance is large or very large.

Medium coarse sediment mass:

- From the available streamflow data or regional curve, determine the 10-year flood peak.
- If streamflow data are available, sort the flood peak data and find the date where a flood peak occurred that is close in magnitude to the 10-year flood peak. Continue with the following steps:
  - Compute the ratio of the 10-year flood peak to the actual flood peak.
  - Find the measured hydrograph data (e.g., daily, hourly, 15 minute) associated with the actual flood, which is close to the 10-year flood peak. The hydrograph data should include the discharge values greater than the base flow prior to and after the 10-year flood. Do not use the instantaneous flood peak discharge because the duration may be too short and the transport capacity rate at this discharge may over estimate the transport capacity of the entire hydrograph. The use hourly or 15-minute hydrograph data, if available, will provide the most accurate estimate.
  - Multiply the measured discharge hydrograph values by the ratio of flood peaks.

- Determine the hydraulic properties for each discharge of the 10-year flood hydrograph at the cross section representing the downstream channel.
- Using a suitable predictive equation, calculate the sediment transport capacity rate for each discharge of the 10-year flood hydrograph and multiply these transport capacity rates by the hydrograph time step. Sum the transport capacity mass for each discharge of the hydrograph to compute the transport capacity mass for the entire hydrograph.
- Compare the 10-year flood transport capacity mass with the coarse reservoir sediment mass for each grain size.
    - If the reservoir sediment mass is less than or equal to the 10-year flood transport capacity mass for each grain size, then the significance is medium. The coarse sediment transport capacity for the 2-year flood hydrograph may need to be computed to determine if the coarse sediment mass is small.
    - If the reservoir sediment mass is greater than the 10-year flood transport capacity mass, then the significance is at least large. The transport capacity of the 50-year flood needs to be computed to determine if the significance is very large.

Large coarse sediment mass:

- From the available streamflow data or regional curve, determine the 50-year flood peak.
- If streamflow data are available, sort the flood peak data and find the date where a flood peak occurred that is close in magnitude to the 50-year flood peak. Continue with the following steps:
    - Compute the ratio of the 50-year flood peak to the actual flood peak.
    - Find the measured hydrograph data (e.g., daily, hourly, 15 minute) associated with the actual flood, which is close to the 50-year flood peak. The hydrograph data should include the discharge values greater than the base flow prior to and after the 50-year flood. Do not use the instantaneous flood peak discharge because the duration may be too short and the transport capacity rate at this discharge may over estimate the transport capacity of the entire hydrograph. The use hourly or 15-minute hydrograph data, if available, will provide the most accurate estimate.
    - Multiply the measured discharge hydrograph values by the ratio of flood peaks.
- Determine the hydraulic properties for each discharge of the 50-year flood hydrograph at the cross section representing the downstream channel.
- Using a suitable predictive equation, calculate the sediment transport capacity rate for each discharge of the 50-year flood hydrograph and multiply these transport capacity rates by the hydrograph time step. Sum the transport capacity mass for each discharge of the hydrograph to compute the transport capacity mass for the entire hydrograph.
- Compare the 50-year flood transport capacity mass with the coarse reservoir sediment mass for each grain size.

- If the reservoir sediment mass is less than or equal to the 50-year flood transport capacity mass for each grain size, then the significance is large. The coarse sediment transport capacity for the 10-year flood hydrograph may need to be computed to determine if the coarse sediment mass is medium.
- If the reservoir sediment mass is greater than the 50-year flood transport capacity mass, then the significance is very large and no other transport calculations are needed for classification.

Appendix E: Tips on Collecting a Representative Set of Sediment Samples for a Dam Removal Project

Written by Joe Rathbun

Characterizing the composition and possible contamination of reservoir sediments can be a great challenge. The reservoir sediments are generally not visible (unless the reservoir is first dewatered) and so they must be assessed and sampled remotely. Particle sizes and contaminant distributions can be highly heterogeneous. The history of land use, contaminant discharges, and dam operation all influence the magnitude and extent of sediment contamination, but are not always known. Steps to improve the representativeness; that is, how well the collected samples represent the true magnitude and extent of contaminant distribution; of a sediment quality survey are described below.

It is strongly recommended that a qualitative "probing" reconnaissance survey be conducted prior to designing a quantitative survey and collecting sediment samples. If water levels are shallow enough to wade or work from a small boat, a long piece of rebar, a soil auger, or a thin metal tube (~ 2" in diameter) can be used to both measure the depth of the unconsolidated sediments and qualitatively assess their grain size (clay, silt, sand, and gravel/cobble "feel" differently when probed). If the reservoir is deeper (> 10 feet), a grab sampler or gravity corer can be used to collect samples for visual assessment. Simultaneous collection of geographic coordinates allows the creation of a map of sediment type.

To design a more quantitative sediment sampling survey that is representative of *in situ* conditions, the following three factors must be considered:

1. How the samples will be collected
2. How many samples will be collected
3. Where the samples will be collected

MacDonald and Ingersoll (2002) provide a good introduction to these topics, and a brief summary of these three factors is below.

The two principal types of sediment samplers are grab samplers and core samplers. The local regulatory agency may require one or the other, or both, depending on site conditions such as the depth of unconsolidated sediments behind the dam. Both samplers work best (i.e. penetrate deepest) in silty sediment, usually work well in unconsolidated sand, and do not efficiently sample dense clay or gravel/cobble. Grab samplers (e.g., Ponar or Ekman samplers) collect the surficial 6-8 inches (maximum) of unconsolidated sediment. Core samplers collect 2 to 4 inch diameter cores from 2 feet to over 15 feet long, depending on the coring device used and the compaction of the sediments. There are several types of sediment core samplers, and those most commonly used in reservoirs are hand cores, gravity cores, and vibrocores.

The number of samples to collect is often prescribed by the local regulatory agency. This document recommends:

- Performing a screening level survey of 3 to 4 cores if the reservoir sediment is less than 10,000 cubic yards (Step 4c), unless local regulations say otherwise.
- Performing a definitive survey of 1 core per 1,000 cubic yards if the reservoir sediment is less than 10,000 cubic yards (Step 4d), unless local regulations say otherwise.

In many instances, best professional judgment (BPJ) also plays a role in deciding how many samples to collect. Factors to consider when exercising BPJ include expected sediment deposition patterns (which will be known if a probing survey has been performed), expected contaminant spatial heterogeneity (considering location of contaminant sources, location of fine-grained sediment deposits, prior sediment removals or reservoir flushing, the physiochemical properties of the contaminant(s) of interest, etc.), and the possible fate of the sediment (left in-place, removed, or allowed to transport downstream).

A more quantitative approach is to use geostatistical calculations to estimate the number of samples needed to detect a contaminant 'hot spot' of a certain size with a known certainty. A useful, and free, geostatitical program is Elipgrid, which is included in the U.S. Department of Energy's Visual Sampling Plan software package, available at:

http://vsp.pnl.gov/

An example of the results of the Elipgrid calculations is given in the box below. As expected, detecting small contaminant hot spots with high confidence can require a very large number of samples; hence, the popularity of BPJ.

Scenario	Hot Spot Radius (m)	Required # of Samples
• Canals on Lake St. Clair, MI • Surface area = 21,700 m^2 (~ 6 football fields) • Assume a square grid, and desire 95% confidence of detecting a circular hot spot • Calculate how many samples for different hot spot sizes	1 5 10 15 20	7,787 312 78 35 20

The results of the probing survey will greatly assist in deciding where to collect sediment samples; generally preference is given to fine-grained, highly organic sediments. The four most commonly used sampling strategies in sediment quality studies are:

- Simple random sampling
- Systematic grid sampling

- Subjective sampling (where known or suspected contaminant sources influence the selection of sampling points)
- Stratified random sampling

Gilbert (1987) gives an excellent discussion of these and other sample collection strategies.

While all four strategies can be useful in sediment quality studies (box, below), stratified random sampling is often recommended because sediments in reservoirs often exhibit distinct "strata"; e.g., fine-grained organic sediments near the dam and along the edges of the reservoir, and coarser sediment in the upstream end of the reservoir.

Known or Suspected Contaminant Distribution	Recommended Strategy
Random and uniform	Random sampling
Known strata	Stratified random sampling
Known hot spots	Subjective sampling
Linear trends, or mapping of data important to project	Systematic grid sampling

In addition to sampling sediments within the reservoir, it is often desirable (and sometimes required) to also collect a few samples from upstream and/or downstream of the reservoir. These samples provide a "local background" against which to compare the reservoir samples.

References

Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold, New York, NY. 320 pp.

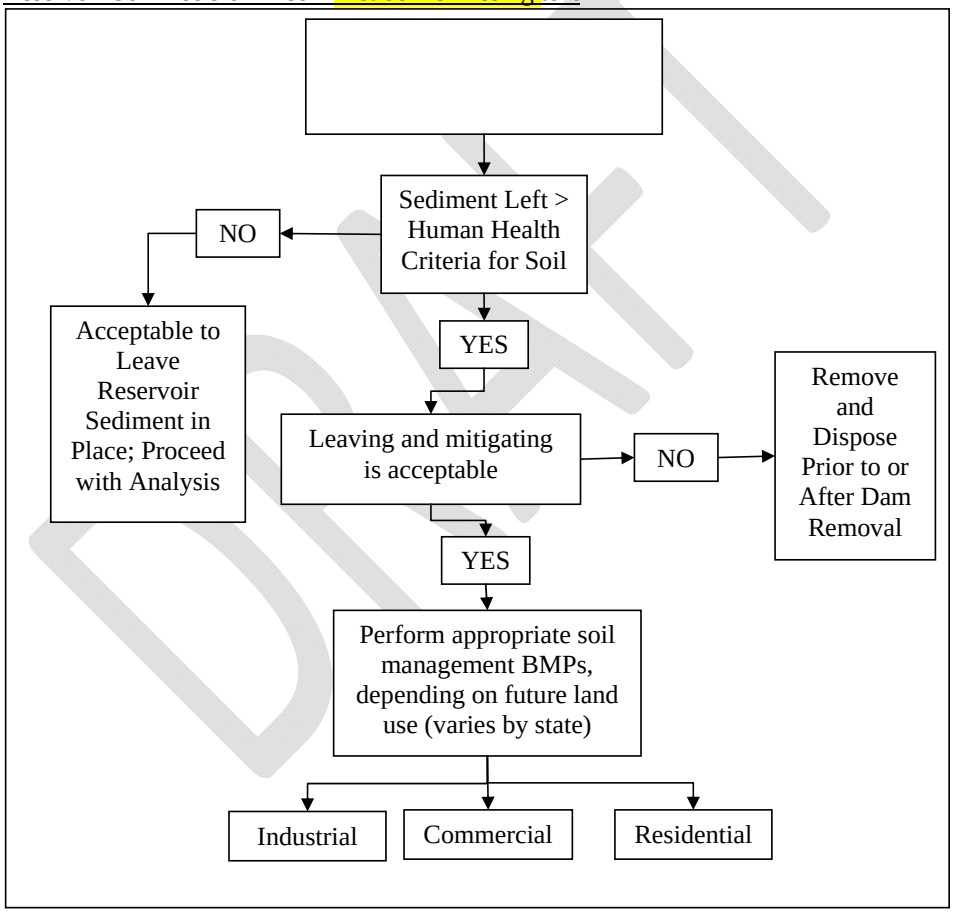
MacDonald D.D., and C.G. Ingersoll. 2002. *A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater Ecosystems. Volume II: Design and Implementation of Sediment Quality Investigations*, (PDF) EPA-905-B02-001-B, USEPA Great Lakes National Program Office, Chicago, IL. 136 pp.

Appendix F: Sample Contaminant Flow Charts to Assist With Impact Evaluation

The purpose of this appendix is to provide sample decision trees that may assist with determining what sediment management plan is acceptable when contaminated sediment is present in the reservoir deposit.

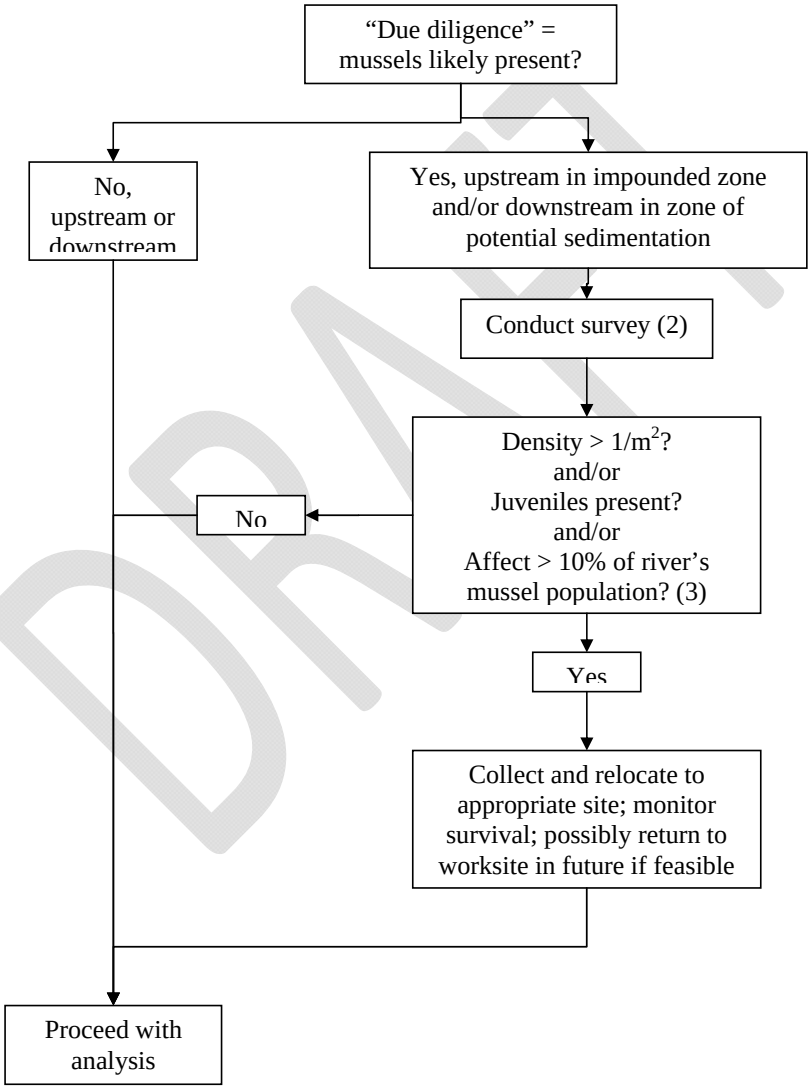
Step C1: If dam removal and sediment management plan expect to leave contaminated sediment in the reservoir, evaluate reservoir soil decision tree, if not continue to Step C2.

Reservoir Soil Decision Tree – first box is missing text



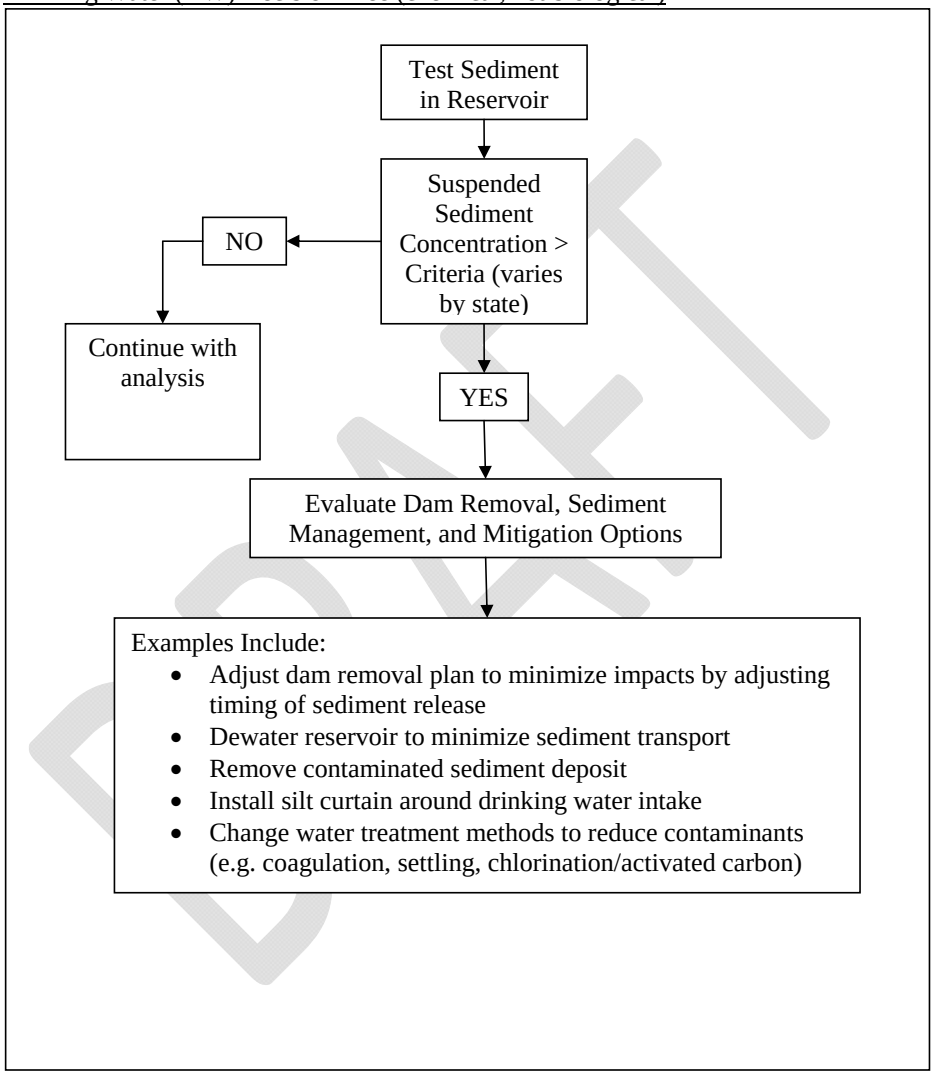
Step C2: If contaminated sediment is planned to be released into the downstream river channel, evaluate the potential impact on aquatic biota (endangered, threatened, or other sensitive species). If impacts are tolerable and contaminated sediment will still be released, continue to Step C3.

Aquatic biota decision tree
Example decision tree for mussels



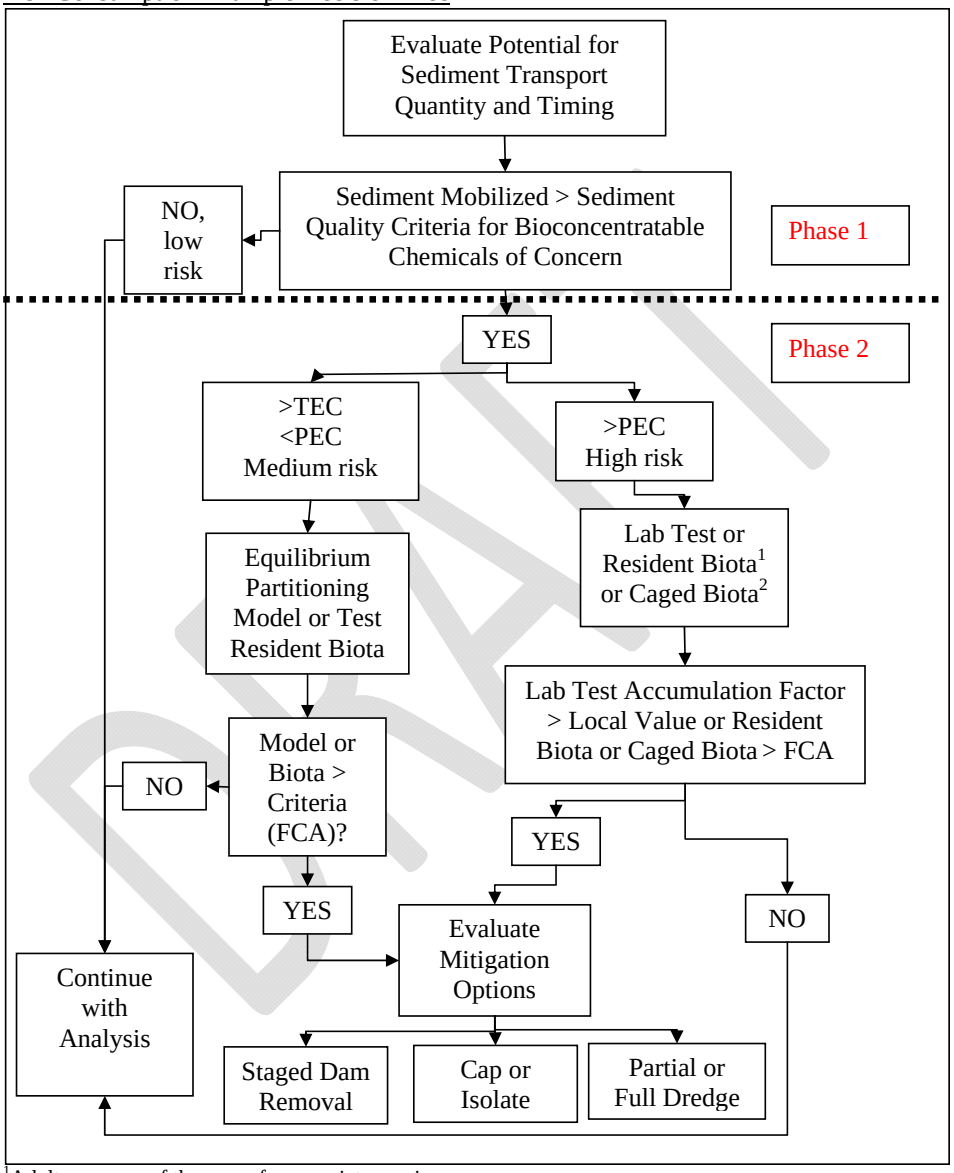
Step C3: If contaminated sediment is planned to be released into the downstream river channel, evaluate potential impact to drinking water.

Drinking Water (DW) Decision Tree (chemical, not biological)



Step C4: If contaminated sediment is planned to be released into the downstream river channel, evaluate potential impact to drinking water.

Fish Consumption Example Decision Tree



[1]Adult or young of the year of appropriate species
[2] Young of the year of appropriate species
FCA = fish consumption advisory
TEC = threshold effects concentration
PEC = probable effects concentration

Appendix G: Reservoir Trap Efficiency

Information is referenced from Chapter 2 of the Erosion and Sedimentation Manual produced by the Bureau of Reclamation (Reclamation, 2006).

The amount of sediment deposited within a reservoir depends on the trap efficiency. Reservoir trap efficiency is the ratio of the deposited sediment to the total sediment inflow and depends primarily upon the fall velocity of the various sediment particles, flow rate and velocity through the reservoir (Strand and Pemberton, 1982), as well as the size, depth, shape, and operation rules of the reservoir. The particle fall velocity is a function of particle size, shape, and density; water viscosity; and the chemical composition of the water and sediment. The rate of flow through the reservoir can be computed as the ratio of reservoir storage capacity to the rate of flow. The potential for reservoir sedimentation and associated problems can be estimated from the following six indicators:

- The reservoir storage capacity (at the normal pool elevation) relative to the mean annual volume of riverflow.
- The average and maximum width of the reservoir relative to the average and maximum width of the upstream river channel.
- The average and maximum depth of the reservoir relative to the average and maximum depth of the upstream river channel.
- The purposes for which the dam and reservoir are to be constructed and how the reservoir will be operated (e.g., normally full, frequently drawn down, or normally empty).
- The reservoir storage capacity relative to the mean annual sediment load of the inflowing rivers.
- The concentration of contaminants and heavy metals being supplied from the upstream watershed.

The ratio of the reservoir capacity to the mean annual streamflow volume can be used as an index to estimate the reservoir sediment trap efficiency. A greater relative reservoir size yields a greater potential sediment trap efficiency and reservoir sedimentation. Churchill (1948) developed a trap efficiency curve for settling basins, small reservoirs, flood retarding structures, semi-dry reservoirs, and reservoirs that are frequently sluiced.

Using data from Tennessee Valley Authority reservoirs, Churchill (1948) developed a relationship between the percent of incoming sediment passing through a reservoir and the sedimentation index of the reservoir (Figure 2.19). The sedimentation index is defined as the ratio of the period of retention to the mean velocity through the reservoir. The Churchill curve has been converted to a dimensionless expression by multiplying the sedimentation index by *g*, acceleration due to gravity.

The following description of terms will be helpful in using the Churchill curve:

Capacity—Capacity of the reservoir in the mean operating pool for the period to be analyzed in cubic feet.

Inflow—Average daily inflow rate during the study period in cubic feet per second.

Period of retention—Capacity divided by inflow rate.

Length—Reservoir length in feet at mean operating pool level.

Velocity—Mean velocity in feet per second, which is arrived at by dividing the inflow by the average cross-sectional area in square feet. The average cross-sectional area can be determined from the capacity divided by the length.

Sedimentation index—Period of retention divided by velocity.

Brune (1953) developed an empirical relationship for estimating the long-term reservoir trap efficiency for large storage or normal pond reservoirs based on the correlation between the relative reservoir size and the trap efficiency observed in Tennessee Valley Authority reservoirs in the southeastern United States (see Figure 2.19). Using this relationship, reservoirs with the capacity to store more than 10 percent of the average annual inflow would be expected to trap between 75 and 100 percent of the inflowing sediment. Reservoirs with the capacity to store 1 percent of the average annual inflow would be expected to trap between 30 and 55 percent of the inflowing sediment. When the reservoir storage capacity is less than 0.1 percent of the average annual inflow, then the sediment trap efficiency would be near zero.

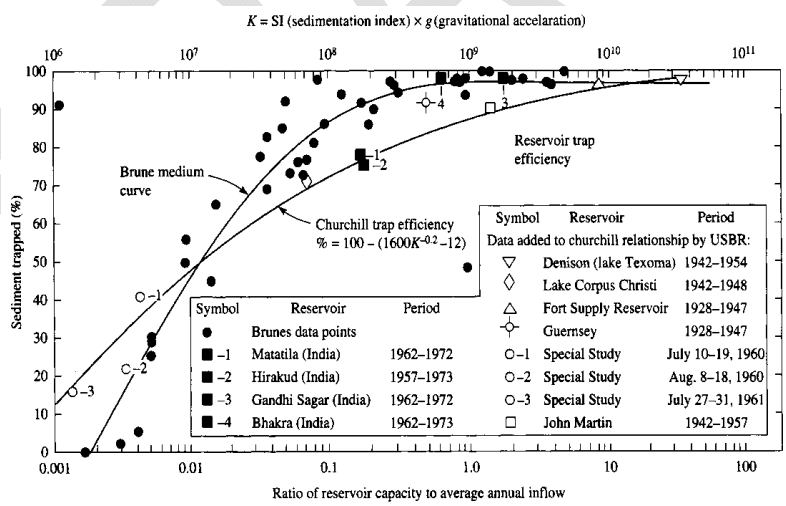


Figure 4. Trap efficiency curves (Churchill, 1948; Brune, 1953).

Figure 4 provides a good comparison of the Brune and Churchill methods for computing trap efficiencies using techniques developed by Murthy (1980). A general guideline is to use the Brune method for large storage or normal ponded reservoirs and the Churchill curve for settling

basins, small reservoirs, flood retarding structures, semi-dry reservoirs, or reservoirs that are continuously sluiced. When the anticipated sediment accumulation is larger than 10 percent of the reservoir capacity, it is necessary that the trap efficiency be analyzed for incremental periods of the reservoir life.

The width and depth of the reservoir, relative to the width and depth of the upstream river channel, can also serve as indicators of reservoir sedimentation. Even if the reservoir capacity is small, relative to the mean annual inflow, a deep or wide reservoir may still trap some sediment.

The purpose for which a dam is constructed, along with legal constraints and hydrology, determine how the reservoir pool will be operated. The operation of the reservoir pool will influence the sediment trap efficiency and the spatial distribution and unit weight of sediments that settle within the reservoir. The reservoir trap efficiency of a given reservoir will be greatest if substantial portions of the inflows are stored during floods when the sediment concentrations are highest. If the reservoir is normally kept full (run of the river operation), flood flows pass through the reservoir and sediment trap efficiency is reduced. Coarse sediments would deposit as a delta at the far upstream end of the reservoir. When reservoirs are frequently drawn down, a portion of the reservoir sediments will be eroded and transported father downstream. Any clay-sized sediment that are exposed above the reservoir level will compact as they dry out (Strand and Pemberton, 1982).

Once sediment capacity is reached, the entire sediment load supplied by the upstream river channel is passed through the remaining reservoir. For example, the pool behind a diversion dam is typically filled with sediment within the first year or two of operation. For a large reservoir like Lake Powell, the average annual sediment inflow is 0.1 percent of the reservoir storage capacity.

If contaminants and heavy metals are transported into a reservoir, they will likely settle with the sediments in the reservoir. This may improve the water quality of the downstream river, but the water quality in the reservoir may degrade over time as the concentrations of contaminants and metals accumulate.

Once the estimated sediment inflow to a reservoir has been established, attention must be given to the effect the deposition of this sediment will have upon the life and daily operation of the reservoir (Strand and Pemberton, 1982). The mean annual sediment inflow, the trap efficiency of the reservoir, the ultimate density of the deposited sediment, and the distribution of the sediment within the reservoir all must be considered in the design of the dam.

Usually, to prevent premature loss of usable storage capacity, an additional volume of storage equal to the anticipated sediment deposition during the life of the reservoir is included in the original design. Reclamation has designed reservoirs to include sediment storage space whenever the anticipated sediment accumulation during the period of project economic analysis exceeds 5 percent of the total reservoir capacity (Strand and Pemberton, 1982). A 100-year period of economic analysis and sediment accumulation was used for those reservoirs. The allocated sediment space is provided to prevent encroachment on the required conservation storage space for the useful life of the project.

A schematic diagram of anticipated sediment deposition (figure???) shows the effect of sediment on storage. A distribution study with 100-year area and capacity curves similar to those shown on the left side of Figure 2.20 is needed whenever the 100-year sediment accumulation is more than 5 percent of the total reservoir capacity. In operational studies of a reservoir for determining

the available water supply to satisfy projected water demands over the project life, an average can be used for the sediment accumulation during the economic life period. However, the total sediment deposition is used for design purposes to set the sediment elevation at the dam, to determine loss of storage due to sediment in any assigned storage space, and to help determine total storage requirements.

Anticipated reservoir sediment deposition diagram?

Template from case study in appendix?

	Generic Matrix Table for Probability, Consequence, and Risk				
Potential Sediment Impacts to Resources	**Reach of concern**	**Timing or Season of Concern**	**Probability (Sediment Volume)**	**Consequence (User Input)**	**Risk (use table X)**
Fish passage	Reservoir tributaries; at dam	All year	Large	High	High +
Habitat (finer substrate)					
Ecosystem Examples					
Increased suspended sediment concentration and turbidity					
Release of contaminants during reservoir sediment erosion					
Changes in water temperature due to loss of reservoir pool					
Other					
Infrastructure and Property Examples					
Burial of intakes					
Streambank erosion					
Flooding increase					
Other					
Socio-Economic Examples					
Fast-water recreation access and availability					
Slow-water recreation access and availability					

Reservoir restoration (vegetation and topography)					
Other					
Cultural and Historic Examples					
Loss or restoration of traditional and cultural properties					
Loss or preservation of historic properties					
Other					