# GUIDELINES FOR ASSESSING SEDIMENT-RELATED EFFECTS OF DAM REMOVAL

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**Abstract** Dam removal is becoming more common in the United States as dams age and environmental concerns increase. Sediment management is an important part of many dam removal projects, but there are no commonly accepted methods to assess the level of risk associated with sediment stored behind dams. Therefore, the interagency Subcommittee on Sedimentation (SOS) is sponsoring the development of a decision framework for assessing sediment-related effects from dam removals.

The decision framework provides guidance on the level of sediment data collection, analysis, and modeling needed for reservoir sediment management. The framework is based on criteria which scale the characteristics of the reservoir sediment to sediment characteristics of the river on which the reservoir is located. To assist with the framework development, workshops of invited technical experts from around the United States were convened October 2008 in Portland, Oregon and October 2009 in State College, Pennsylvania. The decision framework developed at these workshops is currently being validated with actual dam-removal case studies from across the United States including small, medium, and large reservoir sediment volumes. This paper provides the latest thinking on key components of the guidelines. The paper represents contributions from over 26 entities who have participated in the development of the guidelines. After completion of the case study application, the framework will be finalized and published.

## INTRODUCTION

The interagency Subcommittee on Sedimentation has recognized that some dams no longer serve the purpose for which they were constructed. For example, when a dam has significantly deteriorated, the costs of repair may exceed the expected benefits and dam removal may be a less expensive alternative. If fish cannot adequately pass upstream of the dam and reservoir, the cost of adequate fish passage facilities might exceed the project benefits and dam removal may be a less expensive alternative. Some dams and reservoirs may inundate important cultural or historic properties and dam removal may restore those properties. Along some rivers, the demand for white-water recreation might be a compelling reason to remove a dam.

The management of reservoir sediment is often an important and controlling issue related to dam removal decisions. Sediment erosion, transport, and deposition are likely to be among the most important physical effects of dam removal. The sediment-related impacts associated with dam decommissioning can occur in the reservoir and in the river channel, both upstream and downstream from the reservoir. Depending on the local conditions and the decommissioning alternative, the degree of sediment impact can range from negligible to very large.

**Need for Guidelines** The total number of dams in the United States is not known. A U.S. National Inventory of Dams website is hosted by U.S. Army Corps of Engineers for 2007 data.

This inventory has identified slightly more than 80,000 dams that are at least 25 feet (7.6 m) high, store at least 50 acre-feet (64,000 $m^3$), or are considered a significant hazard if they fail. Of the dams in the inventory, less than 2 percent are over 100 ft (30 m) high and about half are less than 25 ft (7.6 m). The most common purposes of dams and reservoirs are the management of water supply for industrial, municipal, and agricultural uses; flood control; recreation; and power generation. Dams and reservoirs also provide benefits for wildlife and fishery enhancement. In the last 2 to 3 decades, dam decommissioning has become an option for dam owners to consider when the dam no longer meets its original purpose, or the benefits of dam removal outweigh the lost benefits and costs to maintain the dam's operations.

When dam removal is being considered, the following questions often arise:

- What will the reservoir look like following dam removal?
- How long will it take for reservoir sediments to erode following dam removal?
- What short and long-term impacts are expected along the downstream river channel if sediments are allowed to erode from the reservoir?
- Are special sediment management actions needed during dam removal to reduce impacts?

Several useful publications have been produced on the subject of dam removal:

- American Society of Civil Engineers (1997).
- Aspen Institute (2002).
- H. John Heinz III Center for Science, Economics, and the Environment (2002).
- U.S. Department of the Interior, Bureau of Reclamation (2006).

In the past, there has been a wide range of sediment data collection, analysis, and decisions made related to sediment management for dam removal. On each dam removal project, individuals or regulating agencies may have their own thresholds on what constitutes significant sediment impacts, and what level of information is needed to make decisions. Existing manuals do not provide users a framework or guideline for determining level of analysis needed, significance of sedimentation issues, or certainty that can be attained with analysis tools.

The Subcommittee on Sedimentation has recognized the need for a national sediment analysis guideline for dam removal investigations. In order to meet this need, the Subcommittee formed a workgroup to convene workshops of national experts and prepare these dam removal sediment analysis guidelines. The merits of dam removal have to be determined by stakeholders on a case-by-case basis. The Subcommittee on Sedimentation is only providing technical guidance and makes no endorsement on the merits of dam removal.

**Subcommittee on Sedimentation** The Subcommittee on Sedimentation (SOS) is comprised of representatives from eleven Federal Agencies and four University and Professional Organizations. SOS reports to the Federal Advisory Committee on Water Information, (ACWI) which in turn reports to the U.S. Department of the Interior, Assistant Secretary for Water and Science (See http://acwi.gov/sos/index.html for a list of specific member organizations and more information).. The long-term goals and objectives of the SOS are listed below:

- 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.

**Guideline Objectives** The objectives of the guidelines are listed below:

- Provide guidance on the type and level of data collection, analyses, modeling, and monitoring necessary to assess dam removal impacts related to sediment.
- Provide guidance on how to scale the level of assessment with scale of the reservoir sediment volume.
- Provide guidance on how to adjust the dam removal and sediment management alternatives so that effects are acceptable to local stakeholders and decision makers.

**Intended Use of Guidelines** The guidelines are intended to be a planning-level document to assist with determining how to analyze sediment impacts associated with a wide range of potential dam removals (Figure 1) with a wide range of sediment issues (Figure 2). The document is not intended to provide direct answers, but provides questions that need to be answered to determine the sediment impacts. Suggested data collection and analysis methods to answer these questions are scaled with the reservoir sediment mass and the sediment loads of the river channel. The guidelines are not intended to be a regulatory document. The guidelines may be used to inform state and local regulatory agencies, but the guidelines are not intended to place requirements on such agencies.

Gold Hill Dam on the Rogue River near Gold Hill, OR

Matilija Dam on Matilija Creek near Ventura, CA

Elwha Dam on the Elwha River near Port Angeles, WA

Savage Rapids Dam on the Rogue River near Grant Pass, OR

Chiloquin Dam on the Sprague River near Chiloquin, OR

Glines Canyon Dam on the Elwha River near Port Angeles, WA

Figure 1 The guidelines will be applicable to a wide variety of dam removal projects.

Reservoir sediment behind Matilija Dam


Reservoir sediment in Lake Mills behind Glines Canyon Dam

Former site of Savage Rapids Dam


Former site of Chiloquin Dam

Figure 2 The guidelines will be applicable to a wide variety of sediment management issues.

## GUIDELINE DEVELOPMENT PROCESS

A SOS workgroup developed the dam removal sediment analysis guidelines for sediment by convening two workshops of invited experts from around the United States:

1. October 14–16, 2008 in Portland, Oregon
2. October 27–29, 2009 in State College, Pennsylvania

Although these guidelines primarily focus on the physical impacts of dam removal related to sediment, they also address linkages to water quality and effects on the aquatic environment. Therefore, biologists and water quality experts were invited to the workshops in addition to hydraulic engineers and geomorphologists. Workshop participants represented 26 entities that have been involved in planning or analyzing dam removal projects including federal, state, academic, private, non-profit, and local resource managers.

Prior to the first workshop, the Subcommittee workgroup produced documents detailing the workshop agenda and logistics and draft decision flowcharts to determine the scale of the reservoir sediment mass and prediction of impacts corresponding to this scale. The first draft of the guidelines began with a two-tiered analysis decision tree:

1. Assess the scope of the sediment problem.

2. Predict the sediment impacts that will result from the dam removal.

The first day's agenda of each workshop included introductions, objectives, technical presentations, and a field trip, which were all designed to get everyone thinking about dam removal and reservoir sediment analysis and management.

The first workshop was held at Portland State University in Portland, Oregon (October 14-16, 2008) and included a field trip to the site of the former Marmot Dam on the Sandy River in Oregon (Wallick and Randle, 2009). This first workshop was led and organized by following organizations and individuals:

- U.S. Bureau of Reclamation
  - Tim Randle
  - Blair Greimann
  - Jennifer Bountry
- U.S. Geological Survey
  - Rose Wallick
  - Chauncey Anderson
  - Jon Major

The first workshop divided participants into three teams to address the following sediment impact categories:

- Reservoir sediment erosion and redistribution (team led by Peter Downs)
- Downstream sediment transport and deposition (team led by Will Graf)
- Water quality changes and impacts on biologic resources (team led by Chauncey Anderson)

The first workshop produced the draft decision criteria for the analysis guidelines. The SOS Workgroup produced draft guidelines and e-mailed them to workshop participants for their review and comment prior to the second workshop.

The second workshop was held at and near Pennsylvania State University in State College, Pennsylvania (October 27-29, 2009) and was convened to test and improve the draft guidelines by applying them to 20 case studies in small groups of four to five participants. These small groups were able to concurrently test the guidelines on case studies and report findings to the large group. This second workshop included a field trip to the former site of McCoy Dam on Spring Creek and Reedsville Mill Dam on Tea Creek. The second workshop was led and organized by following organizations and individuals:

- U.S. Bureau of Reclamation
  - Tim Randle
  - Jennifer Bountry
- Pennsylvania Fish and Boat Commission
  - Scott Carney
- Advisors
  - Laura Wildman (Princeton Hydro)
  - Joe Rathbun (Michigan Department of Environmental Quality)

The review and discussion from the second workshop produced many valuable improvements to the guidelines. The next major steps are for the SOS Workgroup to incorporate the comments obtained at the second workshop, retest the updated guidelines, and obtain independent peer review. The plan is to seek SOS and ACWI review during the later part of 2010.

## GUIDELINE PROCUDURES

The guideline procedures are still a work in progress, but the procedural steps evaluated at the second workshop are summarized below.

**Step 1: Reconnaissance of dam history, watershed context, and sediment concerns.** Several reconnaissance questions are provided to help guide the initial data collection for a dam removal and sediment analysis study. The level of effort needed to answer these questions would depend on the size and complexity of the project. The user of the guidelines is advised to use simple, but accurate, data collection methods to gather background information and gain a reasonable perspective of historical and present conditions of the watershed, dam, and reservoir. In step 1a, more than a dozen questions are provided concerning the dam and reservoir history and their context within the watershed. In step 1b, several questions are provided about the local impact concerns to help decision makers ascertain the consequence of any potential sediment impacts. Risk can be defined as the product of the probability of a particular impact and the consequence or cost associated with that impact.

The probability, consequence, and resulting risk of sediment impacts should be periodically reassessed throughout the analysis process to help determine the level of accuracy needed to make decisions. Project managers, engineers, and stakeholders should work together to define the consequence or cost of particular dam removal and sediment management actions.

**Step 2: Characterize the reservoir sediment deposit.** The purpose of this step is to make a determination of the reservoir sedimentation volume, mass, spatial distribution, and particle size gradation. This is a critical step in the analysis guidelines because it is used to determine the scale of the reservoir sediment mass. More effort would be needed to characterize a large reservoir sediment mass than a small sediment mass, so an initial estimate is needed to guide the data collection efforts. Several questions are provided in this step to help determine if there is likely to be a small or large reservoir sediment mass. If the ratio of reservoir width to channel width is less than 1.5, then the reservoir sediment volume can potentially be estimated by extrapolating upstream and downstream river slopes through the reservoir and then calculating reservoir sediment volume as a wedge. For ratios greater than 1.5, the data collection effort to determine sediment volume should be scaled to the level of perceived risk of sediment impacts.

**Step 3: Contaminant Concerns?** Contaminated reservoir sediments could have a major effect on dam removal and sediment management plans. For example, contaminated reservoir sediment may have to be mechanically removed or stabilized in place to prevent release into the downstream channel. All or a portion of the dam may be left in place to help stabilize the reservoir sediment. The significance of contaminants in the reservoir sediment would depend on their concentration relative to background levels and their risk to the human and aquatic environment if released downstream.

Determining if contaminants may be present in the reservoir sediment begins with an examination of the historical land use activities, in the watershed upstream from the dam, which would have potentially contributed to contaminants within the reservoir. A historical examination may suggest that there are no likely sources of contaminants or the examination may suggest likely sources and types contaminants that may be present in the reservoir. A historical examination of dam and reservoir operations may suggest if contaminants were likely trapped within the reservoir sediments or if such contaminants would have been flushed downstream.

The significant presence of silt or clay-sized reservoir sediments could be a potential indicator of contaminants because contaminants are typically associated with these finer-sized sediment particles. However, there are examples where contaminants have been associated with sand and gravel-sized sediments. Therefore, the likelihood of contaminated reservoir sediments is primarily determined from the watershed investigation rather than the particle size.

If the watershed investigation concludes that the reservoir sediments may be contaminated, then an initial sampling program is recommended to test for the presence of contaminates. If the presence of contaminates is confirmed, then additional sampling is recommended to determine the full extent.

**Step 4: Determine the scale of the coarse and fine reservoir sediment volumes.** The significance of the reservoir sediment volume is based on the ability of the stream to transport the sediment mass. If the stream has the capability to rapidly transport and disperse the reservoir sediment along the downstream channel, then the significance of the reservoir sediment volume is small. The reservoirs behind some dams are so small, relative to their stream channel, that essentially no sediments are trapped and the significance would be negligible. However, if the reservoir sediment mass were large relative to the sediment transport capability of the downstream channel, then the significance of the reservoir sediment volume would be large because channel aggradation or high and sustained suspended sediment concentrations may occur.

Sand and gravel-sized reservoir sediment that are released to the downstream channel would typically be transported as bed-material load, while silt and clay-sized sediment would typically be transported as wash load. Therefore, the coarse reservoir sediment mass (sand and gravel) should be scaled separately than the fine reservoir sediment mass (silt and clay).

Objective criteria to scale the coarse reservoir sediment mass include the average annual sediment load or the sediment load of the 2-year flood (Equation 1). The sediment transport capacity of the stream could be computed to represent the sediment load. An order of magnitude scaling to these criteria would be a useful way to classify the significance of the coarse or fine reservoir sediment volume or mass (Table 1).

$$Scale = \frac{M}{Q_s} \tag{1}$$

where $M$ = mass of coarse or fine reservoir sediment
$Q_s$ = average annual sediment load or the sediment load of the 2-year flood,
$Scale_s$ = numerical scale or non-dimensional value of the coarse or fine reservoir sediment mass.

Table 1 Scale of coarse or fine reservoir sediment mass and classification.

| Reservoir Sediment Classification | Reservoir Sediment Scale |
|---|---|
| Small | $0.01 < Scale \leq 0.1$ |
| Medium | $0.1 < Scale \leq 10$ |
| Large | $10 < Scale$ |

Simplified methods will be provided to determine negligible classifications that do not require sediment transport calculations.

Determining the sediment load or transport capacity of the 2-year flood would require less discharge data, and perhaps less effort, than determining the average annual sediment load or transport capacity. However, for streams where the 2-year flood peak may be significantly greater than the mean-daily discharge, the time-step discretization and duration of the 2-year flood hydrograph would be an important and sensitive consideration. The use of mean-daily discharge values for decades of stream flow, combined with a sediment-discharge rating curve, would be an objective method to compute the average annual sediment load.

Sediment load measurements are ideal for scaling the reservoir sediment mass when such data are available. The average annual coarse sediment load can be computed directly from the coarse reservoir sediment mass if the period of reservoir sedimentation is known. The computation of sediment transport capacity for bed-material load is the only alternative when measured loads are not available and the period of reservoir sedimentation is not known. For streams where the sediment transport capacity is significantly greater than the supply, the use of the transport capacity would better indicate the downstream channel response.

The sediment transport capacity for fine reservoir sediment that would be transported as wash load is typically much greater than the supply and predictive equations are not readily available. If suspended sediment load measurements are not available for fine reservoir sediment on the stream of interest, the next best alternative may be to estimate the annual fine sediment load from the following data:

- Fine reservoir sediment mass
- Estimated period of reservoir sedimentation (use one year if not otherwise known)
- Estimated reservoir sediment trap efficiency for fine sediment

The reservoir sediment trap efficiency can be estimated using the Brune (1953) or Churchill (1948) trap efficiency curves. The total fine sediment load over the period of reservoir sedimentation can be computed by dividing the fine reservoir sediment mass by the reservoir sediment trap efficiency. The average annual fine sediment load can be computed by dividing the total fine sediment load by the estimated period of reservoir sedimentation.

Once the reservoir sediment scale has been classified, the next steps are to estimate the amount of sediment that would be eroded from the reservoir and then scale the potentially eroded mass to the sediment load of the stream. For reservoirs that are much wider than the stream channel, a large portion of the sediment is typically expected to remain in the reservoir over the long term. Additional work is being done to assist with the development of methods to provide qualitative assessment of the amount of reservoir sediment that would be eroded.

**Step 5: Select initial dam removal and sediment management plan.** Initially, assume that the dam and reservoir would be completely and rapidly removed and that stream flows will be allowed to erode sediments from the reservoir. Based on an initial assessment of sediment impacts, determine if the initial dam removal and sediment management plans need to be adjusted to reduce impacts to acceptable levels (Figure 3). This approach will provide justifications for additional management actions, which may be expensive, as opposed to just assuming that additional actions are needed without verification. However, some circumstances will require that additional management actions be included prior to the initial sediment impact analysis. Such circumstances are listed below:

- Presence of contaminants above background concentrations.
- Reservoir sediment mass is classified as large.
- Potential for downstream channel degradation to migrate upstream of the dam and reservoir after their removal.
- Erosion resistant materials are present within the reservoir that could create fish or boat passage problems after dam removal and prevent the erosion of reservoir sediments.
- Sensitive aquatic species (threatened or endangered) are present downstream of the dam that cannot tolerate sediment impacts without dire consequence to the species primary production or community composition.

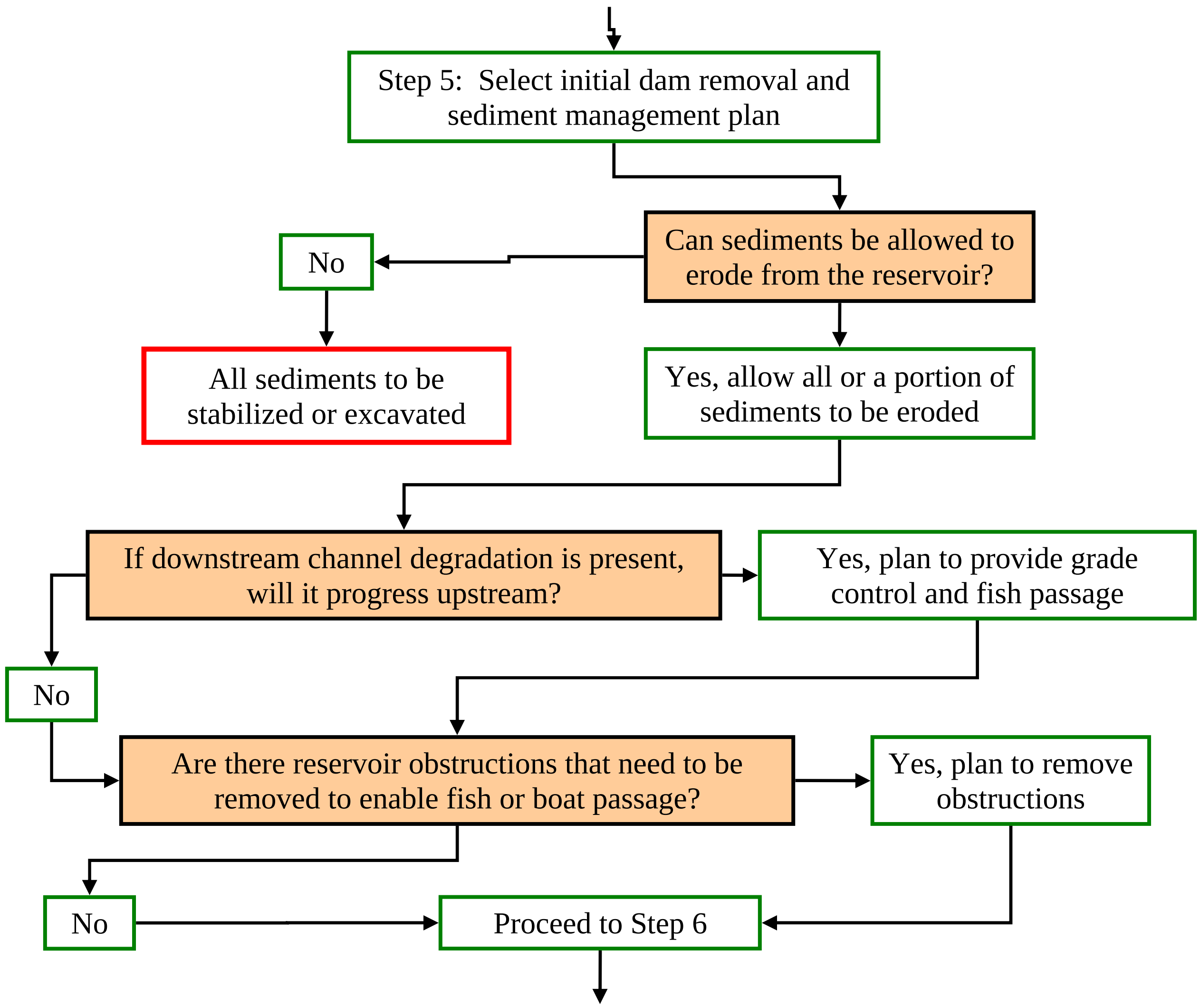


Figure 3 Flowchart for step 5 of the guideline procedure.

**Step 6: Evaluate reservoir and downstream sediment impacts according to sediment scale.** In this step, the amount and rate that reservoir sediment that is eroded past the dam is predicted over the short and long-term periods. In addition, the fate of the eroded reservoir sediments that enter the downstream river channel will be predicted. The level of effort to predict these effects will depend on the reservoir sediment classification and the level of perceived risk if the reservoir sediment is released downstram. Categories of predictive tools are listed below:

- Mass balance Models
- Analytical Models
- One-dimensional Hydraulic and Sediment Transport Models
- Two-dimensional Hydraulic and Sediment Transport Models
- Three-dimensional Hydraulic and Sediment Transport Models
- Physical models

Minimal predictive efforts would be needed for a negligible reservoir sediment mass while extensive predictive efforts would be recommended for a large reservoir sediment mass.

**Step 7: Assess confidence, impact probability, and risk.** The risk of sediment impacts is the product of the probability of impact and the consequence of the impact. The high probability of an impact, combined with a very low consequence of impact, would produce a low risk of impact. Conversely, a low probability of impact, combined with a very high consequence of impact, would produce a high risk of impact. High uncertainty of impact would lead to higher probabilities of impact.

If the risk of impact is too high because of high uncertainties and probabilities, then more data collection and analyses may be needed to reduce the uncertainty. If the risk of impact is too high because of high consequences of impact, then additional management actions may be needed to reduce or eliminate the probability of impact.

**Step 8: Determine if sediment impacts are tolerable.** 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. Present these sediment effects to decision makers and stakeholders. Determine if predicted impacts can be tolerated or if they can be avoided or mitigated. Then, modify the dam removal and sediment management alternatives as necessary.

**Step 9: Develop monitoring and adaptive management plan.** Monitoring and adaptive management plans are recommended to determine if the predicted sediment effects associated with dam removal are accurate and if they begin to exceed tolerable levels. With an adaptive management plan, corrective actions can be recommended for possible implementation before sediment effects begin to exceed tolerable levels.

**Proceed with dam removal planning.** Once dam removal and sediment management plans have been formulated with predicted effects that are tolerable, then more detailed dam removal planning can proceed, including compliance with the National Environmental Policy Act and permitting.

## TESTING OF ANALYSIS GUIDELINES

The dam removal sediment analysis guidelines will be tested with data from at least 20 actual dam removals case studies. These case studies will include dams from the eastern, Midwestern, and western United States and include reservoirs with negligible to very large sediment scales. A suggestion was made at the second workshop to include additional project areas in the south and will be incorporated in the future if case study data become available.

## CONCLUSIONS

The sediment-related impacts of dam removal fundamentally depend on the reservoir sediment characteristics (mass, size gradation, quality, and spatial distribution) and on the extent and rate of reservoir sediment erosion. The mass of reservoir sediment should be scaled to the transport capacity of the downstream river channel. The level of investigation for sediment impact predictions should be a function of this sediment scale.

The next steps to complete the guidelines are listed below:

- Incorporate workshop comments
- Finalize case study evaluations based on updated guidelines
- Obtain independent peer review
- Obtain approval from Subcommittee on Sedimentation
- Obtain approval from Federal Advisory Committee on Water Information
- Publish guidelines

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