# Dam Removal Analysis Guidelines for Sediment

## Advisory Committee on Water Information
## Subcommittee on Sedimentation


U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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**Bureau of Reclamation**
**Technical Service Center, Denver, Colorado**

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Prepared by:

Timothy J. Randle, Ph.D., P.E., D.WRE.
Supervisory Hydraulic Engineer and Manager, Sedimentation and River Hydraulics Group

Jennifer Bountry, M.S., P.E.
Hydraulic Engineer, Sedimentation and River Hydraulics Group

Peer Reviewed by:

Blair P. Greimann, Ph.D., P.E.
Hydraulic Engineer, Sedimentation and River Hydraulics Group

In addition, the information presented in this guideline has been externally peer reviewed by the following subject matter experts listed below (in alphabetical order) from other federal agencies, universities, private consultants, and non-governmental organizations:

- American Rivers
- Chris Bromley (Scottish Environment Protection Agency)
- Chauncey Anderson (U.S. Geological Survey)
- Mathias J. Collins (National Marine Fisheries Service, NMFS)
- Joanna Curran (Northwest Hydraulic Consultants)
- Tom Augspurger (U.S. Fish and Wildlife Service)
- Jeff Duda (U.S. Geological Survey)
- Amy East (U.S. Geological Survey)
- Ken Finkelstein (National Marine Fisheries Service)
- Jon Fripp (USDA - Natural Resource Conservation Service)
- Alex Hackman (Massachusetts Department of Fish and Game)
- Eric Hutchens (National Marine Fisheries Service)
- Jim MacBroom (Milone & MacBroom)

- Jon Major (U.S. Geological Survey)
- Toby Minear (Cooperative Institute for Research in Environmental Sciences)
- Joe Rathbun (Michigan Department of Environmental Quality)
- Marcin Whitman (California Department of Fish and Game)
- Molly Wood (U.S. Geological Survey)

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The Pennsylvania Fish and Boat Commission hosted the 2009 workshop. Scott Carney is acknowledged for his efforts to host the workshop and organize and lead the field visits to two local dam removal projects.

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List of participants at the October 2008 workshop in Portland, Oregon and their affiliation at the time of the workshop are provided in the table below.

| 2008 Workshop 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 |
| Scott Carney | Pennsylvania Fish and Boat Commission |
| Dan Cenderelli | U.S. Forest Service |
| Brian Cluer | National Marine Fisheries Service |
| Matt Collins | National Marine Fisheries Service |
| Yantao Cui | Stillwater Sciences |
| Pete Downs | Stillwater Sciences |
| 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 Podolak | National Center for Earth-Surface Dynamics |
| Cynthia Rachol | U.S. Geological Survey |
| 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 |

List of participants at the October 2009 workshop in State College, Pennsylvania and their affiliation at the time of the workshop are provided in the table below.

| 2009 Workshop Participant | Affiliation |
|---|---|
| Chauncey Anderson | U.S. Geological Survey |
| Travis Bauer | Bureau of Reclamation |
| Jerry Bernard | National Resources Conservation Service |
| Jennifer Bountry | Bureau of Reclamation |
| Scott Carney | Pennsylvania Fish and Boat Commission |
| Dan Cenderelli | USDA Forest Service |
| Matt Collins | National Marine Fisheries Service |
| Yantao Cui | Stillwater Sciences |
| Joanna Curran | University of Virginia Engineering |
| Pete Downs | Stillwater Sciences |
| Brian Graber | American Rivers |
| John Gray | U.S. Geological Survey |
| Jeffrey Hartranft | Pennsylvania Department of Environmental Protection |
| Lisa Hollingsworth-Segedy | American Rivers |
| Vincent Humenay | Pennsylvania Department of Environmental Protection |
| Christopher Magirl | U.S. Geological Survey |
| Jim MacBroom | Milone and MacBroom |
| Marty Melchior | Interfluve |
| Katie Ombalski | Clearwater Conservancy of North Central Pennsylvania |
| Charles Podolak | National Center for Earth-Surface Dynamics |
| Tim Randle | Bureau of Reclamation |
| Joe Rathbun | Michigan Department of Environmental Quality |
| Matt Romkens | Agricultural Research Service |
| Gary Smillie | National Park Service |
| Sara Strassman | American Rivers |
| Tim Straub | U.S. Geological Survey Illinois |
| Marcin Whitman | California Department of Fish & Game |
| Shelby Zelonis | University of South Carolina |

# Acronyms and Abbreviations

| | |
|---|---|
| ASCE | American Society of Civil Engineers |
| DRIP | Dam Removal Information Portal |
| EPA | Environmental Protection Agency |
| ESA | Endangered Species Act |
| FEMA | Federal Emergency Management Agency |
| GPS | global positioning system |
| NEPA | National Environmental Policy Act |
| NID | National Inventory of Dams |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| PAH | polycyclic aromatic hydrocarbons |
| PCB | polychlorinated biphenyls |
| SETAC | Society of Environmental Toxicology and Chemistry |
| USACE | U. S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |
| WRD | World Register of Dams |

# Glossary

**Biota:** The fish, wildlife, and vegetation along a stream channel.

**Lakebed sediment:** Alluvial deposits of fine sediment along the reservoir bottom.

**Low-head dam:** A dam or weir built across a stream to pass flows from upstream over all, or nearly all, of the width of the dam crest on a continual and uncontrolled basis (U.S. Army Corps of Engineers, Nationwide Permit 53). In general, a low-head dam does not have a separate spillway or spillway gates but it may have an uncontrolled spillway. The dam crest is the top of the dam from left abutment to right abutment, and if present, an uncontrolled spillway. A low-head dam provides little water storage function.

**Reservoir delta:** Alluvial deposits of coarse sediment where stream channels enter a reservoir. Not all reservoirs have deltas, but when present, the top surface of a delta deposit is near the normal water surface elevation. Overtime, the deposits prograde both downstream toward the dam and upstream along the stream channels entering the reservoir.

**Relative reservoir sediment volume**: ratio of reservoir sediment volume or mass to the mean annual sediment load (volume or mass) of the river.

**Reservoir impoundment:** River water stored behind a dam or weir.

**Risk analysis:** An estimate of the risk of consequences occurring from releasing sediment as a result of a dam removal. Risk is determined from the product of the probability of sediment impact (relative reservoir sediment volume) and the consequence of that impact resulting from dam removal.

**Risk assessment:** The process of considering the quantitative or qualitative estimate of risk, along with all related social, environmental, cost, temporal, and other factors to determine a recommended course of action to mitigate or accept the risk.

**Risk management:** Actions implemented to communicate the risks and either accept, avoid, transfer, or control the risks to an acceptable level considering associated costs and benefits of any action taken.

**Sediment:** Weathered rock particles transported by water or wind. In this guideline, sediment is referred to by three classifications: particle grain size, transport mechanism, or sediment source as defined below:

- Particle grain size
  - Fine Sediment (<0.062 mm)
    - Clay (< 0.004 mm)
    - Silt (0.004 to 0.062 mm)
  - Coarse Sediment (> 0.062 mm)
    - Sand (0.062 to 2 mm)
    - Gravel (2 to 64 mm)
    - Cobble (64 to 256 mm)
    - Boulder (> 256 mm)
  - Sediment Particle Diameter Size (percentile)
    - $D_{50}$: Particle diameter representing the 50% cumulative percentile value, median particle (50% of the particles in the sediment sample are finer than the $D_{50}$ grain size)
    - $D_{90}$: Particle diameter representing the 90% cumulative percentile value (90% of the particles in the sediment sample are finer than the $D_{90}$ grain size)
- Transport Mechanism
  - Bed load: particles that are rolling, sliding or saltating in either continuous or intermittent contact with the channel bed
  - Suspended Load: particles moving in the water column and suspended above the channel bed by turbulence
- Sediment Source
  - Bed-material load: sediment in transport that is comprised of particles that are found in appreciable quantities in the channel bed.
  - Wash load: suspended sediment load that is finer than the bed-material load and not found in appreciable quantities in the channel bed.

## Disclaimer

The Dam Removal Analysis Guidelines for Sediment are intended to assist engineers and scientists with determining the level of sediment data collection, analysis, and modeling for dam removal projects using a risk-based approach. The guidelines will not address every unique dam removal case or circumstance nor the 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, and to provide a starting point for evaluation of potential sediment-related aspects for new dam removals.

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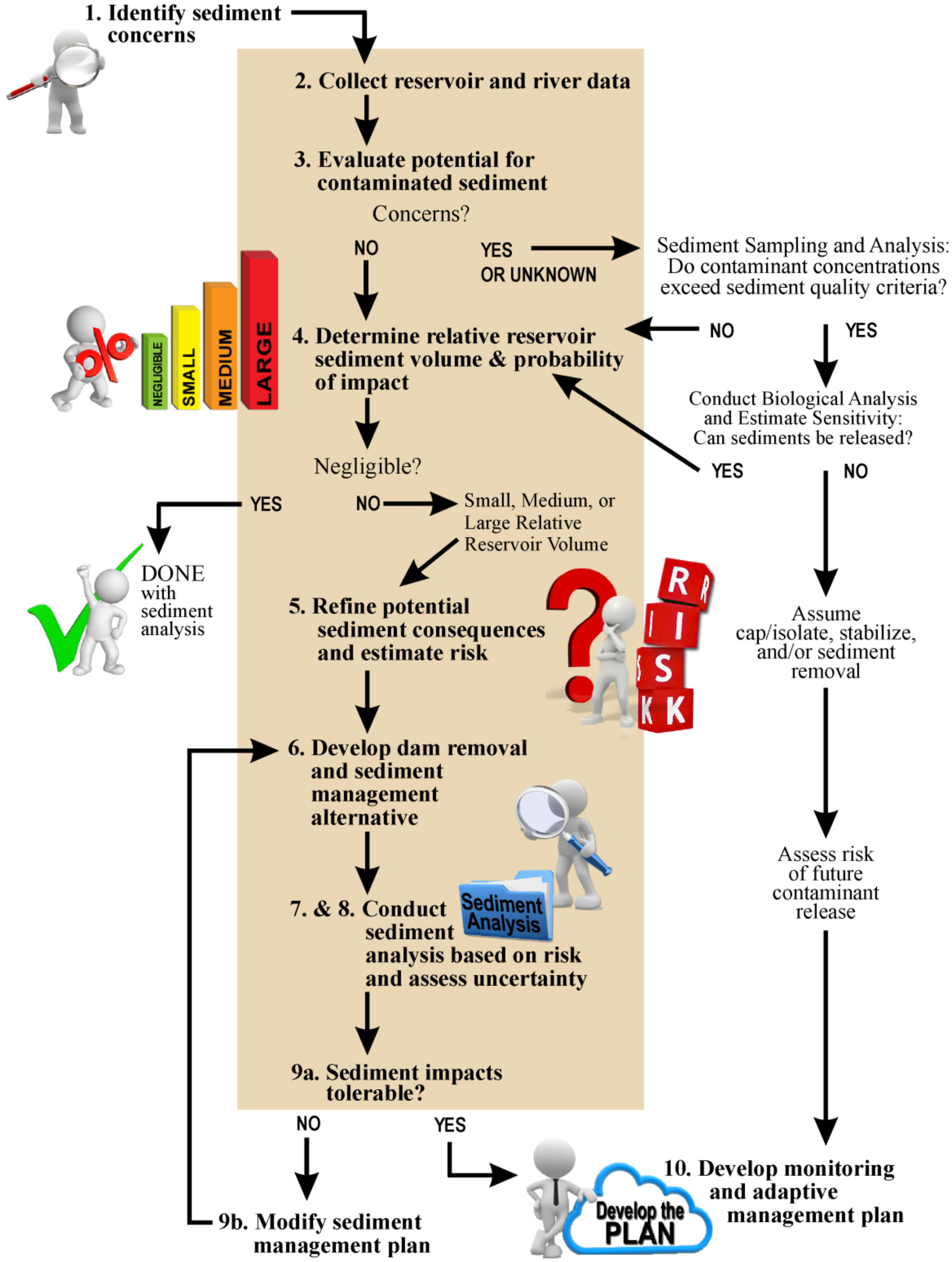
# EXECUTIVE SUMMARY

As of 2016, American Rivers reported that nearly 1,400 dams have been removed in the United States. Dam removal is expected to continue in the future with changing environmental values, aging infrastructure, and continued reservoir sedimentation. Sediment management can be an important aspect of a dam removal projects and significantly affect the implementation cost. The amount of required sediment data collection and analysis for dam removal projects has varied widely across the United States and is not always in concert with the actual risk of sediment impacts. Therefore, the interagency Subcommittee on Sedimentation has sponsored the development of national guidelines for assessing sediment-related effects from dam removals. These guidelines build upon concepts developed at workshops with national experts from government, universities, consultants, and non-governmental organizations, and from the benefit of numerous case studies from locations across the United States.

The dam removal analysis guidelines for sediment are written for engineers and scientists who have at least a basic understanding of river hydraulics and sediment transport (see Appendix A for additional reservoir sedimentation background). The guidelines include ten steps that match the level of data collection, analysis, and mitigation to the estimated risk of potential sediment impacts (see flow chart below). The guidelines suggest an iterative analysis approach, starting with readily available information and revisiting or repeating analysis steps as more data become available. Once the user of these guidelines is aware of various sections and the analysis flowchart, the guidelines do not have to be read in sequential order.




Flow Chart: **Sediment analysis guideline steps for dam removal.**

Many low-head dams have very little sediment trapped within their impoundments and, therefore, there is little risk of sediment impacts and no need for extensive sediment investigations. The guidelines offer special simplified procedures to verify cases of negligible reservoir sediment where no additional analysis is necessary. Negligible reservoir sediment volumes are less than 10% of the average annual load, and similar to a typical alluvial feature (e.g. sand bar or gravel bar) in nearby river reaches.

Except for negligible sediment volumes, the potential for contaminants is evaluated using a screening survey. If there is no cause for contaminant concern and the reservoir sediment contains less than 10% clay and silt, then the probability of contaminated sediment can be considered low and additional contaminant testing and analysis is not necessary. If contaminants are a concern, sediment chemistry sampling and analysis is conducted to determine if contaminants can be safely released into the downstream river without impairing human health or aquatic species. Comparison with local, state and federal sediment quality criteria and background sediment quality are integrated to ensure analysis meets regulatory requirements. If the contaminants cannot be safely released, mitigation must be implemented that often consists of removal and disposal of contaminated sediment or capping contaminated sediment in place with adequate protection from future seepage and erosion. If contaminants can be safely released into the downstream river channel, the guideline user can proceed with determination of risk of sediment-related impacts.

For cases considering release of reservoir sediment downstream, a key part of the guidance is using estimated risk of sediment impacts to drive decisions on the amount of data collection, analysis, and mitigation. Risk is the product of the probability of sediment impacts and the consequence of those impacts should they occur. The probability of sediment impact is based on the relative reservoir sediment volume (small, medium, or large). The relative reservoir sediment volume is based on the ratio $T_S$, which represents the years of upstream sediment supply trapped within the reservoir. The years of trapped sediment is representative of the reservoir sediment volume and the river's capacity to transport it. A logarithmic scale is used to classify $T_S$ into small (0.1 to 1 yr), medium (1 to 10 yr), and large (greater than 10 yr) relative reservoir sediment volumes. Potential consequences are qualitatively determined through discussions among the project team and stakeholders and may be unique for released fine and coarse sediment volumes within the reservoir.

The guidelines present a broad range of dam removal and sediment management alternatives and tools for evaluating sediment-related impacts associated with those alternatives. The recommended level of sediment investigations are proportional to the risk of sediment impacts. Conceptual models are recommended for every case, while more quantitative numerical modeling, physical modeling, and field experiments are recommended for higher risk cases.

A final step is to determine if the predicted sediment impacts are tolerable to stakeholders and decision makers. Uncertainty of key input parameters such as the reservoir sediment volume are reviewed as part of the discussion. The conversation should also include how potential benefits of released sediment and long-term restoration benefits of dam removal weigh against impacts that are potentially short-term. If predictions of sediment impacts are not tolerable, dam removal and sediment management plan can be revised, such as phasing dam removal to slow the rate of released sediment. Other options include mitigation for predicted sediment impacts such as raising levees or temporary treatment of higher sediment concentrations. Once the sediment-related impacts are judged to be tolerable, then the guidelines recommend the development of a monitoring and adaptive management plan to help implement the project and inform planning of future dam removal projects.

# INTRODUCTION

Dams serve many useful purposes, but with the very large number of dams in the United States, and around the world, dams occasionally need to be removed for a variety of reasons. When dams are removed, special consideration may be needed for the sediments that have been trapped within their reservoirs or impoundments[1]. The potential impact of these reservoir sediments during and after dam removal, either within the reservoir or on downstream receiving waters, can range from negligible to very significant. Thus, management decisions regarding those sediments are often among the most important technical considerations for many dam removals. These guidelines propose that the level of sediment data collection, analysis, modeling, reservoir sediment management, and mitigation be proportional to the risk of potential impacts from the reservoir sediment. The volume of reservoir sediment relative to the stream's average annual sediment load, concentration of any contaminants relative to sediment quality guidelines, and potential downstream impacts are key parameters for determining environmental impacts and for helping to choose a sediment management alternative (Reclamation, 2006, Grant and Lewis, 2015, Major et al., 2017). The guidelines incorporate options for reservoir sediment management that allow sediments to be eroded and released downstream, stabilized in place, or removed and relocated depending on identified risks and uncertainty.

People have been building dams for thousands of years to utilize fresh water resources provided by rivers, streams, and lakes. The constructed dams come in a variety of sizes, serve a variety of purposes, and have a variety of environmental effects (Figure 1). The World Register of Dams (WRD) documents information for large dams defined as having heights over 15 m (49 ft) (ICOLD, 2017). Within WRD, the oldest dam noted is the Proserpina Dam in Spain, built in 130 A.D. The world's tallest three dams are over 300 meters high - located in Tajikistan (335 m or 1,099 ft), Iran (315 m or 1,033 ft), and China (305 m or 1,001 ft). In ancient times, dams were typically built for water supply or irrigation. According to the World Register of Dams, irrigation remains the most common purpose of dams worldwide. Among "single purpose dams" in WRD, 49 percent are for irrigation, 20 percent for hydropower (production of electricity), 11 percent for water supply, 9 percent for flood control, 5 percent for recreation, less than 1 percent for navigation and fish farming, and 6 percent for other purposes. Some dams are constructed to provide benefits for recreation, wildlife, fishery enhancement, and sediment retention. Many dams are constructed to provide multiple purpose benefits from their reservoirs (e.g. water supply, flood control, hydropower, and recreation).

[1] For the purposes of this document the terms reservoir and impoundment are used interchangeably.


**Figure 1.—Dams exist in a wide variety of sizes and serve a wide variety of purposes.**

Dams continue to be an important part of the worldwide infrastructure with new dams being built each year, but some dams have become obsolete. Dams built several decades to centuries ago can have structural or recreational safety issues or reservoirs full of sediment that impact water management operations. Dams were also historically constructed in low population areas, but in the intervening years as populations expanded into the country, more people today live in close proximity or downstream of a dam, changing the amount of risk for some dams that are aging and in need of repair. In other cases, the original purpose of the dam is no longer needed, the dam is abandoned, no longer economical to operate, or there may be significant environmental benefits achieved if the dam were removed. While dams provide numerous benefits, they also alter intrinsic riverine processes of continuity and upstream-downstream linkages involving water, sediment, wood, nutrients, biota, and floodplains between the watershed area upstream and downstream of the dam.

Dam removal may be a viable management option to restore lost ecosystem processes when the operational purpose of a dam and reservoir are no longer needed, can be met through alternative means, or the costs to address safety and infrastructure exceed the cost of removal. For example, a pumping plant with proper fish screens constructed along the channel margin may negate the need for a diversion dam that impedes fish passage. Electricity generated from a hydroelectric dam could be generated by other power plants. Structural damage resulting from natural disasters such as flooding or earthquakes may be too costly to repair relative to project benefits, or the structure may simply have been abandoned and at risk for failure due to lack of maintenance. On the other hand, water supply storage and flood control benefits, provided by many large dams, would be difficult to replace if a dam were removed. In fact, very few (if any) dams that provide significant water supply storage or flood control benefits have been removed.

Dam removal may not always be a preferred option by some because of the historical significance of the structure and intrinsic value to the local community (Magilligan et al. 2017). Certain dams have historical significance and serve as landmarks important to local residents. In other cases sediment impacts from dam removal may be deemed unacceptable or funds may not be available to address the impacts or cost of removal. As a result, each dam removal tends to be unique (although there are common considerations), and decisions on their removal are subject to individual criteria and processes. Nonetheless, in the absence of sustainable reservoir sediment management, more dams will be removed in the future as their reservoirs fill with sediment and then no longer provide benefits.

Case studies of dam removals over the last several decades have found that rivers are resilient in that the sediment transport capacity of a river generally increases in response to increases in sediment loads, such as the Elwha River in Washington (Magirl et al. 2015). Ecosystem processes and aquatic species respond favorably to restoring connectivity with upstream sediment, wood, and nutrient loads (O'Connor et al. 2015). Low-head dams[2] often do not trap much sediment relative to sediment loads of the river and their removal may only have a negligible effect from a sediment perspective. Dam removal, and the downstream release of reservoir sediment, can have short-term, but notable impacts on the downstream channel and aquatic habitat. Characterizing the quantity and quality of reservoir sediment, and expected river response as a result of dam removal, can inform the rate and style of dam removal with consideration of potential consequences. Possible resources and human uses that could be affected from dam removal include the aquatic environment and river health, water quality, water use and infrastructure (e.g. water intakes, wells), downstream channel morphology, flood stage, and topography of the reservoir and upstream river channel (Tullos et al. 2016). Consequently, reservoir sediment management costs can be a substantial portion of the total cost of dam removal.

These sediment analysis guidelines have been developed to provide engineers, scientists, and resource managers with a risk-based approach for determining the level of data collection, analysis, and modeling to evaluate a dam removal project and the type of sediment management actions that may be needed. These

[2] Definition of low-head dam from Decision Document Nationwide Permit 53: "the term low-head dam' is defined as a dam built across a stream to pass flows from upstream over all, or nearly all, of the width of the dam crest on a continual and uncontrolled basis. (During a drought, there might not be water flowing over the dam crest.) In general, a low-head dam does not have a separate spillway or spillway gates but it may have an uncontrolled spillway. The dam crest is the top of the dam from left abutment to right abutment, and if present, an uncontrolled spillway. A low-head dam provides little storage function."

guidelines have been developed for a wide range of dam removals and sediment issues. Simplified analysis procedures are recommended for dam removals with little or no (negligible) sediment.

In addition to sediment impacts from dam removal, these guidelines may have some applicability for the practice of passing upstream sediment loads through or around the reservoir for long-term sustainable management.

# DAM CONSTRUCTION AND REMOVAL BACKGROUND

## Dam construction in the United States

The earliest dam construction recorded in the National Inventory of Dams (NID) database was in 1640—the 1.8-m high Old Oaken Bucket Pond Dam near Scituate, Massachusetts (NID, 2013). As more settlers arrived, tens of thousands of dams were estimated to be built in the mid-Atlantic region of the eastern United States to support mills, forges, and other industries that needed mechanical hydropower throughout the 17th to early 20th centuries (Merritts et al. 2013). The height of early mill dams was often limited to the diameter of their wood water wheels. Merritts et al. (2013) note that typical dam heights in this era were 2 to 3 m (6 to 10 ft) and built on headwater streams. Larger dams came later as the country grew in population, required increased navigation, and expanded agriculture into the drier western portion of the U.S. The history of federal involvement in U.S. dam construction goes back at least to the 1820s, when the U.S. Army Corps of Engineers (USACE) built wing dams to improve navigation on the Ohio River (Billington et al. 2005). The work expanded after the Civil War, when Congress authorized the USACE to build storage dams on the upper Mississippi River and regulatory dams to aid navigation on the Ohio River. In 1902, when Congress established the Bureau of Reclamation (initially named the "Reclamation Service"), the role of the federal government increased dramatically and set the stage for large dam construction on the country's western rivers. In addition, numerous canal networks were established in the early 1900's to deliver water to newly formed irrigation districts in the west. Dams for flood control, water supply, and recreational use were also built by the Natural Resources Conservation Service which has constructed 11,800 dams in 47 states since 1948 (NRCS, 2017).

The USACE maintains the NID to track construction of large federal, state, and private dams in the U.S., including information about the dam such as height, dam type, and purpose (USACE, 2016a). The current NID, published in 2016, includes information on 90,580 dams that are at least 7.6 m (25 feet) high with reservoir storage capacity of at least 18,500 $m^3$ (15 acre-ft, 50 percent of dams listed), or are at least 1.8 m (6 ft) high and store at least 61,700 $m^3$ (50 acre-feet) of water, or are considered a significant or high hazard should they fail. In addition to the 90,580 dams in the NID, there are estimated to be perhaps millions of smaller dams that do not meet the minimum height, storage, or hazard criteria to be included in the NID. Approximately 60 percent of U.S. dams (50,000 dams) were constructed between 1950 and 1979. The rate of dam construction documented in the NID significantly increased in the 1950's to 1970's and has since slowed after many of the prime dam sites were developed (Figure 2). Building of new dams continues, however, as 212 new dams were constructed between 2010 and 2012 with the majority ranging between 4 to 16 m (13 to 52 ft), and five exceeding 32 m (105 ft).

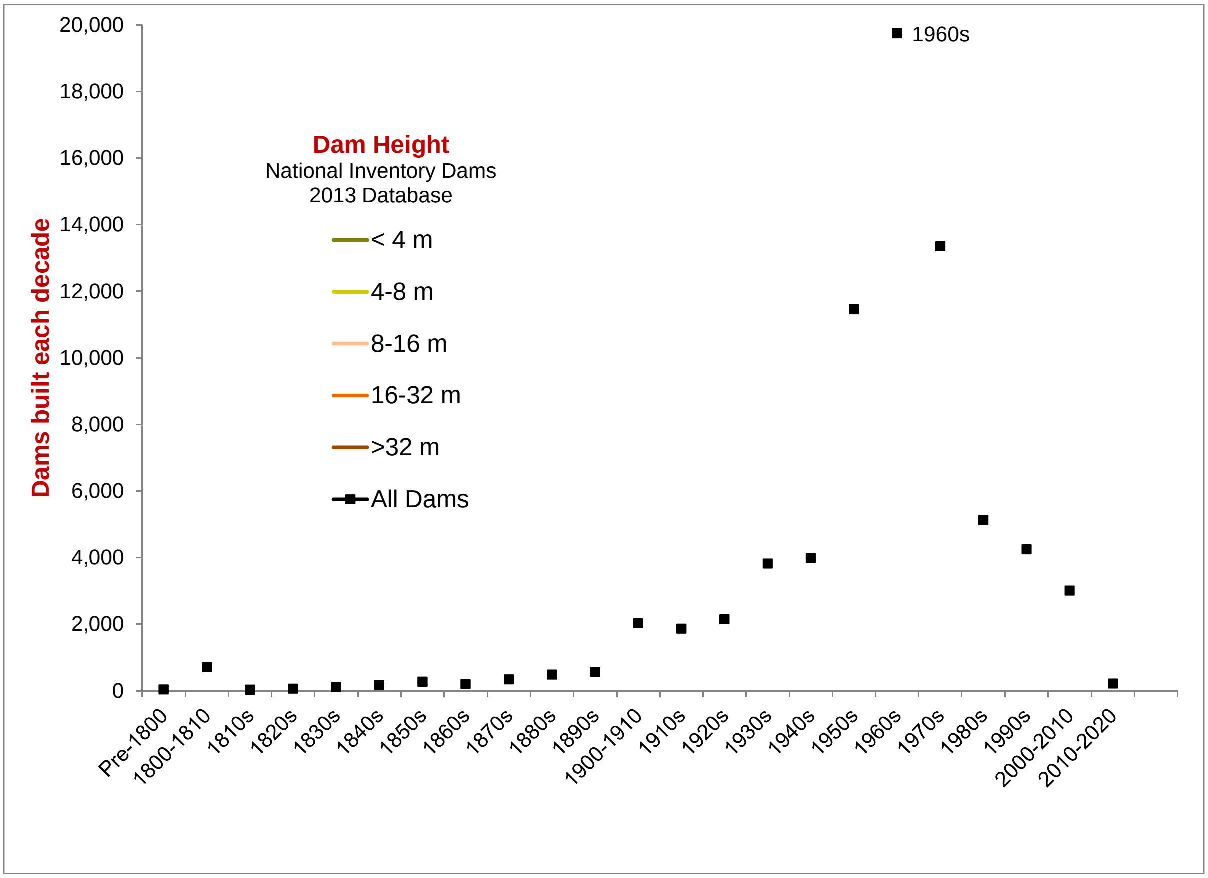



**Figure 2.—The rate of dam construction peaked during the 1950s to 1970s (2013 NID).**

The 90,580 dams in the NID are widely distributed throughout the United States, with the most per state (more than 5,000) in Texas, Kansas, Missouri, and Georgia (Figure 3). Of the dams in the inventory, fewer than 2 percent are over 30 m (100 ft) high. The current primary purposes for the U.S. dams in the NID include recreation (28 percent), flood control (18 percent), fire protection (12 percent), irrigation (9 percent), water supply (6 percent), and hydropower (2 percent). According to the NID, Oroville Dam, on the Feather River in California, is the tallest dam in the United States, measuring 235 m (771 ft). The dam with the largest reservoir is Hoover Dam, on the Colorado River on the Arizona-Nevada border, which stores approximately 37 billion $m^3$ (30 million acre-ft) of water. The dam that provides the most hydroelectric power capacity in the United States is Grand Coulee Dam, on the Columbia River in Washington, which can generate 6,180 megawatts of power.

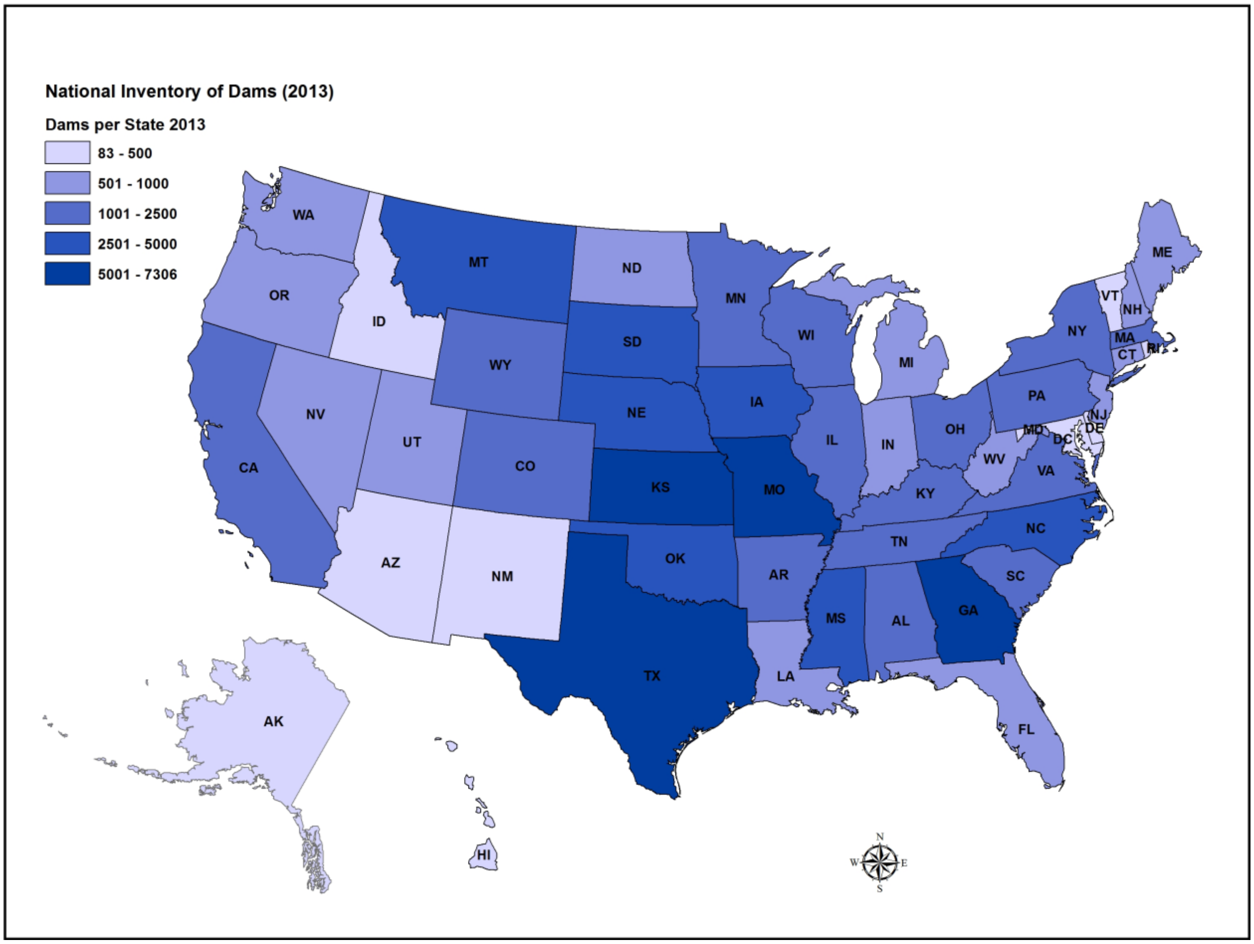



Figure 3.—Spatial distribution of NID dams (2013) across the United States.

## Dam removals

The rate of dam removal has been increasing notably since the 1970’s (Figure 4). American Rivers reported that 1392 dams have been removed in the United States between 1912 and 2016, and that the majority of the dams were removed within the past 20 years (American Rivers, 2016). For context, the total number of removals documented so far in the U.S. is very small compared with the total number of dams in the U.S. The need to consider dam removal as a possible river restoration tool is anticipated to continue in the future. Dam removal may be a preferred alternative for cases with aging or abandoned dams with hazard issues or intakes no longer operational due to sedimentation. It is also common for post-industrial dams that block fish passage or have contaminated sediment. Removal can often accomplish environmental benefits that can in part be obtained by reconnecting the supply of sediment, wood, and nutrients to areas from the upstream watershed to the river downstream of the dam.

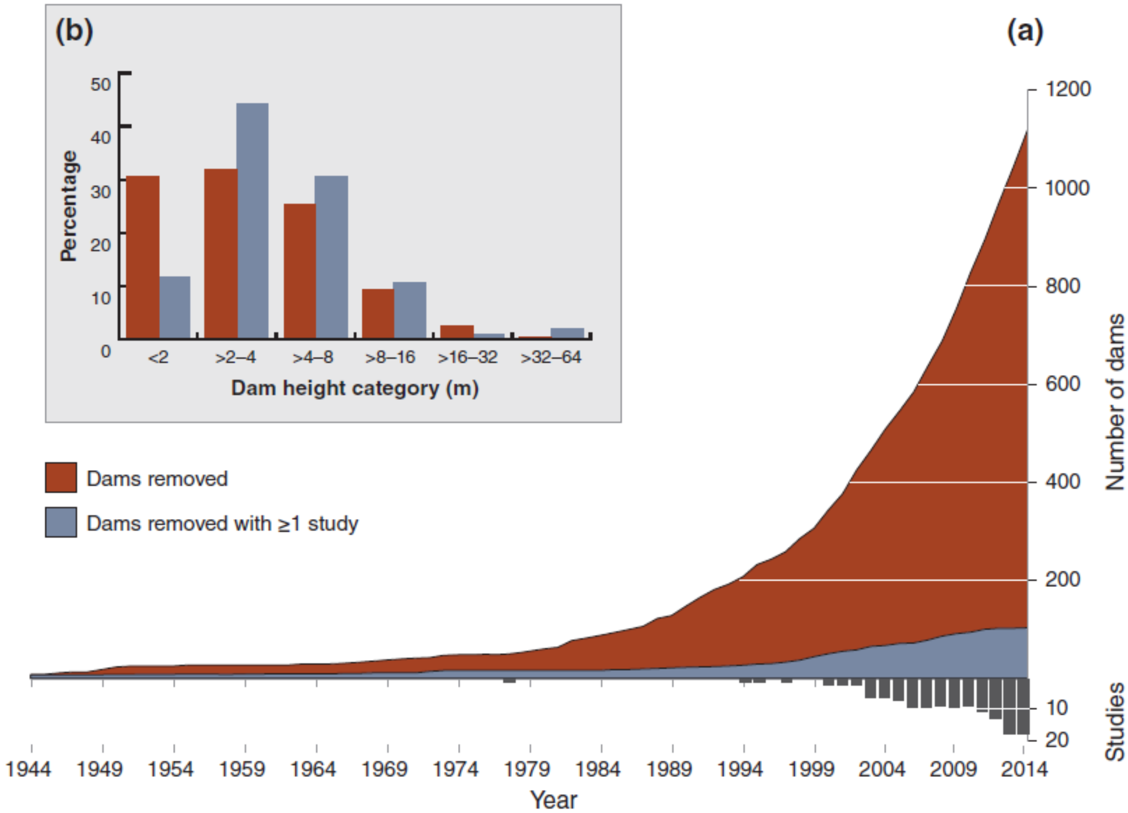



**Figure 4.—Compilation of dams removed and dams with at least one published study on the physical or ecological river response to dam removal (a) by dam height and (b) the cumulative number of dams removed by year (Bellmore et al. 2017, data from Bellmore et al. 2015 and American Rivers, 2014).**

Dam removal of all sizes has occurred across the country, with the most dam removals documented in Pennsylvania, the Great Lakes region, northeast, and along the west coast (Figure 5). An interactive map with dam removal site information within the United States is provided by American Rivers (2017). USGS (2017a) has also developed a useful online site called the Dam Removal Information Portal (DRIP) that provides a map-based visualization of dam removal information and associated scientific studies. Dam removal has also occurred in many other parts of the world (Edwards, 2015).

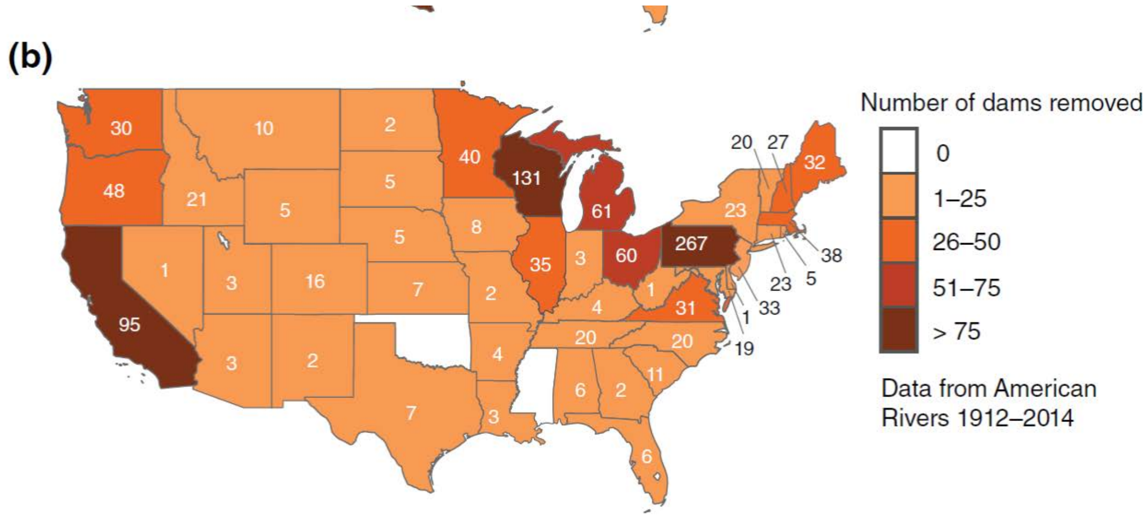



**Figure 5.—Spatial distribution of dam removals within the United States (Bellmore et al. 2017, data from Bellmore et al. 2015 and American Rivers, 2014).**

The large majority of dams that have been removed (nearly 90 percent) are less than 8 m (25 ft) tall. However, several U.S. dams were recently removed with larger and more complex reservoir sediment volumes (Table 1). Unfortunately, only a handful of these larger dams have scientific literature to document sediment erosion and transport response to dam removal. Even basic documentation on the reservoir pool is often lacking.

Table 1.—U.S. Dam Removals greater than 15 m (50 ft), sorted by dam height (American Rivers Dam Removal Database Version 2, 11-13-2017).

| Dam Name | State | Year Removed | River/Watershed | Dam Height (m) |
|---|---|---|---|---|
| Glines Canyon Dam | WA | 2011 | Elwha River | 64 |
| Occidental Chem Pond Dam D | TN | 1995 | Duck Creek | 49 |
| Condit Dam | OR | 2011 | White Salmon River | 38 |
| Elwha Dam | WA | 2011 | Elwha River | 33 |
| San Clemente Dam | CA | 2015 | Carmel River | 32 |
| Atlas Mineral Dam | UT | 1994 | Colorado River basin | 28 |
| Two Mile Dam | NM | 1994 | Sante Fe River | 26 |
| Monsanto Dam #7 | TN | 1990 | Duck River | 24 |
| Air Force Dam (Silver Lead Creek Dam) | MI | 1998 | Silver Lead Creek | 21 |
| Lake Bluestem Dam | KS | | | 21 |
| Mike Horse Dam | MT | 2015 | Beartrap Creek | 20 |
| McMillan Dam | NM | 1991 | Pecos River | 20 |
| Bald Knob Dam | PA | 2016 | Potato Garden Run | 20 |
| Hunters Dam | WA | | Hunters Creek | 20 |
| Furnace Creek Dam | PA | 2014 | Furnace Creek | 19 |

Table 1.—U.S. Dam Removals greater than 15 m (50 ft), sorted by dam height (American Rivers Dam Removal Database Version 2, 11-13-2017).

| Dam Name | State | Year Removed | River/Watershed | Dam Height (m) |
|---|---|---|---|---|
| Birch Run Dam | PA | 2005 | Birch Run | 18 |
| Prairie Dells Dam | WI | 1991 | Prairie River | 18 |
| Willow Falls Dam | WI | 1992 | Willow River | 18 |
| Mounds Dam | WI | 1998 | Willow River | 18 |
| Idylwilde Dam | CO | 2013 | Big Thompson River | 17 |
| Indian Rock Lake Dam | MO | 1986 | Tributary to Tyrey Creek | 17 |
| C-Lind Dam #1 | CA | 1993 | | 17 |
| Bluebird Dam | CO | 1990 | Ouzel Creek | 17 |
| Riss East | CO | 2016 | Four Mile | 17 |
| Grangeville Dam | ID | 1963 | Clearwater River | 17 |
| Vaux #2 Dam | MT | 1995 | Lone Tree Creek | 17 |
| Sweasey Dam | CA | 1970 | Mad River | 17 |
| Oahu Reservoir 545A | HI | 2013 | Waiawa | 16 |
| Canyon Creek Meadows Dam | OR | 2015 | Canyon Creek | 16 |
| Monsanto Dam #4 | TN | 1990 | Greenlick Creek | 16 |
| Occidental Chem Dam #6 | TN | 1991 | Tributary to Rutherford Creek | 16 |
| Lake Lehman Dam | PA | 2015 | UNT Codorus Creek | 16 |
| Monsanto Dam #5A | TN | 1990 | Greenlick Creek | 16 |

## Dam removal challenges

The challenges to removing a dam include making decisions related to policy, addressing social issues related to dam removal, obtaining funding, and providing technical information that helps inform possible management strategies (USSD, 2015). Policy decisions center on how water resources should be managed and include legal constraints and regulatory requirements. If the dam and reservoir are still providing benefits, then policy decisions have to be made about whether or not those benefits will still be provided, perhaps through alternate means, or compensated. Policy decisions may include broader resource management topics than the benefits provided by the dams such as environmental or cultural resources. Environmental resources may include aquatic and terrestrial organisms, vegetation, water quality, and aesthetics. Cultural resources may include historical or archeological assets, along with traditional cultural properties of Native Americans. It is not uncommon for East Coast dams to be over 200 years old with no design or construction plans and no known owner which poses a challenge to navigating decisions on dam removal.

Social challenges can play an important role in how to approach the decision whether to remove a dam. Dam operators and owners, water users, landowners adjacent to reservoirs, and recreationalists may all have unique perspectives and opinions about a dam and reservoir and whether removal is the best decision. An example is the community interest in retaining the recreation provided by a reservoir even though the dam is unsafe. In some cases, mitigation may be an important component of dam removal discussions involving social concerns. For example, perhaps a new greenway with bike paths, fishing access, and river raft launch sites can be included to replace lost lake recreational opportunities. Communication is a critical aspect to engage local partners and stakeholders and should consider local circumstances, potential consequences, and benefits identified with a given project. Project leaders may consider use of media outlets such as social media, press releases, and public information meetings to facilitate getting important messages to the public from engineers, scientists, and managers. Non-profit organizations focused on ecosystem restoration can be a good resource to help facilitate getting messages to the community.

Funding has to be obtained for dam removal, including the engineering and science investigations and the permitting requirements. Decisions have to be made on who will pay for dam removal and any compensation for lost benefits of the dam and reservoir. Often funding is a limiting factor on whether and when a dam removal will move forward, even when the owner and interested parties agree to remove a dam. Many projects require supplemental funding beyond what a dam owner can accommodate, particularly when large sediment volumes or contaminated sediments are involved.

Technical challenges include the determinations of how to safely and efficiently remove the dam and at what rate, how to manage stream flow during dam removal and how to provide any required fish passage, how much of the dam and related facilities have to be removed to achieve the policy objectives, how to manage the reservoir sediment, and how to deal with the uncertain and changing conditions during and shortly after the dam removal. Engineers and scientists are often tasked with estimating the effects of dam removal, including the direction, magnitude, and extent of the effects as well as the timing and duration of the effects. Water and sediment will often be the primary drivers while the resources of concern may include such things as aquatic habitat, water use (municipal, agricultural, and industrial), recreation, flooding, cultural resources, and public safety. As dam removal case studies continue to be documented, the knowledge base grows, but the number of dam removals well studied is far fewer – less than 10% – than the actual number of dams that have been removed (Bellmore et al. 2017). Several conceptual, numerical, and physical models have been applied to help inform analysis of sediment effects, but pinning down the timing of sediment effects and the magnitude and timing of biological responses still needs improvement (Tullos et al. 2016). Sediment quality criteria have been developed to assess the biological relevance of contaminants, but how to translate the level of contaminants into downstream risks remains a challenge (Evans, 2015).

## Dam removal guidelines and resources

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)
- Reservoir Sedimentation Handbook, Chapter 17 ─Decommissioning of Dams (Morris and Fan, 1997)
- Dam Removal - A New Option for a New Century (Aspen Institute, 2002)─ focus on policy decisions related to dam removal
- Dam Removal: Science and Decision Making (H. John Heinz III Center for Science, Economics and the Environment, 2002) ─documents the results of panel findings on small dam removals and a guideline on how to blend science into the dam removal decision-making process
- Dam Removal Research Status and Prospects (H. John Heinz III Center for Science, Economics and the Environment, 2003) ─documents a workshop on science and state of knowledge of dam removal through a series of papers on research, physical processes, policy, social perspectives, economics, and ecology
- A summary of existing research on low-head dam removal projects, prepared for American Association of State Highway and Transportation Officials (ICF Consulting, 2005)
- Dam Decommissioning Chapter of the Erosion and Sedimentation Manual (U.S. Department of the Interior, Reclamation, 2006)
- Data needs and case study assessment for dam fate determination and removal projects (Conyngham, 2009)
- DAM_Explorer: A modeling framework for assessing the physical response of streams to dam removal (Conyngham and Wallen, 2009)
- The Challenges of Dam Removal and River Restoration (De Graff and Evans, 2013)
- Guidelines for Dam Decommissioning Projects (USSD, 2015) ─Provides an overview of the engineering aspects of dam removal based on information from numerous case studies.
- Removing Small Dams – A Basic Guide for Project Managers (American Rivers, 2015)
- Exploring Dam Removal (American Rivers and Trout Unlimited, 2002)

- Frequently asked questions on removal of obsolete dams (U.S. EPA, 2016)
- U.S. Army Corps of Engineers Regulatory Guidance Letter 05-04 (USACE, 2005): Guidance on the Discharge of Sediments From or Through a Dam and the Breaching of Dams, for Purposes of Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899.
- U.S. Army Corps of Engineers Decision Document Nationwide Permit 53 for the removal of low-head dams (USACE, 2016b).

Several state guidelines for dam removal projects are also available:

- Massachusetts Dam Removal and the Wetland Regulations (Massachusetts Department of Environmental Protection, 2007)
- A Guide of Project Proponents: Developing Sediment Management Plans for Dam Removal Projects in Massachusetts (Massachusetts Division of Ecological Restoration and Department of Environmental Protection, draft in progress)
- Michigan Dam Removal Guidelines for Owners (Michigan Department of Natural Resources, April 2004)
- Guidelines to the Regulatory Requirements for Dam Removal Projects in New Hampshire (New Hampshire Department of Environmental Services, Revised 2007)
- Dam Removal and Barrier Mitigation in New York State (New York State Department of Environmental Conservation, 2017)
- Small Dam Removal in Oregon – A guide for Project Managers (Hay, 2008)
- Texas Dam Removal Guidelines (Texas Commission on Environmental Quality, September 2006)
- Weir removal, lowering and modification: A review of best practice (Elbourne et al. 2013)

Two databases for dam removal have been developed that provide case study information:

1. DRIP: As part of an interdisciplinary working group on dam removal at the U.S. Geological Survey, John Wesley Powell Center for Analysis and Synthesis (Powell Center), reports and a database was developed that identifies scientific publications relevant to the emerging field of dam removal science (Bellmore et al. 2015). The database is updated and visualized at DRIP (USGS, 2017a).

2. Clearinghouse for Dam Removal Information: Database hosted by the University of California at Riverside (2017) that provides dam removal project metadata.

# SEDIMENT GUIDELINES OVERVIEW

In addition to the existing guidance and literature, the U.S. Subcommittee on Sedimentation recognized the need for technical guidelines addressing sediment analysis for dam removal investigations. 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.

## Guidelines objective

The objective of these guidelines is to assist engineers and scientists, who generally understand physical river processes, with determining the level of sediment data collection, analysis, modeling, and management necessary to plan and implement dam removal projects using a risk-based approach.

## Guidelines applicability

The guidelines are written for a technical audience with a general 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. Special sections are provided to help the guideline user in cases where there is potential for contaminants to be above concentrations of management concern (e.g. polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), metals, and certain pesticides if their presence is suspected). The guidelines approach may also be applicable for evaluating sediment management for sustainability or reservoir sediment response to operational drawdowns (possibly due to climate change or infrastructure maintenance activities). Dam safety programs may also find the guidelines useful for evaluating sediment response and potential consequences to unplanned, rapid dam failure events.

## Guidelines development

The guidelines were developed through a combination of technical workshops, individual efforts, and feedback from technical venues. Much of the development of the core guidelines ideas occurred at two interdisciplinary workshops held in Portland, Oregon in 2008 and in State College, Pennsylvania in 2009 (Figure 6). The various specialties represented at these workshops included engineers, modelers, hydrologists, geomorphologists, geologists, biologists, physical scientists, ecologists, water quality specialists, and resource managers from governmental agencies (federal, tribal, state), university, non-profits, and private consultants. Workshop participants provided a range of dam removal projects that varied in sediment volume and varying landscape settings within the United States for testing the guidelines.

The guidelines were also presented at technical venues with dam removal themed sessions to get input from peers including the 2009 American Geophysical Union Conference (California), 2010 and 2015 Federal Interagency Sedimentation Conferences (Nevada), the 2011 U.S. Society of Dams Conference, the 2011 National Conference on Ecosystem Restoration (Maryland), webinars to federal scientists and resource managers in 2015 and 2016, a dam removal workshop organized by the U.S. Society of Dams in November 2015 (California), and the 7th Society of Environmental Toxicology and Chemistry (SETAC) World Congress/SETAC North America 37th Annual Meeting in 2016 (Florida).

**Figure 6.—Workshop group discussions and field visits to assist with dam removal guidelines development.**

## Using risk to guide level of investigation

This guidance focuses on the tasks needed to conduct a risk assessment of sediment issues at proposed dam removal sites. The engineer or scientist may ask "What is the predicted fate of the reservoir sediment if dam removal occurs?" However the resource manager, regulator, or stakeholder may be asking – "Will the released sediment cause any harm or increased costs and for how long?" Combining these questions to understand how the river will handle the sediment and if any resources will be impacted during its journey downstream help us determine what level of investment is needed to understand sediment effects from dam removal. The level of data collection and analysis selected for a dam removal project is recommended to be, initially, a function of the level of risk associated with the sediment impacts. Identifying risk is intended to be a qualitative evaluation in collaboration with technical experts, stakeholders and resource managers.

> ***The risk is defined as the product of the probability (e.g. likelihood) of a sediment impact and the magnitude of the resulting consequences.***
>
> ***The greater the risk, the greater the recommended level of sediment data collection, analysis, modeling, and management.***

The use of risk assessment is consistent with a long history of risk assessment science as a basis for decision-support and risk management (NRC 1983, 1996, 2009). This sediment evaluation guideline links to the ecological risk assessment framework developed by the U.S. Environmental Protection Agency and others, and their resources can be consulted for additional detail on terminology and best practices (U.S. EPA, 1992 and 1998, Suter, 2006). However, in many cases, formal risk assessments are not required and a more informal evaluation of risk can provide sufficient information to make decisions, at a fraction of the costs of a formal risk assessment.

The sediment guidelines were also informed by the Bureau of Reclamation (2017) approach to risk analysis that has been utilized as the primary support for dam safety decision-making since 2000. The Bureau of Reclamation risk approach to dam safety relies on a balance of engineering judgment and calculations to estimate potential failure modes to "build the case" for what is influencing the risks the most. In the context of managing dam and levee safety, life safety is paramount, with significant economic and environmental consequences as additional considerations (Reclamation and USACE, 2015). The approach also allows risk analysis to be conducted at different levels, from screening level analyses performed by an individual (with peer review) to full-blown facilitated team risk analyses.

The results of the risk assessment of potential sediment impacts can then be used to inform how to manage the risk of predicted sediment impacts through discussions with project decision makers, regulators, and stakeholders. The management of risk associated with sediment can be addressed during dam removal through sediment management plans and dam removal timing, with predam removal mitigation measures, and with adaptive management that utilizes real-time monitoring and analysis.

# APPLICATION OF GUIDELINES

Application of these guidelines to dam removal cases includes ten steps guided by the magnitude of relative reservoir sediment volume (Figure 7). The relative reservoir sediment volume represents the number of years of sediment load stored in the reservoir, which is then interpreted to be the probability of reservoir sediment impact (see Step 4) used in the risk calculation (see Step 5). A streamlined, simplified procedure is recommended for cases with little or no sediment, noted as negligible sediment (see next section of the guidelines).

## Guideline Steps

1. Identify sediment concerns
2. Collect reservoir and river data
3. Evaluate potential for contaminated sediment
4. Determine relative reservoir sediment volume and probability of impact
5. Refine potential sediment consequences and estimate risk
6. Develop dam removal and sediment management alternative
7. Conduct sediment analysis based on risk
8. Assess uncertainty
9. Determine if sediment impacts are tolerable and, if needed, modify sediment management plan
10. Develop monitoring and adaptive management plan

The guideline steps can be applied in an iterative approach. Initially, some assumptions may have to be made when applying the guidelines, but these assumptions can be updated as more information becomes available. First, apply the guidelines with readily available information and develop the initial scope of sediment data collection, synthesis, analysis, and risk assessment. Even if a dam removal or sediment management plan has already been selected, assuming full, rapid dam removal combined with a river erosion option will provide a valuable baseline for comparison of predicted impacts from other alternatives. By this methodology, many possible impact questions may be generated in the first iteration with an order of magnitude estimate of sediment impacts (e.g. what is a big deal versus no big deal). The initial possible impacts list is likely to greatly shrink with this first iteration so that a smaller subset is brought forward into subsequent iterations.

Once more detailed data and predictions become available, go back through the guidelines and re-evaluate the questions posed at each analysis step. This iterative approach to utilizing the guidelines should be employed whenever new information becomes available. Once the analysis level is complete, make one additional pass through the guidelines to determine whether recommendations of mitigation, monitoring, and adaptive management of sediment related processes from dam removal are warranted.

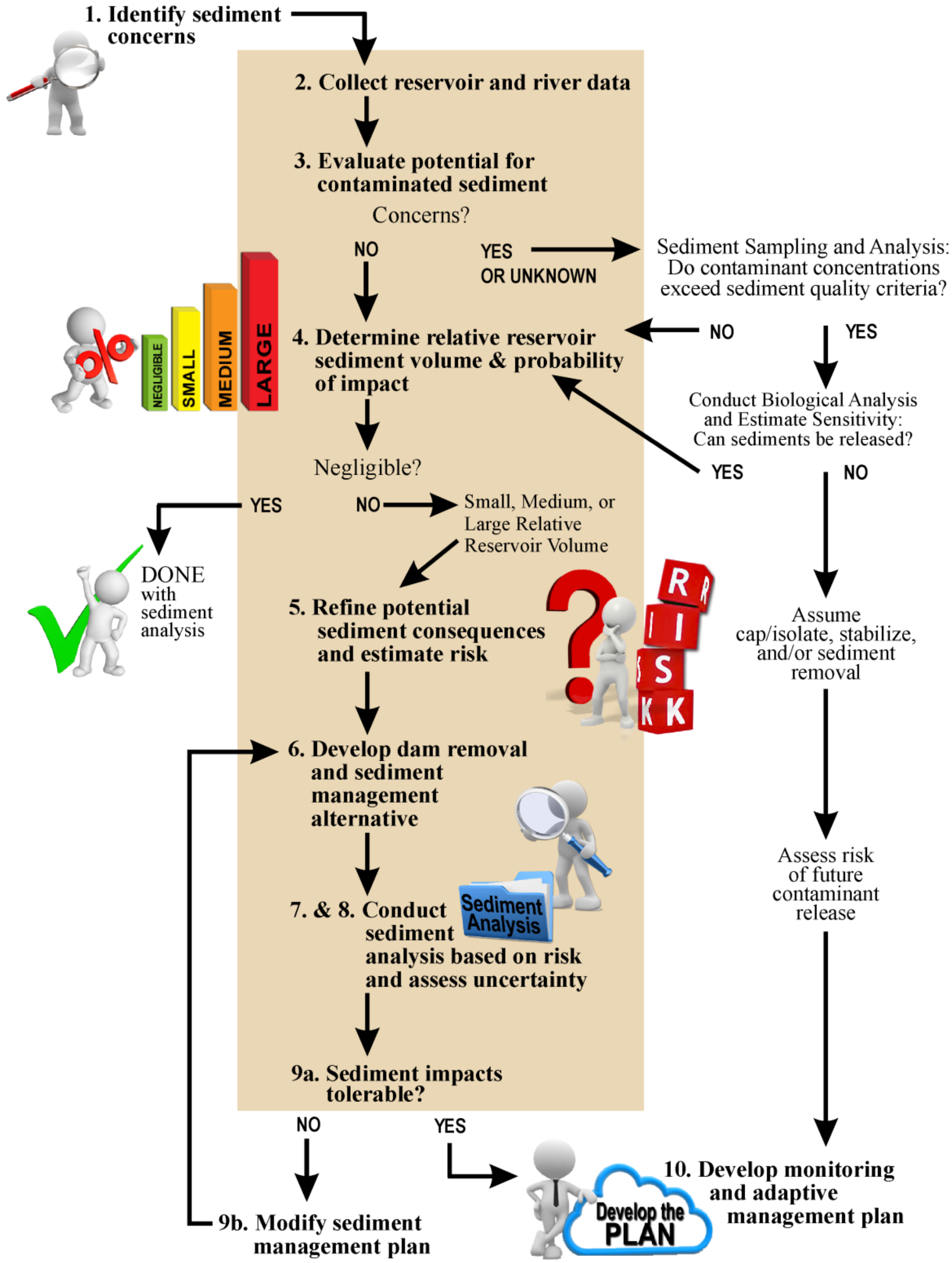



**Figure 7.—Sediment analysis steps for dam removal.**

# Understand project objectives

Before embarking on scoping the sediment analysis, it is important to identify why the dam (or group of dams) is being considered for removal and what is hoped to be achieved by its removal. Establish how success will be measured, including any project performance expectations both during and after dam removal. For some cases, the objectives and expectations may be well documented and there may be consensus among stakeholders regarding these objectives. However, for other cases, the project objectives may not be fully or clearly defined and different stakeholders may have different objectives. In some cases, the objectives may not be fully or clearly defined because the project proponents are not aware of what can actually be achieved within available budgets. Information from engineers and scientists on what can be achieved can help the project proponents define the measureable objectives, but the objectives are largely a policy decision rather than a technical decision.

A list of questions to consider, with some example answers, is provided below to help the technical team identify the dam history, dam removal objectives, and potential sediment impact concerns related to reservoir sediment management.

- Who is the present owner and operator of the dam and associated facilities?

- How was the dam constructed and when? Has it ever been rebuilt?
    - Records on dam design and construction may be kept by the owner and also by local historical societies and described in old newspaper stories.

- What were the original and present purposes of the dam and reservoir? Is there still a need for these purposes and, if so, can these purposes be achieved through other means?
    - A water diversion dam replaced with a pumping plant or an infiltration gallery.
    - Hydroelectric power replaced by power from other existing power plants that feed into the electrical grid.

- Why is the dam being considered for removal?
    - Improve fish (or other aquatic species) and boat passage
    - Eliminate dam safety hazard
    - Improve hydraulic connectivity of ecosystem features upstream and downstream of the dam
    - Dam operations and repair costs are too expensive (i.e. economic decision)
    - Dam facilities are no longer needed or have been abandoned by owner
    - Permit or license expiration
    - Lost function of the reservoir due to sedimentation

- How will success be measured?
    - Restoration of natural flow regime (e.g. percent of year or percent of total annual flow restored by removing dam)
    - Reduction in temperature impacts from dam operations (e.g. improved temperature conditions from restoring natural flow connectivity to upstream river)
    - Increase in riverine habitat in former reservoir (e.g. length of channel including tributaries that meet potential habitat criteria, area of riparian forest formed in former reservoir for wildlife)
    - Restoration of sediment and wood loads to the downstream river (e.g. percent of watershed upstream of dams reconnected)
    - Improvement in habitat suitability for aquatic and riparian species throughout a target river reach (e.g. length of downstream channels with improved conditions)
    - Increase in aquatic species populations upstream from dam (e.g. length of channel opened up that meets potential habitat criteria,
    - Demonstration of safe boat passage (e.g. no remnant metal or debris
    - Demonstration of improved fish passage (e.g. meets velocity and depth requirements for passage throughout former dam and reservoir without barriers from exposed infrastructure or remnant boulders)
    - Elimination of dam safety hazard (e.g. unsafe infrastructure or hazards removed)
    - Net decrease in operations and maintenance costs
    - Eliminate liability
    - Increased river recreation (e.g. length of new hiking trails along former reservoir, length of river rafting available, number of fishing access points, area of new park open to public)
    - Restoration of cultural sites inundated by former reservoir

## Establish communication plan

A communication plan is essential to facilitate gathering of information, provide a forum to discuss key decisions, and engage the technical team with important partners, regulators, and stakeholders. Frequent and open communication between the dam owner, contractors, engineers, scientists, and stakeholders is essential to identify concerns and benefits and to maximize the likelihood of success. Communication plans identify who is involved and their role in the project, along with establishing mechanisms to share information and gather input. The communication plan should address the following questions:

- Who are the **decision makers** and what role will they play?
  - Dam owners
  - Facility operators
  - Land use managers
  - Federal, Native American, state agencies, or local government
  - Project managers

- Who will likely fund the project?

- Who are the **stakeholders** and how will information be conveyed to them and when?
  - Dam owners
  - Hydropower or water diversion users of dam facility
  - Federal, Native American, state agencies, or local government
  - Local government (county and city)
  - Landowners in reservoir impact area (may include river reach upstream of reservoir) and in downstream river
  - Water users
  - Private citizens
  - Recreation community
  - Local businesses
  - Non-governmental organizations (e.g. The Nature Conservancy, American Rivers, Trout Unlimited, Friends of the Earth)

- Who will comprise the **project team** and how will findings be conveyed to other groups in the communication plan?
  - Engineer
  - Geomorphologist and/or geologist
  - Botanist
  - Water quality specialist
  - Fish and wildlife biologist
  - Ecologist
  - Economist
  - Cultural resource specialist
  - Construction specialist
  - Cost estimator
  - Legal advisor

- Who will the **dam removal contractor** be and how and when will they be engaged?
    - Engaging an experienced contractor early in the dam removal decision making process can help inform how to remove the dam most efficiently and cost effectively.
    - Communicate expectations for completion of construction activities and metrics for project success such as was the desired riverbed elevation achieved or fish passage barriers removed.
    - Identify construction manager to facilitate interaction with other teams
- What types of **time sensitive, critical information** need to be conveyed during dam removal?
    - Altered flow or sediment releases during dam removal
    - Emergency notifications
    - Blasting or construction activities that may cause noise disturbance or unsafe conditions at the dam site, former reservoir, or in the downstream river
    - Traffic disruptions, including any haul and disposal routes
- What information needs to be conveyed to the **general public** and in what forums?
    - Community forums or town halls
    - Media releases including social media
    - Websites with pertinent information
    - Public education opportunities
    - Schedules and any required road detours
    - Closure of recreation areas or access points
    - Emergency notifications
- How will **land access** be authorized to collect reservoir and river data before, during, and after dam removal?

## Establishing a sediment analysis team

For a given dam removal, a team should be established to apply the sediment analysis guidelines and evaluate potential 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 2). 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 the relative sediment volume or potential risks, it may be worth investing in multiple, independent estimates from different methods or entities. If there is a risk that contaminated sediment may be present, expertise in sediment toxicology and 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, sediment quality, and based on the potential impacts to human health, ecosystem, and infrastructure. Inter-disciplinary teams are often utilized to evaluate impacts of concern with added expertise from ecologists, fisheries scientists, or natural resource specialists for ecosystem effects, water supply designers for intake modifications, or water quality specialists to evaluate contaminants.

Table 2.—Recommended expertise for the sediment analysis team.

| **Sediment Impact Risk (defined in Step 5)** | **Recommended Expertise** |
|---|---|
| Negligible | Engineers or scientists conducting the planning study should have general knowledge of river hydraulics, sediment processes, and geomorphology. |
| Small or moderate | The sediment analysis and planning study should be conducted by engineers or scientists who have expertise with river hydraulics, sediment transport, and geomorphology. Water quality expertise is required for contaminant assessment. Ecologists, biologists, and/or natural resource expertise should be represented to assess sediment impacts. |
| High | The sediment analysis and planning study should be conducted by engineers and scientists who have expertise and experience with river hydraulics, sediment transport, and geomorphology and have experience with other dam removal projects. Water quality expertise is required for contaminant analysis. Ecologists, biologists, and/or natural resource expertise should be represented to assess sediment impacts. |

## Review Permit Requirements

The release of reservoir sediment will require application and approval of permits that may be issued by federal, state, tribal, or local governments. The following agencies typically handle permits:

- Federal Energy Regulatory Commission for dams with hydroelectric power plants

- USACE for Clean Water Act Section 404 permit to discharge dredged or fill material into waters of the United States and the state agency responsible for issuing water quality certifications and permits (Sections 401 and 402)
- Environmental Protection Agency for actions affecting air quality (Clean Air Act)
- U.S. Fish and Wildlife Service and the National Marine Fisheries Service for actions affecting threatened and endangered species (Endangered Species Act)
- Tribal governments and the Bureau of Indian Affairs for actions affecting Native Americans
- State water resource agency having regulatory authority over dams or ordinary high water in river corridors.
- Federal Emergency Management Agency (FEMA) to address changes to floodway and floodplain
- State fish and wildlife agency
- Public utilities, local landowners, and other stakeholders
- County or city governments may require a demolition permit and regulate the transportation and disposal of waste materials
- Tribal and Federal agencies managing any historical or cultural assessments at the site

## CASES OF “NEGLIGIBLE” 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. This section describes how to verify if the sediment volume is “negligible” with minimal to no risk of inducing sediment-related impacts. If the sediment volume is verified to be negligible, the design team can focus on structural and river hydraulic issues related to removing the dam rather than on assessing sediment impacts. Reservoir impoundments with little or no sediment are typically behind low-head dams that are operated as run-of-the river facilities (i.e., no regular drawdown of reservoir storage for water supply or flood control).

For the purposes of these guidelines - *a negligible reservoir sediment volume is less than 0.1 (10 percent) of the average annual sediment load entering the reservoir*. Stream flows would be expected to rapidly erode and transport such a negligible reservoir sediment volume. Since computation of the average annual sediment load can require considerable effort, an alternative procedure is provided specifically for negligible cases that compares the reservoir sediment volume with typical alluvial channel dimensions.

First, estimate the reservoir sedimentation volume by probing of the reservoir sediment to the predam surface and/or underwater dive inspections to develop a map of sediment thickness (see Step 2b). Historical information and local knowledge is often helpful to verify the reservoir sediment volume. Historic dam operations and upstream land use may provide clues as to how much or how little sediment may be in the reservoir.

Next, compare the reservoir sediment volume to sediment storage features commonly see on the river, such as sand and gravel bars or other depositional features. These features can have a plan area similar to the river width squared and have a depth similar to the bank full depth. Therefore, the criteria for negligible reservoir sediment volume can be written as:

$$V_{sed} < W_B{}^2 D_B \tag{1}$$

Where $W_B$ is the average bankfull channel width and $D_B$ is the average bankfull channel depth in a nearby alluvial reach of the stream that is not significantly influenced by structures, tributary confluences, or other dams.

If the reservoir sediment volume is less than the volume of a sand or gravel bar as defined by equation 1, then conduct a few checks to help verify that the volume is negligible.

- The hydraulic height of the dam (reservoir water surface elevation minus the downstream river water surface elevation) would typically be smaller than the depth of a deep river pool at the bankfull discharge in a nearby river reach with a similar geomorphic setting. The selected river reach should be not significantly influenced by tributary flows between the reach and reservoir impoundment.
- A longitudinal profile plot of the reservoir thalweg (lowest point of a cross section) should be compared with the longitudinal channel profiles of the upstream and downstream river channels. The profile plots should include both the water surface and channel bottom along the upstream and downstream channel and through the reservoir impoundment. If little or no reservoir sediment is present, then the bottom profile through the reservoir should not be significantly elevated above the slope of the river channel thalweg. In some cases, a thin layer of fine sediment may be present along the reservoir bottom. Fine or coarse sediment may be trapped only within a former pool of the predam reservoir bottom profile or form a short ramp immediately upstream of the dam.

The removal of Gold Hill Dam in Oregon is an example case study with negligible sediment (see Example Case Studies). This was a low-head dam that was operated as run-of-the river. The reservoir sediment volume was less than the volume of a gravel bar, less than 10% of the average annual sediment load, and did not significantly alter the longitudinal profile of the riverbed. The ratio of the reservoir sediment volume to the average annual sediment load was 0.005 yr which is less than 0.1 and satisfies the negligible relative reservoir sediment volume criteria.

If the reservoir sediment is determined to be negligible, then the guideline user may skip the remainder of the guidelines and proceed with dam removal planning. The project may be eligible for nationwide permit 53 from the U.S. Army Corps of Engineers (2016). “Because the removal of the low-head dam will result in a net increase in ecological functions and services provided by the stream, as a general rule compensatory mitigation is not required for activities authorized by” Nationwide Permit 53. “However, the district engineer may determine for a particular low-head dam removal activity that compensatory mitigation is necessary to ensure the authorized activity results in no more than minimal adverse environmental effects.”

Determination of negligible sediment assumes any presence of contaminants is small enough to not pose any risks from downstream release to human health or ecological resources. If the reservoir sediment volume is greater than negligible, or if contaminants are present and thought to be harmful, then the guideline user should apply the full guidelines starting with Step 1.

# STEP 1: IDENTIFY SEDIMENT CONCERNS AND BENEFITS

In this first step, the project objectives, communication, concerns, and benefits need to be identified to properly scope the data collection and analysis. For example, project objectives for dam removal done primarily for dam safety can be quite different than those where dam removal is to improve fish passage. Communication with stakeholders is necessary to identify concerns and benefits. A conceptual model helps inform identification of concerns and benefits from release of sediment during dam removal.

## Step 1a: Develop initial conceptual model

To identify which sediment concerns apply for a given dam removal site, an initial conceptual model based on readily available information may be useful. Readily available information at this stage may be as simple as observations of reservoir and downstream river conditions from a site visit, aerial photograph comparisons, and previously developed topographic maps. The conceptual model should describe how the reservoir landscape may respond to dam removal and an estimate of how far upstream the erosion may extend. The conceptual model should also describe the potential downstream fate of eroded reservoir sediment by size class. In this first step, the conceptual model can simply assume the dam removal is rapid, meaning that the conceptual model does not have to include the period of time of actual dam removal. The conceptual model will later be expanded with more detail regarding sediment erosion and transport processes in Step 7, using information gathered in Step 2. Using the conceptual model as a guide to potential locations and timing of sediment impacts, the following questions can help guidelines users identify potential sediment concerns. If there is potential for contaminants, the conceptual model should also include potential sources at the dam site or upstream and potential pathways for transporting contaminants and receptors of concern in the downstream environment.

## Step 1b: identify sediment concerns

Concerns may be related to the amount of sediment released, the timing of sediment released, physical or chemical properties of material released, possible contaminants released, or duration of impacts. Stakeholders may be concerned about sediment impacts in the reservoir, downstream channel, and/or receiving waters. Document local sediment concerns after reviewing the following lists of possible impacts with stakeholders. The number of different impacts could range from very few to many and would typically increase with increases in reservoir sediment volume.

## Sediment impact concerns within the reservoir and upstream river reach

- Aesthetics of future landscape after dam removal
- Speed at which future reservoir landscape will revegetate and become more stable
- Invasive vegetation establishing on newly exposed landscape after dam removal
- Chronic reservoir sediment erosion for several years post-dam removal
- Potential for hillslope failure and bank erosion during or following reservoir drawdown that could endanger infrastructure, roads, recreation access points, impact land use functions, or human safety
- Impacts to cultural or historical resources from the possible erosion, exposure, or burial of cultural properties
- Reduced water level and yield for wells and water intakes associated with the reservoir (related to extent of reservoir drawdown)
- Reduced capacity of wells impacted by reservoir drawdown
- Temporary or permanent loss of recreation activities in the reservoir and downstream river channel
- Knickpoint migration endangering upstream infrastructure such as bridge piers, culverts, utility crossings, or property that may be at risk from undermining or bank erosion
- Stranding of fish during reservoir drawdown
- Erosion of spawning areas upstream of the reservoir during or after drawdown
- New access upstream or downstream past dam site by aquatic invasive species
- Odor of exposed organics in exposed sediment
- Increased mosquito or insect populations once reservoir is drawn down
- Trash or numerous mill logs remaining in former reservoir once drawn down

## Sediment impact concerns in the downstream river

- Possible release of contaminants during reservoir sediment erosion
- Deteriorated water quality due to increased suspended sediment levels or contaminants that could impact drinking water, cost of water treatment, or aquatic species (mussels, fish, etc.)
- Increased sediment concentration in diverted water that can lead to sedimentation in pipelines and canals
- Reduced permeability and capacity in wells due to fine sediment deposition along the river channel and floodplain
- Sediment deposition or burial at downstream water diversion structures, effluent or drainage outfalls
- Significant sediment deposition leading to increased flood stage and ground water levels in downstream river that would put land or infrastructure at risk such as levees, bridges, or culverts
- Increased streambank erosion and channel widening that would result in loss of land or infrastructure (e.g., levees, bridges)
- Burial of downstream aquatic spawning, rearing, and holding areas for threatened or endangered species or species of concern
- Burial of downstream aquatic species that cannot find refuge or quickly mobilize out of sediment impact areas (mussels, invertebrates, etc.)
- Increased deposition in floodplains that could result in change in riparian vegetation when existing species are not tolerant of burial
- Change in aesthetics of river landscape or water color
- Increased wood loads that could block culverts or impact conveyance through bridge openings
- Burial or erosion of recreational use areas including boat ramps, swimming areas, beaches, campgrounds, fishing areas, docks, and moorings
- Increased sediment loads from legacy sediments that may have been deposited during periods of excessive landscape erosion due to land use impacts (see Appendix A)
- Increased exposure to ice jams whose impact are currently mitigated by the dam and reservoir

### Sediment impact concerns in the downstream receiving waters (e.g. lakes, marine environment)

- Deteriorated water quality due to increased suspended sediment levels or contaminants that could impact aquatic species (mussels, fish, etc.).
- Increased nutrient and pollutant loads in downstream bays or estuaries where released sediment deposits
- Sediment burial of aquatic habitat in the estuary or near-shore zones for threatened or endangered species or species of concern
- Sediment deposition blocking aquatic species migration routes
- Expansion of estuary channels leading to channel widening and increased streambank erosion that would result in loss of land or infrastructure
- Sedimentation in downstream reservoirs
- Deposition along recreational use areas including navigation channels at the river mouth and fishing or harvest areas
- Increased deposition at or near river mouth affecting coastal seawalls, jetties, and docks
- Deposition at coast exasperating tidal inundation of coastal roads or infrastructure

## Step 1c: identify benefits from sediment release

While release of sediment may have temporary adverse impacts, restoration of sediment loads to downstream river reaches often initiate positive long-term ecosystem responses. Step 1c provides an opportunity to frame a discussion on weighing the impacts of sediment release against the benefits. A few examples of potential benefits from dam removal and sediment release are listed below:

- Restoration of riverine habitat in reservoir area
- Restoration of heterogeneous grain sizes and sediment bars that support development of more diverse channel processes such as channel migration
- Increase in physical habitat features that provide ecosystem benefits, such as channel spawning gravels, bars, islands, large wood features, and side channel activation
- Facilitate growth of invertebrate communities
- Natural disturbance and sedimentation required for riparian vegetation
- Replenishment of sediment sources to coastal beaches at the mouths of rivers potentially reversing erosion

- Positive benefits to estuary ecosystem
- Turbidity may benefit certain species by providing protection from predators (e.g. humpback chub and razorback sucker on Colorado River native)
- Sedimentation may help reconnect floodplains where lack of sediment supply has caused incision
- Connectivity of nutrients and organic matter (vegetation and all sizes of woody material) from upper watershed can be restored
- Restoration of the floodplain and of sediment bars for wildlife use
- Enhanced river recreation opportunities
- Less chance of uncontrolled flow releases

# STEP 2: COLLECT RESERVOIR AND RIVER DATA

To determine the probability of sediment impacts in Step 4, baseline data are needed to estimate the reservoir sediment volume, sediment gradation and spatial distribution, and whether contaminants are present. Several questions have been created to help guide this initial data gathering for a dam removal study. The guideline's user should synthesize existing information to help answer the questions and determine if there is enough information to move forward with the guidelines steps (Step 2a), and supplement with reservoir and river data collection where data gaps exist (Steps 2b and 2c). Initially, assumptions can be made where information is sparse, but these assumptions must be verified later. New field data are typically collected in more detail to fill in possible gaps in the existing data and to verify previous assumptions. The reservoir sediment volume, grain size characterization, and bulk density surveys should be coordinated when possible for efficiency and improved characterization. For example, if coring is utilized to determine sediment thickness, then cores could also be sampled for grain size and analyzed for bulk density concurrently. For the purposes of this document sediment is categorized as either fine (silt and clay) or coarse (sand, gravel, and cobble).

## Step 2a: compile and synthesize available information

Many projects have a wealth of available information and resources that should be compiled and synthesized. Step 2a includes compiling existing data, conducting a site reconnaissance, and developing a conceptual site diagram of sediment sources, sediment concerns, and potential data collection needs. While reviewing historical reports for the site, look for reservoir sedimentation studies or bathymetric survey reports that document reservoir topography, reservoir sediment gradation, and deposition patterns within the reservoir. A potential resource for federal reservoirs is the RESSED database (Subcommittee on Sedimentation, 2013).

### Conduct site reconnaissance

The site reconnaissance should document physical conditions for the reservoir, upstream river, and downstream river areas of interest including:

- Spatial extent of reservoir sedimentation both laterally and upstream
- Qualitative probing of reservoir sediment to estimate potential grain sizes present or various geophysical techniques
- Vegetation and large wood presence in the reservoir

- Geomorphic setting of the reservoir
- Geologic controls along the reservoir (e.g. constrictions, bedrock, terraces)
- Infrastructure and land use along the reservoir
- Tributary confluences within the reservoir
- Old infrastructure that may be partially buried or located along the reservoir
- Sediment and wood sources and depositional features upstream from the reservoir delta
- Assess the reaches of concern downstream of the dam
    - Depositional zones with relatively lower transport capacity such as inlets to natural or dammed lakes
    - Reaches that have relatively wide floodplains and sediment storage potential
    - Tributary junctions and relative flow and sediment contributions
    - Confluences with a downstream river
    - Infrastructure built on low-level floodplains
    - Areas containing bridges, levees, recreation use
    - Reaches with water intakes or effluent outfalls
    - Estuary and coastal zones expected to have new deposition
    - Marinas or docks

## Develop conceptual diagram

Early in the process of dam removal it is often useful to develop a working diagram of the project site (sediment sources) and potential areas of concern for sediment impacts (see Step 1). This diagram can help communicate information to stakeholders, permitting agencies, and decision makers on where the sediment originates and how it may interact with downstream reaches of interest. The diagram can also be utilized to identify proposed data collection locations for Step 2 where gaps and uncertainties need to be addressed. The diagram can be generated as a table, a graphical image from a longitudinal perspective along the river corridor, or a watershed perspective. The complexity of the conceptual diagram should be proportional to the risk of sediment impacts, and may be iterative as more information is gathered throughout the project.

In addition to the conceptual diagram, there should be a narrative synthesis of existing information and data gathered during reconnaissance field trip. The purpose of synthesis is to (1) develop a good understanding of how the entire catchment has physically changed (river planform, incision, etc.) from predisturbance conditions; (2) how the river reach is functioning geomorphically with the dam in place; and (3) how the river reach may respond geomorphically once the dam is removed. The river reach should include the channel upstream from the reservoir area to the downstream limit of possible impacts.

Wildman and MacBroom (2010) developed a classification system for dam removals that can help predict the nature of the reservoir landscape post dam removal, along with a qualitative assessment of potential downstream sediment impacts. Data needed to apply the classification system include the relative amount of reservoir sediment (minimal versus significant), reservoir width relative to a typical river channel width, whether or not there is a highly defined legacy (predam) channel, the reservoir sediment grain sizes (fine or coarse), and if the fine reservoir sediment is cohesive. Gaps in data can be addressed when undertaking Steps 2b and 2c.

## Describe the dam history and site conditions

A list of questions is provided below to help engineers and scientists learn about the dam's history, reservoir operations, and watershed and stream channel. The level of effort needed to answer these questions depends on the size and complexity of the project. At a minimum, each question should be answered with a sentence or short paragraph or note that the question is not applicable for the specific project. Potential sources of historical information include: ground photographs or postcards (local museums, dam owners, and dam operators), design drawings, log books of reservoir operations for the project, aerial photographs, topographic maps, and other data of the project area that document the project history. Technical reports describing the dam may be found from government agencies, consultants, universities, or dam operators and owners.

- What is the hydraulic height and crest length of the dam?
    - Dimensions of the dam can be obtained from design drawings, but can also be obtained by direct measurement in the field. The hydraulic height is the difference between the normal reservoir pool elevation and the downstream river water surface during the mean discharge. The hydraulic height is usually less than the structural height. (If a dam were built on a bedrock waterfall, the hydraulic height could be greater than the structural height.) The structural height of a dam includes the foundation and portions above the reservoir water surface. Dam foundations are often keyed into bedrock. Removal of the foundation below bedrock is normally not needed to restore the hydraulic function of the stream channel. However, construction requirements should specify that any remaining portions of the dam foundation should not pose a public safety hazard or, where applicable, impede fish passage.

- Has the reservoir pool been lowered or raised in the past (e.g. use of stop logs, flashboards, low-level outlets)?

- What is the type of dam to be removed (e.g. concrete, earth, rock, or masonry; gravity, arch, or buttress)?

- What type of topography was the dam located on? (e.g. narrow bedrock canyon, wide river valley, natural lake)

- Was any natural ground excavated to create a reservoir pool or enlarge an existing lake?

- If a dam was constructed to enlarge a natural lake, was an outlet created to drain the lake below the natural outlet elevation?

- Were the vegetation and stumps cleared prior to reservoir filling?

- Was the dam rebuilt at any time in the past? Is there a cofferdam still located upstream of the dam? Did the dam inundate a previous dam?

## Describe reservoir sedimentation and operations history

Sometimes the purpose and function of a dam and reservoir evolve since the time of dam construction. For example, dams constructed to serve an abandoned industry such as the old saw mills in Maine. A change in operational practices (e.g. reservoir pool level and range in fluctuation) can affect the sediment trap efficiency and the sedimentation volume and spatial distribution. For example, reservoir sediment trap efficiency would be less if a dam had sluice gates that are normally used to pass sediment downstream or if the reservoir were frequently drawn to a low pool elevation. Conversely, the reservoir sediment trap efficiency would be higher if the reservoir was normally kept full and the dam did not have, or utilize, sluice gates. The following questions can improve understanding of temporal changes in reservoir sedimentation.

- 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 maximum 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.

- o Normally empty for flood control. Under this type of reservoir operation, any sediment would tend to accumulate near the dam.

- What is the original and current reservoir storage capacity for water?

- 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 filled to near capacity.

- Have there been 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 average annual river flow and reservoir sediment trap efficiency? A very low sediment trap efficiency (< 5 percent) is an indicator that the reservoir has not accumulated significant quantities of sediment. In contrast, high sediment trap efficiency (> 90 percent) is an indicator that the reservoir has accumulated a large volume of sediment.

- 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 small fraction of the reservoir age.

- What is the lateral and longitudinal extent of reservoir sediment deposits from the site reconnaissance observations, available topography data, or aerial imagery?

## Characterize the watershed context

Answers to the following questions will help provide context for the reservoir within the watershed setting:

- Where is reservoir located within the watershed?

- What are the general trends in slope and valley confinement within the watershed?

- What are the longitudinal channel slopes and active channel widths upstream and downstream of the reservoir and how does that compare the expected predam conditions of the reservoir?

- What is the general vegetation cover and have there been significant fires or disturbance that affects sediment yields?

- Where are the major types of sediment sources and locations in the watershed upstream and downstream from the dam site (e.g. tributaries, river terraces, debris flows, landslides) and how does this compare to expected reservoir sediment volume and sediment gradation? Answers can be used to put the volume of reservoir sediment in context with the proximity and magnitude of other sediment sources in the watershed.
    - What is the watershed geology and what types of sediment are contributed to the river as a result?
    - Is there a glacial history in the watershed that resulted in high sediment loads?
        - Are glaciers still active and contributing sediment to the downstream river?
        - Are there any moraines?
    - Where are there significant sediment sources upstream from the dam?
    - Where are the closest major tributaries that enter the downstream channel?

- Are there significant wood loads into the reservoir?

- Are there any upstream or downstream dams and reservoirs that trap sediment?
- Is sediment currently transported past the dam or is the reservoir still accumulating sediment?
- What are the watershed land uses, both current and historical?
- Have recent forest fires or landslides occurred that may have affected incoming sediment, nutrient, and wood loads?
- Are there any potential sources of sediment contamination upstream or around the reservoir (also see contaminant source investigation)?
- What other engineering modifications of the river channel have taken place upstream and downstream from the reservoir and dam site and how have these modifications altered the channel from natural conditions?

## Characterize hydrology

Using available stream gage data or hydrology reports for the watershed, identify the key hydrologic parameters (see list below) for the project site that could influence dam removal methods, dam removal construction, and sediment release timing. If no stream gages are available, the StreamStats Program (USGS, 2017b) can be used to estimate streamflow statistics. Hydrologic trends over recent decades may be needed to analyze how removal of a storage reservoir(s) will change downstream hydrology for both low and high flows.

- What is the typical annual hydrologic regime (e.g. when do floods and low flows typically occur)?
- What are the average annual stream discharge and the peak discharge of the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year floods?
- Is flow perennial or intermittent?
- How often do high flows occur that may help flush sediment?
- Are there any major flood control reservoirs upstream that alter hydrology and reduce flood peaks or frequency?
- Have there been significant changes to runoff events due to land cover, land use, and/or climatic changes?
- Are there any significant tributary inputs of flow and sediment within the reservoir or downstream?

- How do stream flows, during in-water work periods of dam removal, compare to the typical annual hydrologic pattern of stream flows?
- Are there any diversions in the vicinity of the dam and reservoir site?
- Do ice jams occur?

## Step 2b: conduct reservoir sediment survey

Initially, existing data and qualitative field reconnaissance should be used to get an order of magnitude estimate of the reservoir sediment volume. 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 chimney sweep rod 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 coring device can be used to collect samples for visual assessment. Divers may also be useful to identify the location and general character of sediment deposits. In large reservoirs, sediment present in the exposed delta or reservoir margins may provide a first indication of sizes present. Simultaneous collection of geographic coordinates allows the creation of a map of sediment type. This estimate should then be used to determine the level of effort necessary for additional field measurements.

Reservoir sediment deltas, if they exist, typically extend upstream from the reservoir and often look like a river channel with alluvial bars. However, the longitudinal slope of the delta is typically about one-half of the natural river channel slope (Reclamation, 2006). Longitudinal profile surveys are needed of the reservoir bottom and upstream river channel. The longitudinal profile should extend far enough upstream to capture sedimentation within riverine areas beyond the full reservoir pool. An existing longitudinal profile of the top and bottom of reservoir sediment, along with the upstream and downstream river profiles, help describe the thickness of the reservoir sediment, which can be related to the total reservoir sediment volume.

In addition to identifying the upstream extent of reservoir sedimentation, the lateral extent of reservoir sediment deposits should be delineated. The original reservoir shoreline is a good guide to where sedimentation may occur. Some sources may include project data books, historical maps, design drawings, aerial photographs, and historical accounts. In reservoirs that have fluctuating pool elevations, sediment deposits may extend laterally beyond the normal operating pool. Vegetation can grow on the exposed reservoir sediment deposits, so the location of vegetation may not be a good surrogate for the extent of deposition.

Another way to identify reservoir sediment deposits is to look at the vertical stratigraphy. Lake and reservoir deposits will have a different signature than fluvial deposits. An experienced geomorphologist can help differentiate reservoir and fluvial deposits. Historical land use and records of old dams that are no longer present may also be informative with mapping.

## Produce topographic and bathymetric map

When the reservoir sediment volume may be significant, a bathymetric survey of the reservoir pool, and topographic survey of sediment exposed above the reservoir pool, is recommended. Bathymetric surveys are typically conducted from boats using single or multi-beam depth sounders and global positioning system (GPS) survey instruments (Reclamation, 2006). The above-water surveys can be conducted using GPS, photogrammetry, or LiDAR.

Reservoir sediment survey data collection tips include:

- Perform a topographic ground survey of the reservoir exposed above the water surface, including the shoreline and upstream deltas that typically extend beyond the reservoir pool
- Measure the bathymetry of the submerged reservoir bottom using a depth sounder mounted on a boat
- Document any tree stumps within the reservoir pool that may provide an indication of the predam reservoir bottom
- Document any vegetation growing on the reservoir sediment deposits
- Document topographic or bathymetric slope breaks that can help identify the predam river, floodplain, terraces, and valley hillslopes
- Document any known or observed infrastructure (e.g., old dams, coffer dams, buildings, roads, bank protection) that may be inundated by the reservoir or buried by sediment

## Estimate the predam topography and reservoir sediment volume

The predam topography is important for either verifying or computing the reservoir sediment volume. The predam topography will also help predict the reservoir topography after dam removal, especially if nearly all of the sediment is eroded or removed. An accurate estimate of the reservoir sediment volume is needed to compare with the average annual sediment load of the stream channel and to predict downstream impacts if it were allowed to erode downstream.

The reservoir sediment volume is computed either by subtracting the predam topographic surface (if available) from the present surface of the reservoir bottom or from direct measurements of sediment thickness and the sediment surface area corresponding to that thickness. The predam valley bottom topography is often the most challenging component with the greatest uncertainty in development of a reservoir sediment volume. This is mostly because previous surveys were done so long ago. If the reservoir sediment thickness is about the same or less than the predam contour interval, it is difficult to accurately estimate volumes from a surface difference.

If the predam map topography is inaccurate, not at a high enough resolution, or simply not available, then the sediment volume is computed from thickness measurements. The thickness of sediment over the predam topography often varies spatially throughout the reservoir, so areas where the thickness is significantly different need to be identified. The sediment volume of each area is the product of the surface area and average thickness. The number of different areas will depend on the number of thickness measurements and their variability. The total reservoir sediment volume is the sum of the sediment volumes from all the individual areas of the reservoir, including the upstream deltas that extend beyond the reservoir pool.

The reservoir sediment thickness is measured by the use of coring, drill holes, or thickness probes. For example, coring was used to estimate reservoir sediment volume for three reservoirs on the Klamath River where sediment thicknesses were typically equal to or less than the 3-m (10-ft) contour interval of the predam maps (CDM, 2011). Thickness probes may only extend 1 or 2 m (3 to 6 ft) and subsequently measure the minimum thickness. Sediment samples can be collected using vibracoring methods. The vibracore operates on hydraulic, pneumatic, mechanical, or electrical power from an external source. Geophysical methods (e.g. seismic refraction) or dual frequency depth soundings may help determine the spatial variation in sediment thickness.

Another method is to estimate the predam channel slope by extrapolation of the existing upstream and downstream river profile slopes into the reservoir area (Figure 8). 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 tens of meters thick above the reservoir pool stage. 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.

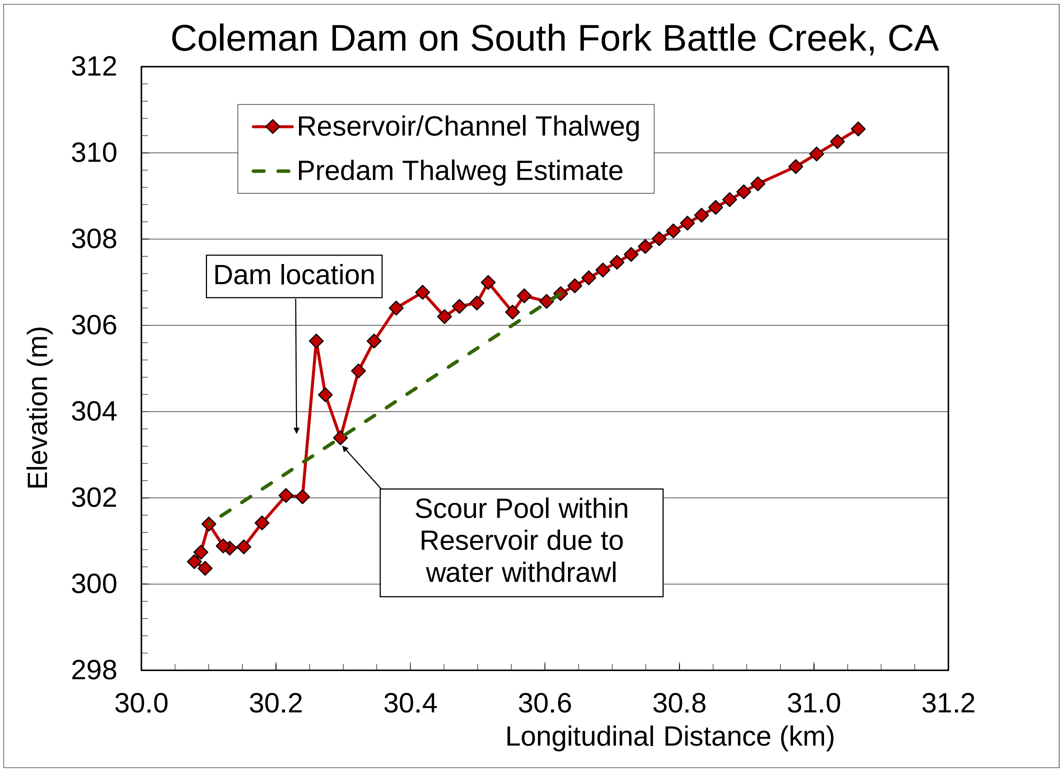



**Figure 8.—Example estimate of the predam profile through reservoir sediments at Coleman Dam on South Fork Battle Creek, CA.**

The channel bed downstream of the dam can be significantly lower than the pre-dam channel because of two reasons: 1. Sediment starved flow in the river below the dam will pick up sediment from the downstream river bed and lower bed elevations. This lowering of bed elevations can occur for several miles downstream of the dam; 2. Local scour or channel degradation can occur from decades of water being passed over or through the dam with high velocity and the trapping of coarse sediments within the reservoir. Therefore, the existing channel profile immediately downstream from the dam may be lower than the predam channel profile in areas affected by local scour. For example, the channel bed below Savage Rapids Dam on the Rogue River in Oregon had been scoured by high velocity releases through radial gates each spring and fall.

## Measure the reservoir sediment sizes and spatial deposition patterns

Reservoirs may have trapped coarse sediment, fine sediment, or a combination of both depending on the upstream sediment supply and the reservoir sediment trap efficiency. The reservoir trap efficiency for fine sediment can be much less than the trap efficiency for coarse sediment. For example, the sediments trapped behind a small diversion dam may be predominantly coarse with little or no fine sediment. A medium sized reservoir may trap a significant volume of fine sediment, but this volume may be less than the coarse sediment volume if the travel time of water through the reservoir is short (e.g. hours). A large reservoir would likely trap the entire sediment load of coarse and fine sediment and the volume of fine sediment may dominate.

Determining the quantities of coarse sediment and fine sediment is important because these sediment types respond differently to dam removal. Fine sediment can resist erosion through cohesion and, when eroded, is transported as suspended load throughout the stream flow. Coarse sediment can resist erosion through the particle weight and, when eroded, tends to be transported close to bottom of the stream.

The description of the reservoir sediment spatial distribution and size gradation should identify the quantities of coarse and fine sediment and their locations within the reservoir. There are a variety of methods that can used to collect sediment samples to quantify sediment size gradations, depending on the sediment thickness and accessibility of the site:.

- Draining or lowering of the reservoir pool to allow sampling from the surface and from test pits and terrace banks.
- Hand coring of sediment samples is typically limited to depths of 2 to 3 m (5 to 10 ft) (U.S. EPA, 2001 and Ohio EPA, 2001).
- Bed-material sampling of the submerged sediment surface. Bed-material samplers are sanctioned by the Federal Interagency Sedimentation Project (FISP, 2017).
- Collecting underwater surface samples or cores by divers.
- Core sampling using a vibracore or drill rig from either a barge over water or truck on dry land (U.S. EPA, 2001 and Ohio EPA, 2001). The vibracore operates on hydraulic, pneumatic, mechanical, or electrical power from an external source.

The amount and size of wood that is present within the reservoir sediment should be estimated based on field observations. The potential for old structures or debris buried in the reservoir sediment should also be documented because these features could potentially limit headcut erosion or lateral sediment erosion during dam removal. A series of questions has been crafted to help describe the depositional pattern of the reservoir sediment:

- 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 deposits
  - Reservoir margin deposits

- 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. The predam reservoir channel profile may have to be estimated from profiles downstream and upstream from the reservoir.

- Is a reservoir delta present in the longitudinal profile? The presence of a delta can also be determined 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, document that it cannot be determined at this stage.

- What is the ratio of the reservoir delta length to the original reservoir length?

- Have any debris or structures been observed that would slow or limit reservoir sediment erosion?

- Have logs been noted to deposit in the reservoir or be transported during floods over the dam?

- Were predam trees completely removed, left in place, or logged with stumps remaining? Presence or absence of tree stumps can affect incision rates, collection of debris, and erosion patterns during drawdown.

- 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?

- Are there tributaries that enter the reservoir and create additional depositional features?

## Determine reservoir sediment mass

The reservoir sediment mass or weight (Mg or tons) may have to be determined from the sediment volume ($m^3$ or $yd^3$) for comparison with the estimated annual sediment load if that is also based on mass (Mg/year) or weight (tons/year). The reservoir sediment mass can be determined by multiplying the volume by the unit weight or bulk density (dry weight per unit volume). The sediment unit weights in a reservoir can vary with spatial distribution, depth, particle grain size, and with time. Therefore, the reservoir sediment mass can be computed for each reservoir zone or grain size.

The best source for obtaining the unit weight of reservoir sediment is by direct field measurement (ASTM International, 2014). Sediment samples are collected from a known volume of sediment, the dry weights are measured, and the ratio of dry weight to volume is computed.

The sediment unit weights can also be estimated from empirical data. Morris and Fan (1997) reported unit weights by the dominant grain size. It is reported for various sizes of reservoir sediments for cases where the sediment is always submerged and cases where the sediment is exposed above the water surface (Table 3).

Strand and Pemberton (1982) and Reclamation (2006) reported the initial unit weights for the individual grain size classes of clay, silt, and sand-sized reservoir sediment under different reservoir conditions (Table 4). To develop the unit weight of the entire reservoir deposit, the unit weights of the individual size classes would have to be combined together based upon their mass as described in (Strand and Pemberton, 1982). The unit weights of clay and silt would be expected to increase over time as the sediments compact (Strand and Pemberton, 1982). Clay would be expected to compact the most. Reservoir sediment with fine grained, unconsolidated sediment and significant organic content may have dry unit weight values less than reported in the literature. For example, Copco Reservoir on the Klamath River had a dry unit weight of 0.32 $Mg/m^3$ (20 $lbs/ft^3$) (Greimann et. al, 2012).

Table 3.—Reservoir sediment dry unit weights in Metric and English units reported by Morris and Fan (1997).

| Dominant grain size | Always submerged | Exposed above water |
|---|---|---|
| Clay | 0.64 to 0.96 $Mg/m^3$ | 0.96 to 1.28 $Mg/m^3$ |
| Silt | 0.88 to 1.20 $Mg/m^3$ | 1.20 to 1.36 $Mg/m^3$ |
| Clay-silt mixture | 0.64 to 1.04 $Mg/m^3$ | 1.04 to 1.36 $Mg/m^3$ |
| Sand-silt mixture | 1.20 to 1.52 $Mg/m^3$ | 1.52 to 1.76 $Mg/m^3$ |
| Clay-silt-sand mixture | 0.80 to 1.28 $Mg/m^3$ | 1.28 to 1.60 $Mg/m^3$ |
| Sand | 1.36 to 1.60 $Mg/m^3$ | 1.36 to 1.60 $Mg/m^3$ |
| Gravel | 1.36 to 2.00 $Mg/m^3$ | 1.36 to 2.00 $Mg/m^3$ |
| Sand-gravel mixture | 1.52 to 2.08 $Mg/m^3$ | 1.52 to 2.08 $Mg/m^3$ |

| 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 $lbs/ft^3$ |

Table 4.—Initial unit weights of reservoir sediment reported by Strand and Pemberton (1982).

| Reservoir Condition | Clay | Silt | Sand |
|---|---|---|---|
| Reservoir always full | 0.42 $Mg/m^3$ | 1.12 $Mg/m^3$ | 1.55 $Mg/m^3$ |
| Reservoir periodically drawn down | 0.56 $Mg/m^3$ | 1.14 $Mg/m^3$ | 1.55 $Mg/m^3$ |
| Reservoir normally empty | 0.64 $Mg/m^3$ | 1.15 $Mg/m^3$ | 1.55 $Mg/m^3$ |
| River conditions | 0.96 $Mg/m^3$ | 1.17 $Mg/m^3$ | 1.55 $Mg/m^3$ |

| 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 $lbs/ft^3$ |

## Step 2c: collect river data

The general characteristics of the river channel are necessary to identify potential concerns from released reservoir sediment and to accomplish computations in the guidelines Step 4. The minimum data required for Step 4 are listed below. If the risk assessment identifies a need for river analysis (e.g. modeling, field studies) in Step 7, additional river data including main channel and floodplain topography, bed material gradation, and characteristics will need to be collected.

- Measure the river profile and slope downstream from the dam to inform which reaches might be transport versus depositional reaches. Use readily available topographic data such as USGS quadrangles, LiDAR, or past studies. The extent of analysis should ideally be for the entire watershed within which the dam site is located. Exceptions might occur where large reservoirs are located upstream that have large storage capacity and high trap efficiency.

- Visually estimate the composition of streambed materials along the river channel upstream and downstream of the dam and reservoir site (e.g. clay, silt, sand, gravel, and cobble). Estimate the median and maximum bed material sizes ($D_{50}$, $D_{90}$).

- Topographic surveys of river channel geometry may be needed for Step 4 (incoming sediment load) and Step 7 (downstream river transport capacity). Collect data in each reach where there is concern about sediment accumulation from the release of reservoir sediment.

- Conceptually predict future river patterns and extent of potential migration.

- Visually estimate extent of floodplain and note any geologic controls that influence river slope or lateral confinement (e.g. bedrock canyons, glacial moraines).

# STEP 3 EVALUATE POTENTIAL FOR CONTAMINATED SEDIMENT

To determine if reservoir sediment can be released into the downstream channel during dam removal, the potential presence of contaminants within the reservoir sediment must be addressed. Determination of whether contaminants are an influencing factor in the sediment management plan can be done concurrently with Step 2: Data Collection and Synthesis (see Figure 7).

The guideline user is instructed to first review available data to see if a decision can be made regarding presence of contaminants and if present, if acceptable to release downstream. In lieu of readily available information, a multi-step approach is used to determine if there is “reason to believe” contaminants may be present (Step 3a), and if yes whether the contaminated sediment can be safely released into the downstream river (Steps 3b and 3c). Step 3b focuses on chemical sampling analyses and provides recommendations on how many samples to collect and what types of chemical analysis to conduct to compare with sediment quality criteria and background levels. Step 3c focuses on biological analysis including bioassays, bioaccumulation studies, and elutriate tests for pathways and receptors of concern to determine if contaminated sediment can be released. Pathways considered are suspended sediment in the water column, or deposits that may accumulate along the river bed, in sediment bars, or on the floodplain. Receptors can include aquatic invertebrates, aquatic species such as fish or mussels, benthic invertebrates, birds and wildlife, and humans including consumption through fish/wildlife or drinking water intake. For cases that cannot release the sediment, options are provided for contaminated sediment management. A monitoring program is recommended to ensure sediment management plans are properly implemented and no adverse, unanticipated effects occur. Consideration should also be given to potential benefits from sediment release and dam removal, and if these benefits outweigh impacts while still meeting criteria for release of contaminants.

This document’s contaminant guidance was informed by federal recommendations for evaluating contaminants in sediment proposed to be dredged and disposed or released to inland waters, which has similarities to determining if reservoir sediment can be safely released into the downstream river during dam removal (U.S. EPA and USACE, 1998). Most dams will at a minimum need to address freshwater sediment quality guidelines or standards, but some may also need to address standards related to disposal (downstream transport) into marine environments (U.S. EPA and USACE, 1991). Teams will also need to address any regional sediment management standards developed by state or county agencies. An example from the U.S. Pacific Northwest is the dredged material management program for Washington State and the sediment evaluation framework developed for dredging projects in Oregon, Washington and Idaho (USACE et al. 2015; NRSET, 2016). Teams should also coordinate with fisheries agencies or landowners and resource managers that may have unique requirements, especially with in-water beneficial reuse or habitat creation projects.

An example of toxic contaminant release associated with dam removal was the Fort Edwards Dam on the Hudson River upstream of Albany, removed in 1973. The dam was unsafe and was removed with all applicable permits. As a result of dam removal, reservoir sediments contaminated with polychlorinated biphenyls (PCBs) from upstream industries were released into the downstream river during and after a large flood. Once the presence of contaminants was determined (after dam removal), 2 million $m^3$ of river sediment had to be dredged (Evans, 2015). A more contemporary example was the removal in 2008 of Milltown Dam located at the confluence of the Blackfoot and Clark Fork Rivers in Montana, which had high levels of heavy metals (arsenic, copper, lead, and zinc) from historical mining and was a designated superfund site (Evans and Wilcox, 2014; Moore, 2016). Milltown Dam removal used a combination of sediment management techniques that included passive treatment of sediment pore water, isolation of contaminated sediment from surface water and removal of 2 million $m^3$ in the dry, and mitigation to reduce erosion using bypass channels and regrading techniques. Suspended sediment and copper loads released into the downstream river were increased during substantial remediation activities at the dam and reservoir site relative to background loads; after remediation activities constituent loads approached typical conditions, but monitoring reports noted additional planned restoration activities could cause additional erosion and sediment release from the project site (Sando and Landing, 2011). The Baker and T&H Dams along the Neponset River in Boston have such high PCB concentrations that they have not yet been removed (written communication Jim MacBroom, March 3, 2017). These studies emphasize the importance of linking the contaminant analysis concurrent with the sediment risk assessment.

## Step 3a: determine if contaminants are of concern

The purpose of Step 3a is to perform due diligence assessment to see if there is cause for concern regarding the presence of contaminants. The main factors most commonly associated with contaminant presence include land uses in the upstream watershed and facilities at the dam and around the reservoir that could result in contaminants within the reservoir sediments. If there is no cause for concern, the guideline user can bypass the remainder of Step 3 and proceed to Step 4. If Step 3a yields contaminant concerns or there is insufficient data, then proceed to Step 3b for further testing and analysis.

## Guideline Decision Question: Does the due diligence assessment identify a contaminant concern?

- No concern, proceed to Step 4
    - If no cause for concern from the due diligence assessment AND the reservoir sediments are less than 10 percent silt and clay by volume (Step 2 data), then contaminant testing IS NOT necessary and sediment is safe to be released
- Yes concerns identified, proceed to Step 3b
    - Due diligence identifies potential sources of contaminant and reservoir sediment contains more than 10 percent silt and clay by volume (Step 2 data), then contaminant testing IS necessary

Many states assume reservoir sediments are contaminated until proven otherwise, and require collection and analysis of a certain number of sediment samples at the start of a dam removal project. If contamination is not automatically assumed, the guideline user should perform a due diligence assessment of available information for the site including potential for contaminants based on an upstream watershed history, similar to the Step 3a Site Evaluation and History in the Dredged Material Evaluation and Disposal Procedures (USACE et al. 2015). The upstream extent of the watershed investigation depends on the size of the reservoir and the degree of historical disturbance. A minimum assessment area defined as the stream-reach impounded by the dam, plus a one-mile lateral buffer. The length of the upstream buffer depends on the distribution of contaminant dischargers; for example, reservoirs along the Kalamazoo River in Michigan are contaminated with PCBs from historical point sources located dozens of miles upstream. This approach is consistent with the American Society of Testing and Materials Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process (ASTM International, 2005 and 2008). However, in watersheds with steep slopes (high transport rates) and confined river corridors, perform at least a cursory due diligence assessment of the entire watershed for potential sources of contaminants. The following questions should be answered to complete the Step 3a investigation.

Due Diligence Assessment for Sources of Contaminants:

- Were there any historical or current land use activities (e.g. mining, industrial, agricultural, urban) at or near the dam and reservoir site that could have contributed contaminants to the reservoir?
- Are there any sediment quality data from the vicinity of the site that indicate contaminants?
- Were there any historical or current land use activities (e.g. industrial, agricultural, urban), in the watershed upstream from the reservoir site that could have contributed contaminants to the reservoir?

- Are there any natural sources or atmospheric sources of contaminants within the watershed (e.g. arsenic or mercury)?
- Are there ongoing or historical upstream sources of contaminants?
- What are the most likely contaminants that might be discovered? (Note that many states use a pre-determined list of likely contaminants, usually including PCBs, PAHs, a suite of metals, and certain pesticides if their presence is suspected.)
- Are there industrial wastewater discharges?

Likelihood of Retaining Contaminants:

- How does the historical or current contaminant activity compare with the age of the reservoir and period of time reservoir sedimentation has occurred?
- Are fine-grained sediments present in the reservoir deposit that have the potential to retain contaminants? If this is unknown, either collect sediment samples or estimate the reservoir sediment trap efficiency of the reservoir to estimate the portion of fine sediments in the reservoir.
- Were there major floods that could have transported contaminants to the reservoir impoundment from upstream areas identified as a concern?
- Were there major floods or dam maintenance operations such as periodic drawdowns for repairs or flood relief that could have flushed contaminated sediments from the reservoir?

Data sources to accomplish the due diligence assessment may include:

- agency records and permits,
- historical project operations,
- zoning maps,
- databases for land use (see more detail below),
- databases for ambient water quality
  - NAWQA regional studies accomplished in 2013 to 2018 (about 100 small streams per region)
  - U.S. EPA National Rivers and Stream Assessment (U.S. EPA, 2017a)
  - USGS Columbia Environmental Research Center
- interviews with site managers, property owners, stakeholders, adjacent landowners, and staff knowledgeable on watershed land use and site history,
- National Pollutant Discharge Elimination System permit reviews,
- identification of hazardous waste sites,

- environmental studies for the watershed prepared by others, especially those which may have sediment or water chemistry data, and
- reconnaissance of the site

Databases for land uses frequently associated with pollutant release to the environment can be accessed on line or through files maintained by State and Federal natural resource management agencies. For example, the U.S. EPA’s Facility Registry System identifies facilities, sites or places subject to environmental regulations of air, water, and waste interest (U.S. EPA, 2017b). U.S. EPA’s Envirofacts Database identifies facilities with air and water waste discharge permits, solid or hazardous waste sites, and facilities handling hazardous materials, as do databases administered by state air, surface water, and ground water management agencies (U.S. EPA, 2017c). Sites within the assessment area, or adjacent to tributaries leading to the assessment area, can be screened-in or screened-out for further review based on specific location information.

If the dam removal is very large or especially controversial, a conceptual diagram can help the team communicate with reviewers the locations of potential sources of contaminants relative to the reservoir site, along with locations where the contaminated sediment could be transported downstream. This information can help inform sampling and analysis plans (if needed in Step 3b and 3c) by also identifying potential biological receptors (e.g. humans, fish, invertebrates) and where impacts to human health could occur such as downstream water intakes or wells used for drinking water. For example, a conceptual diagram for the Klamath River was used to identify potential pathway impacts from exposed reservoir sediment that could be released during dam removal (CDM, 2011). The pathways for contaminant impact associated with dam removal included the following components illustrated in Figure 9:

1. Short-term direct toxicity to humans and biota
2. Long-term terrestrial exposure for riparian biota and humans from reservoir terrace deposits and river bank deposits.
3. Long-term aquatic exposure for aquatic biota and humans from river bed and floodplain deposits.
4. Long-term exposure for aquatic biota from marine near shore deposits.

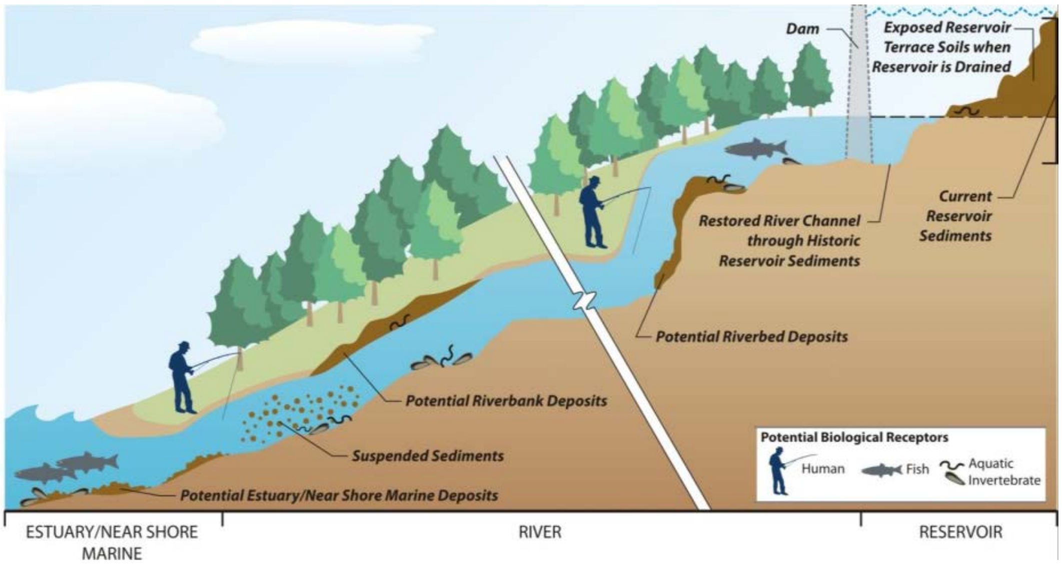



**Figure 9.—Potential pathways of released reservoir sediment into downstream river channel utilized on Klamath River evaluation (CDM, 2011).**

As noted above, many states omit the due diligence assessment described in Step 3a with specific requirements that guide testing. However, if a due diligence assessment is performed, summarize the assessment information to determine if contaminants are a concern and it is necessary to proceed to Step 3b. In general, where there is a lack of fine sediment and the absence of pollutant sources, there is little need to characterize potential sediment contaminants. A few uncommon examples where contaminants can be present in coarse-grained sediment are documented below. A draft report (with maps, conceptual diagram, facility lists, and summary of the subset of any issues that need additional evaluation) is typically prepared for review by permitting agencies and stakeholders. A final report is usually prepared to document the recommendation to stakeholders based on the findings of the due diligence assessment and permitting agency reviews.

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 (screening-level sampling). The following examples illustrate highly contaminated sediments within particle sizes larger than silt:

- “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).
- Sand-based metal casting molds: Elevated concentrations of PCBs have been found in sand-sized sediments in Michigan’s Saginaw River. These sediments are derived from discarded and weathered sand-based metal

casting molds made with high temperature-resistant adhesives containing PCBs.

- Thin films of organic material 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 thin films of organic material on the surface of the particles. These concentrations are well above commonly used sediment quality criteria (~ 0.7 mg/Kg).

## Step 3b: if contaminants are of concern, proceed with sediment chemistry analysis and determine if concentrations exceed criteria

If a sediment chemistry sampling and analysis plan is required, the plan should be guided by specific issues identified in due diligence assessment (Step 3a). The team should meet with permitting agencies and stakeholders to obtain concurrence on the reservoir sediment sampling plan and get consensus on what contaminants to include in analyses. The following sections provide guidance on the contaminant sampling plan and chemical analysis. If not already accomplished, an initial probing reconnaissance of reservoir sediment distribution and grain size is strongly recommended before implementing a sampling and analysis plan (see Step 2). At the end of Step 3b, determine if reservoir sediment exceeds contaminant criteria and background conditions requiring further evaluation in Step 3c.

### Guideline Decision Question: Do contaminant concentrations exceed sediment quality criteria and background conditions?

- Contaminant concentrations would not be exceeded. Reservoir sediment can be released, so proceed to Step 4.
- Contaminant concentrations would be exceeded, collect more samples if required by local regulators and then proceed to Step 3c.

Characterizing the composition and possible contamination of reservoir sediments can be a great challenge. Reservoir sediments are generally not visible (unless the reservoir is first dewatered) and so they must be sampled underwater and below the sediment surface. Particle sizes and contaminant distributions can be fairly 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 “probing” reconnaissance survey be conducted prior to designing a more comprehensive survey and collecting sediment samples (see Step 2).

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

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

MacDonald and Ingersoll (2002) provide a good introduction to these topics, and a brief summary of these three factors is provided below. Evans (2015) also recommends considering vertical stratigraphy of contaminant presence in conjunction with historical land use and flood occurrence. This can help pinpoint where contaminants are present. When combined with numerical or physical modeling of reservoir sediment erosion, the likelihood of contaminant layers being eroded can be estimated.

The two principal types of sediment samplers are grab samplers and core samplers. 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) only collect the surficial 6-8 inches (maximum) of unconsolidated sediment and cannot be utilized to characterize thick sediment deposits with vertical stratification. Core samplers are most commonly employed in impoundments and reservoirs. Core samplers collect 2 to 4 inch diameter cores up to 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 vibracores. Maximum core lengths collected by these three samplers typically range from 4 feet up to 15 feet, respectively. Drill rigs can be employed for locations with thick deposits at deep depths. Drill rigs can be employed from either a floating barge or placed on exposed reservoir sediment deposits after a partial reservoir drawdown.

The number of samples to collect and sampling methodology may be prescribed by the local regulatory agency depending on site conditions such as the depth of sediment behind the dam.

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 for comparison to reservoir sediment quality. If the reservoir sediments are no more contaminated than sediments in the rest of the river, it could be argued that they do not present additional risk to the riverine environment.

An example sampling and analysis scheme is below:

- Conduct screening level survey
  - If reservoir sediment is less than 8,000 $m^3$ (10,000 $yd^3$) of fine-grained sediment, collect three or four cores in the reservoir, one core in the

downstream river channel, and an additional core from the upstream channel.

  - If reservoir sediment is greater than 8,000 $m^3$ (10,000 $yd^3$) of fine-grained sediment, develop a customized sampling plan to meet local regulations.

- Conduct laboratory analysis
  - The laboratory analysis should test for a suite of metals (arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc are common), PAHs, PCBs, and total organic carbon plus any other constituents of concern identified from the historical land use assessment (e.g. pesticides);
  - Based on screening level samples, are contaminants uniformly distributed or are contaminant "hot spots" present? If screening survey finds spatially discrete contaminant hot spots, implement a definitive survey to determine their extent. The details of a definitive survey are site-specific and will have to be negotiated with regulators. However, an hypothetical example is provided below:
    - If reservoir sediment is less than 8,000 $m^3$ (10,000 $yd^3$) of fine-grained sediment, 1 core per 800 $m^3$ (1,000 $yd^3$), unless local regulations prescribe a different sample density
    - If reservoir sediment is greater than 8,000 $m^3$ (10,000 $yd^3$) of fine-grained sediment, develop a customized plan to delineate the extent of contaminant "hot spots" or areas of concern from screening survey.

In many instances, best professional judgment also plays a role in deciding how many samples to collect. Factors to consider when exercising best professional judgment are listed below:

- Expected sediment deposition patterns of different particle size groups (clay, silt, sand, gravel, etc.), 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 contaminants of interest, etc.
- The possible fate of the sediment (left in-place, removed, or allowed to transport downstream).

## Example tool for determining the number of sediment samples

A more quantitative approach to deciding how many cores to collect 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. The Visual Sampling Plan software package is a useful, and free, geostatistical program is available from the U.S. Department of Energy’s Pacific Northwest National Laboratory (2017).

An example of calculation results is given in the box below. Detecting small contaminant hot spots with high confidence can require a very large number of samples.

| Scenario | Hot Spot Radius, m (ft) | Required # of Samples |
|---|---|---|
| • Canals on Lake St. Clair, MI<br>• Surface area = 21,700 $m^2$ (233,600 $ft^2$ or 6 football fields)<br>• Assume a square grid, and desire 95% confidence of detecting a circular hot spot<br>• Calculate how many samples for different hot spot sizes | 1 (3) | 7,787 |
| | 5 (16) | 312 |
| | 10 (33) | 78 |
| | 15 (49) | 35 |
| | 20 (66) | 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 |

## Step 3c: conduct biological analysis and estimate sensitivity to determine if contaminated sediment can be released

If contaminants are present, the project team must work with regulatory agencies and decision makers to determine if the contaminants can be released into the downstream river or otherwise managed.

### Guideline Decision Question: Can contaminated sediment be released?

- Yes, the impacts would be acceptable
    - If the released contaminants will have a short-term and insignificant impact to downstream human health, aquatic species, or ecological resources, assume river erosion can be utilized as the sediment management plan and proceed with Step 4.
- No, the impacts would be unacceptable or too uncertain
    - If the contaminated sediment will take a long time to transport through the downstream river (e.g. longer exposure) and there would be significant impact to human health, aquatic species, or ecological resources, the reservoir sediment cannot be released downstream. Proceed to contaminated sediment management options.

The following stakeholder questions related to contaminants summarize earlier steps and provide guidance on how to walk through discussions related to potential impacts from contaminants (Augspurger, 2016):

- What are the historical or existing pollutant sources of concern upstream of the dam (Step 3a)?
- Do sediment pollutants exceed sediment quality criteria and background levels indicating potential adverse impacts to biota (Step 3b)?
- If contaminants exceed acceptable levels, what are the risks to benthic and downstream aquatic species?
- How will entrained sediments affect water quality and human health?

- Do pollutant concentrations within the reservoir differ from those downstream, which may be impacted by dam removal?
- Is unacceptable bioaccumulation of contaminants an issue for downstream wildlife?

Potential impacts can be evaluated through toxicological analysis done concurrently with Step 3b or as a separate study. Toxicological analysis involves evaluating the effects of contaminant release on biota using methods such as bioassays and bioaccumulation studies. Sediment bioassay testing typically evaluates a 10-day exposure to determine if benthic associated organisms can survive “acute” exposure to released reservoir sediment. This is most commonly done with freshwater species. Bioaccumulation studies assess whether contaminants accumulate in test organisms to concentrations higher than in the sediment, and typically have a 28 day exposure period.

Custom studies of the impacts to biota are beyond the scope of these guidelines, but could be employed for complex sites with localized questions regarding effects of contaminants. Special studies would likely be implemented when contaminant results have too much uncertainty to allow decision making regarding release of reservoir sediment.

# Contaminated Sediment Management Options

For cases with significant impacts from released contaminants, it is likely the contaminated sediments will need to be capped and isolated or removed and appropriately disposed of. Special assessments will be required for either of these activities to assure that disturbance to the sediment during capping and isolation or removal does not release contaminated sediments that could cause more harm than ambient conditions. Removal of contaminated sediment from the reservoir area may be necessary, but care must be taken to ensure that relocated sediments are not subsequently released into the environment in harmful concentrations. Further, reservoir drawdown to accomplish sediment removal along with the removal itself can result in reservoir sediment erosion, disturbance and release of contaminants into the downstream river (Evans, 2015).

Another option is to stabilize the contaminated sediments within the reservoir, but dam removal studies that document the success of this method are limited (Evans, 2015). Due to the uncertainty with stabilization, care must be taken to help ensure that contaminated deposits are not subsequently eroded during future floods or leached into the ground water. A separate geotechnical engineering investigation would be needed to design the containment system. Evans (2015) suggests potential mitigation of stabilization uncertainty may include (1) phased drawdown of the reservoir, exposure, and restoring vegetative ground cover on the reservoir sediments, (2) imposing a designed channel through the former reservoir, and/or (3) containment diking around areas of high contaminant concentrations (hot spots).

# Example contaminated sediment evaluation flow charts

The following flow charts provide sample decision trees that may assist with determining what sediment management plan is acceptable when contaminated sediment is present in the reservoir. The first flow chart evaluates the reservoir sediment deposit remaining after dam removal (Figure 10). If dam removal and sediment management activities leave contaminated sediment in the reservoir, evaluate potential risks associated with future land uses. The second flow chart is a decision tree for fish consumption (Figure 11). If contaminated sediment is planned to be released into the downstream river channel, evaluate potential impact to fish consumption by humans and wildlife and an ecological risk assessment of potential impacts to the fish themselves.

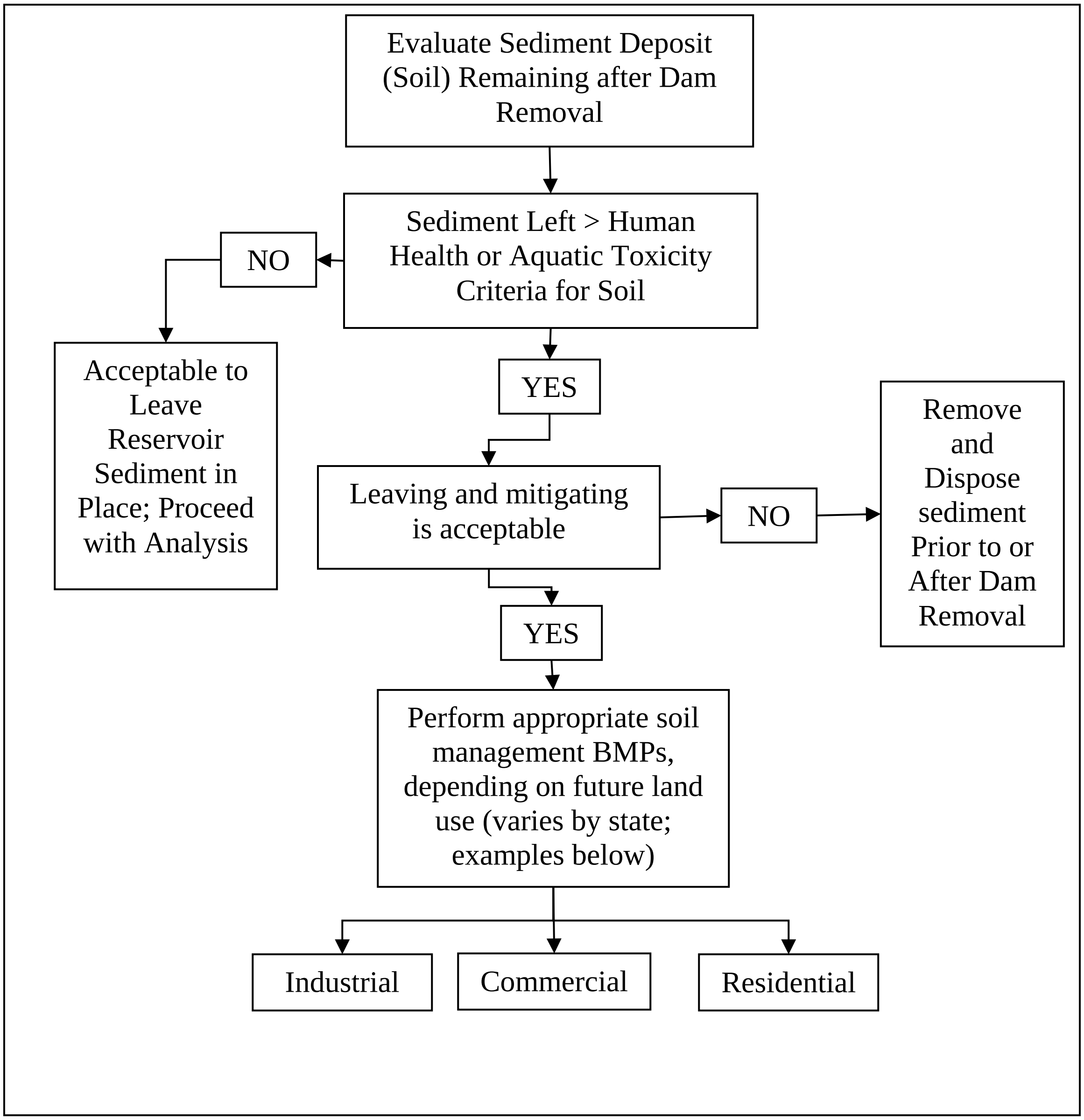



**Figure 10.—Post-removal reservoir sediment (soil) decision tree.**

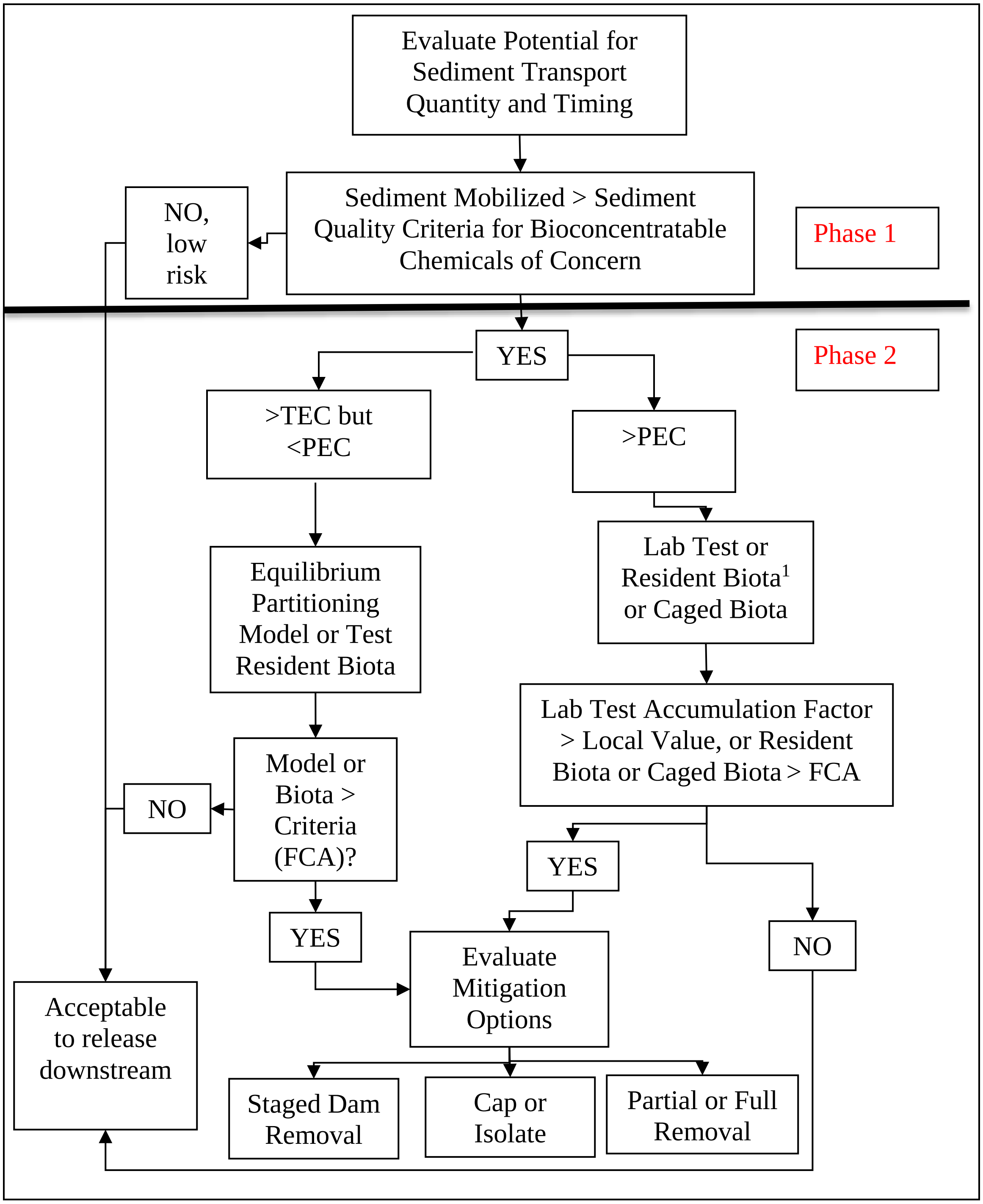



**Figure 11.—Fish consumption example decision tree.**

[1]Adult or young of the year of appropriate species

FCA = fish consumption advisory

TEC = threshold effects concentration

PEC = probable effects concentration

# STEP 4: DETERMINE RELATIVE RESERVOIR SEDIMENT VOLUME AND PROBABILITY OF IMPACT

This section will discuss how to determine the relative reservoir sediment volume, which is defined as the ratio of reservoir sediment volume or mass to the average annual sediment load entering the reservoir (Step 4a). The relative reservoir sediment volume represents the number of years of sediment load stored in the reservoir, which is then interpreted to be the probability of reservoir sediment impact (Step 4b).

## Step 4a: estimate the average annual sediment load

The average annual sediment load entering the reservoir can be estimated from (1) the measured sediment load entering the reservoir, (2) the product of watershed sediment yield and drainage area, (3) the sediment weight as computed from the volume and unit weight in reservoirs, or (4) transport capacity formulas. Average-annual sediment load estimates based on the product of watershed sediment yield and drainage area typically include both fine and coarse sediment and represent the total load. In contrast, sediment transport capacity formulas only represent sediment size classes contained in appreciable amounts within the river bed material, usually the coarser size fractions. The average annual sediment load may represent total load or only the coarse or fine sediment load, but the comparison with the amount of reservoir sediment must be consistent. For example, the total sediment load can be compared with all reservoir sediment whereas coarse sediment load should be compared with only the amount of coarse reservoir sediment. If the annual sediment load is in units of mass, then it should be compared with the reservoir sediment mass. Measured or assumed unit weights or dry bulk densities will be needed to convert the reservoir sediment volume to weight or mass.

### Method 1: continuous sediment load measurement

If continuous measured sediment load data are available upstream of the reservoir (or downstream of the reservoir prior to dam construction), then compute the average annual sediment load from the period of record. However, sediment load data from several years, and over a wide range of stream flows, would be necessary to compute a reliable average annual sediment load. If only suspended sediment concentration has been measured, an estimate may be needed to account for bed load (e.g. 10 to 30 percent of total load) (Meade et al. 1990 and Reclamation, 2006). Sediment load data can be temporally or spatially variable, so available data needs to be reviewed to characterize the variability or gaps. The sediment load data may need to be extrapolated or supplemented with other methods to cover the full range of flows. If the sediment load data are from a location far from the dam site, then adjustments may be needed to account for the sediment contributions from the intervening drainage area between the stream gage and dam site.

## Method 2: sediment yield

The average annual sediment load ($Q_s$) can be computed from the product of the sediment yield ($Y$) and the sediment-contributing drainage area ($A$):

$$Q_s = Y\ A \tag{3}$$

The sediment-contributing drainage area could be less than the total drainage area if upstream lakes or reservoirs are trapping sediment. There could be different sediment yield estimates for different portions of the watershed and, in that case, the average annual sediment load would be computed for each sub-drainage area ($i$) and summed:

$$Q_s = \sum_{i}^{n} (Y_i\ A_i) \tag{4}$$

where $n$ is the number of sub-drainage areas. Reservoir sedimentation can also vary over time depending on hydrologic trends that affect sediment loads and vegetation along with human land use changes in the upstream watershed. Reservoir sediment surveys are a great source for empirical sediment yield data. Sediment yield estimates can be used for data available within the drainage area where the dam is being removed, or from watersheds with similar characteristics. Chapter 2 of the Erosion and Sedimentation Manual (Reclamation, 2006) provides an overview of methods to compute sediment yield. The USGS' national SPARROW model for suspended sediment is an additional resource to provide a rough estimate of sediment load into a reservoir (Schwarz, 2008 and USGS, 2017c).

## Method 3: cases where the reservoir still traps sediment

If a reservoir is still trapping at least 50% of incoming sediment load, then the average annual load can be computed using the reservoir sediment trap efficiency method (Strand and Pemberton, 1982, see Figure 12). Based upon the empirical trap efficiency curves in this reference, a reservoir would trap about 50% of the incoming sediment load when the ratio of remaining reservoir capacity to average annual inflow is 0.01.

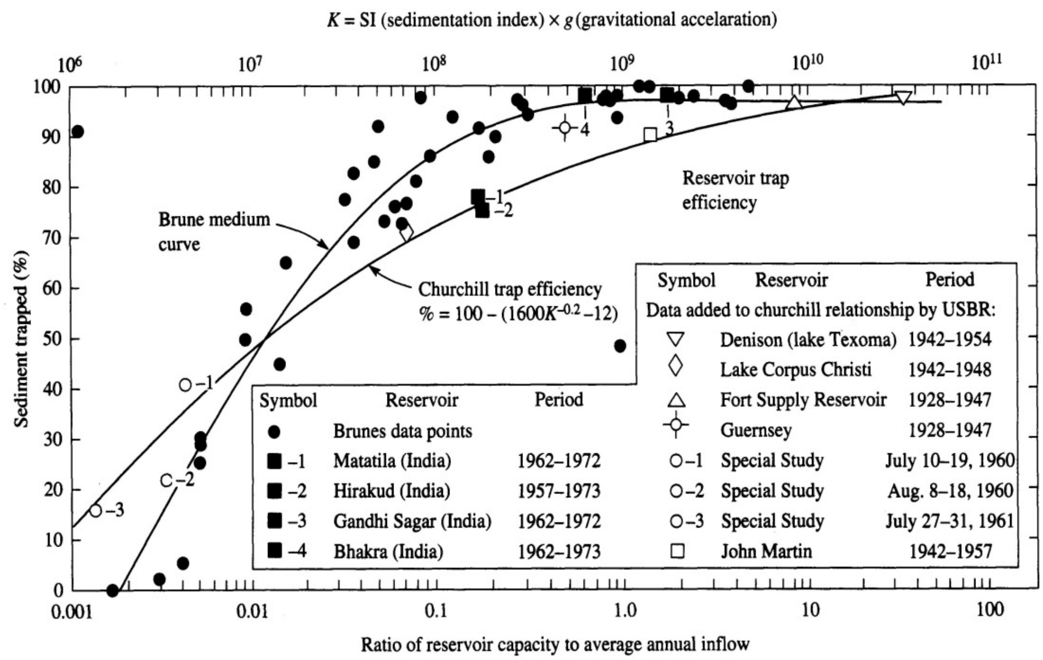



**Figure 12.—Empirical reservoir sediment trap efficiency curves based on Churchill (1948) and Brune (1953) and additional case studies (Strand and Pemberton, 1982).**

When the original reservoir storage capacity is not known, the longitudinal profiles of the existing reservoir sediment and predam channel provide a good indication of whether the reservoir is still trapping sediment. Unless a delta profile has extended downstream all the way to the dam, then the reservoir is likely trapping coarse and perhaps some fine sediment. If the water depth in the reservoir pool is significantly deeper than the upstream or downstream channel, this is also a sign that the reservoir is still trapping sediment.

The average annual sediment load ($Q_s$) can be computed by dividing the reservoir sediment volume ($V$) by the product of time ($T$) and the reservoir sediment trap efficiency ($P$). If change in reservoir storage capacity versus time is known, the equation can be applied incrementally for each time period.

$$Q_s = \frac{V}{T\,P} \tag{5}$$

When the proportions of coarse versus fine sediment within the reservoir sediment volume are known, the above equation can be applied separately. The trap efficiency for coarse sediment is typically near 100 percent such that the average annual load of coarse sediment ($Q_{sc}$) is simply the coarse sediment volume ($V_c$) divided by the years of sedimentation ($T$) (typically the age of the dam). Reservoirs with small relative sizes (ratio of reservoir capacity to average annual inflow < 0.01) may have reached their sediment storage capaicty long ago and the equatioin above would not be applicable.

## Method 4: sediment-discharge rating curve

The average annual sediment load can be determined using a sediment-discharge rating curve and a discharge hydrograph based on measured or computed data. Combining the discharge data and the sediment-discharge rating curves will produce a daily sediment load record. A suspended sediment-discharge rating curve can be developed from a log-log regression of measurements of suspended sediment concentration and stream flow discharge. A separate rating curve for the bed load can be developed from a log-log regression of measurements of bed load and stream flow discharge. At some sites only suspended sediment load measurements are available and the bed load will have to be estimated.

When measured data are not available, predictive transport equations are used to produce a sediment-discharge rating curve. The sediment-discharge rating curve is then applied to the daily discharges entering the reservoir to compute daily bed-material loads, which can be considered equivalent to the coarse sediment loads. The daily coarse sediment loads are then totaled for each year to compute the average-annual coarse sediment load. The average-annual coarse sediment load will be sufficient when the reservoir sediments are predominantly coarse. However, another method such as sediment yield (see Method 2) will have to be used when the reservoir has a significant amount of fine sediment.

The measured or computed sediment-discharge rating curve may have significant uncertainty. When using measurements to create a sediment-discharge rating curve, the uncertainty in the predicted sediment loads can be estimated using standard techniques to compute uncertainty bounds of the linear regression of the logarithmic transformed sediment load data. When a sediment transport formula is used to compute the sediment-discharge rating curve, there may not be a rigorous method to compute the uncertainty of the sediment loads, but multiple transport formulas can be applied to develop a range of possible transport capacities that could serve as a surrogate for the uncertainty.

As an example, the sediment transport formula by Yang (1973) was applied to the Sprague River in Oregon for the Chiloquin Dam removal study to develop a sediment-discharge rating curve for coarse sediment (Figure 13). The historical mean-daily discharge record (Figure 14) was then applied to this rating curve to produce estimates of the daily coarse sediment load (Figure 15) (Randle and Daraio, 2003). The average annual coarse sediment load was then computed from the daily estimates.

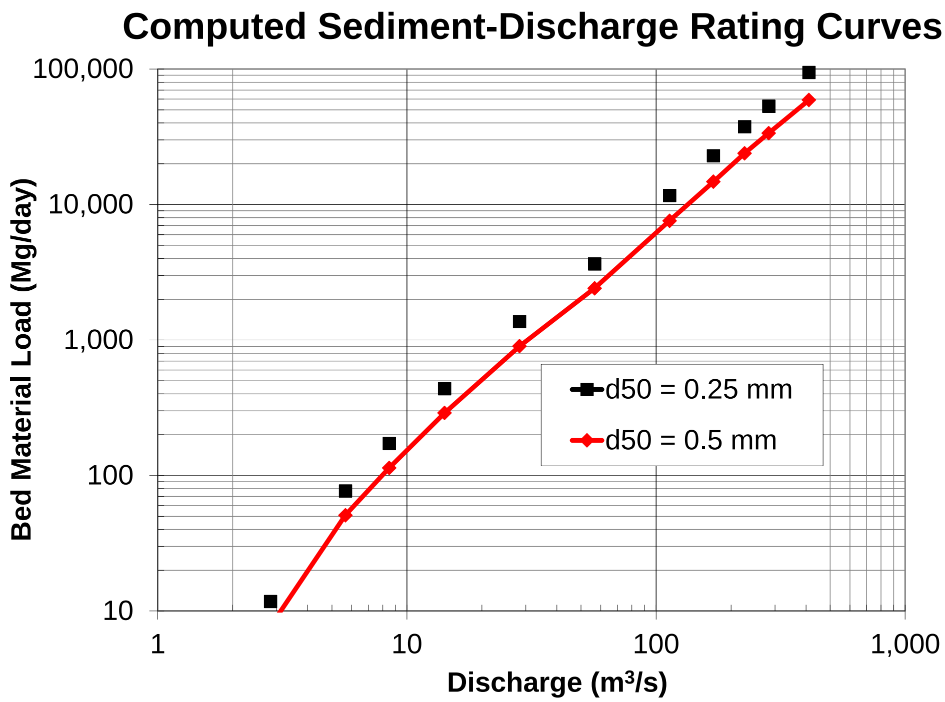



**Figure 13.—Example sediment-discharge rating curves computed for the Sprague River in Oregon, using the sediment transport equation by Yang (1973) for sand, versus discharge for two different median sand sizes (0.25 mm and 0.5 mm).**

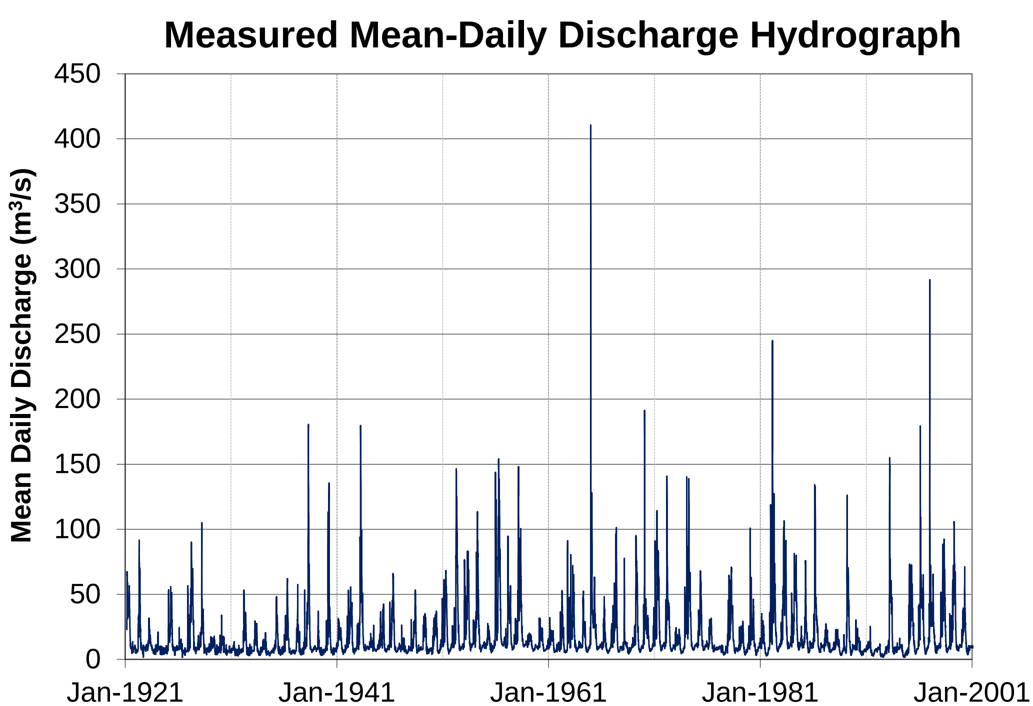



**Figure 14.—Example mean-daily discharge history for the Sprague River in Oregon.**

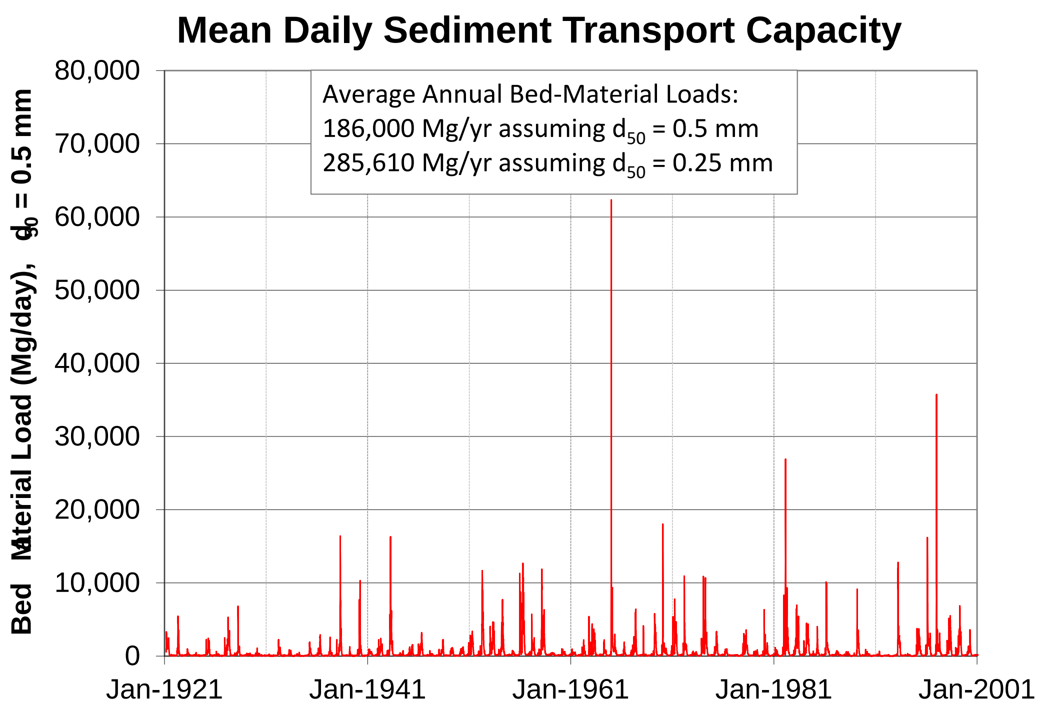



**Figure 15.—Example daily coarse sediment load hydrograph computed for the Sprague River in Oregon.**

Application of a sediment transport equation requires the following types of data:

- Streamflow discharge history
- Channel hydraulic data
- Bed-material particle size gradation

More information is provided below on developing stream discharge hydrographs, measuring channel hydraulic data, and selecting the predictive sediment transport equation.

## Streamflow discharge

If available, streamflow data from a nearby stream gage is the best source of discharge data. For estimating the average annual sediment load, the discharge history (mean-daily flow record) entering the reservoir is most applicable.

If streamflow data from a nearby gage are not available, then discharge will have to be estimated from a stream gage somewhere else in the watershed or from a gage in a nearby watershed with similar characteristics. The streamflow is then scaled with the following equation:

$$Q_d = Q_g \left( \frac{A_d}{A_g} \right)^p \tag{6}$$

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 between 0.5 and 1

Another option is to estimate discharge statistics (e.g., mean discharge, 2-yr flood peak, 10-year flood peak, etc.) from regional regressions. The National Streamflow Statistics Program is a good source for regional regressions in the United States (USGS, 2017d).

Regional regressions also may provide guidance on the appropriate exponent ($p$) to use for extrapolating discharge from a nearby stream gage. Regional regressions include effects of elevation and average annual precipitation. The U.S. Geological Survey StreamStats web application (USGS, 2017b) is a helpful tool that can be used to click on a location of interest and compute discharge estimates using the applicable regional regression equations.

## Channel hydraulic data

Channel hydraulic data are needed in predictive sediment transport equations to represent the hydraulic capacity of the channel to transport sediment. An alluvial reach of stream should be chosen that is not heavily impacted by man-made structures or influenced by the reservoir pool or delta. A reach length equal to at least 10 channel widths would provide a reasonable sample. Sediment transport capacity can be computed at multiple cross sections, so that a range of transport capacities can be considered.

Selection of a typical river cross section(s) that represents average energy slope and transport capacity is recommended. Cross sections at rapids and steep riffles will have relatively high sediment transport capacity, while cross sections at river pools will have relatively low sediment transport capacity, especially during low flows. If possible, selection of a cross-section(s) within a fairly straight reach without large pools and steep riffles is recommended for computing sediment transport capacity.

The required hydraulic data from the selected reach 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. The USACE HEC-RAS model (Brunner, 2016a and 2016b) can be used to compute channel hydraulics for various stream discharges of interest.

If a one-dimensional model is not available, Manning's equation can be used to compute normal depth at a measured cross section.

$$Q = \frac{c}{n} A\ R^{2/3}\ S_o^{1/2} \tag{7}$$

where

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

$S_o$ = average longitudinal bottom slope of the channel.

Normal depth is the water flow depth that will be achieved for a given discharge under steady flow conditions along a channel of uniform cross section. For normal depth, the longitudinal slope of the water surface and channel bottom are the same. By iteration, Manning's equation can be used to compute the cross-section flow depth for a given discharge, longitudinal slope, and channel roughness.

$$\frac{A^{5/3}}{P^{2/3}} = \frac{n\ Q}{c\ S_o^{1/2}} \tag{8}$$

For a given channel cross section, assume a normal depth water surface elevation and then compute the left-hand side of equation 8. Keep adjusting the assumed water surface elevation until the value on the left-hand side of the equation matches the value on the right-hand side of the equation within an acceptable tolerance (e.g., 1%). If detailed cross section measurements are not initially available, the channel width can be estimated from aerial photographs and channel geometry can be assumed (e.g. rectangular, trapezoidal, and triangular). However, stream cross sections should eventually be measured.

## Selection of a predictive sediment transport equation

The choice of a predictive sediment transport equation depends primarily on the sediment particle grain size and transport mode. Example text books on sediment transport are listed below:

- *Sediment Transport Technology, Water and Sediment Dynamics, Revised Edition* (Simons and Senturk 1992).
- *Sediment Transport Theory and Practice* (Yang, 1996).
- *The ASCE Sedimentation Engineering manual* (Garcia, 2008)

Many sediment transport functions are available, each one specified for a certain range of sediment size and flow conditions. 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. There are many computer programs available to estimate sediment transport capacity. The Bureau of Reclamation provides one such program (Huang and Bountry, 2009). This program can compute sediment transport capacity using the equations listed in Table 5.

Table 5.—Sediment transport equations available in SRH-Capacity program.

| Sediment Transport Equation | Bedload | Bed-material Total Load |
|---|---|---|
| Engelund and Hansen sand (1972) | | √ |
| Laursen (1958) | | √ |
| Laursen-Madden (Madden, 1993) | | √ |
| Ackers and White (1973) | | √ |
| Ackers and White with revised coefficients (HR Wallingford, 1990) | | √ |
| Brownlie sand (1981) | | √ |
| Yang sand (1973) and Yang gravel (1984) | | √ |
| Yang sand (1979) and Yang gravel (1984) | | √ |
| Yang (1996) modified for high washload concentrations | | √ |
| Wilcock and Crowe (2003) with and without Einstein's shear stress correction | √ | |
| Wilcock and Crowe (2003) with Engelund and Hansen (1972) sand coupled options 1, 2, and 3 | √ | √ |
| Wilcock and Crowe (2003) modified by Gaeuman et al. (2009) with and without Einstein's shear stress correction | √ | |
| Wilcock and Crowe modified by Gaeuman et al. (2009) with Engelund and Hansen (1972) sand coupled options 1, 2, and 3 | √ | √ |
| Parker gravel (1990) with and without Einstein's shear stress correction | √ | |
| Parker gravel (1990) with Engelund and Hansen (1972) sand coupled options 1, 2 and 3 | √ | √ |
| Meyer-Peter and Müller (1948) | √ | |
| Meyer-Peter and Müller modified by Wong and Parker (2006) | √ | |
| Wu et al. (2000) | | √ |

The HEC-RAS model (Brunner, 2016a and 2016b) can also compute sediment transport capacity using the following equations:

- Ackers and White
- Engelund and Hansen
- Larsen

- Meyer-Peter and Müller
- Taffaleti
- Yang

The BAGS computer software (Bed load Assessment in Gravel Bed Rivers) is a simple, easy to use transport model for uniform flow at individual cross sections that is applicable to compute bed load in gravel-bed rivers. It is prepared by and available for free from the USDA Rocky Mountain Research Station (Pitlick, 2009).

## Step 4b: estimate the probability of sediment impact

For purposes of these guidelines, the relative reservoir sediment volume is associated with the ***probability of sediment related impacts*** associated with dam removal. The relative reservoir sediment volume is defined as the ratio of the sediment volume to the average annual sediment load ($T_S$) (Figure 16). The ratio $T_S$ represents the years of upstream sediment load that is presently stored within the reservoir. A logarithmic scale is used to classify $T_s$ into negligible, small, medium, and large reservoir sediment volumes. The larger the reservoir sediment volume or mass (relative to the average annual sediment load), the greater the probability of impact. The relative reservoir sediment volume was defined by Randle and Greimann (2006) and the $T_S$ is essentially the same as $V^*$ defined by Major et al. (2017).

For reservoirs that are much wider than the river channel or that have cohesive sediment, the analysis may need to estimate the proportion of sediment that would actually be eroded from the reservoir over short and long-term time periods. If the reservoir sediment contains contaminants above concentrations of management concern, the probability of impact increases.

**Dam removal analysis guidelines for sediment decision question: Is there only a negligible risk of sediment impacts?**

For cases of little or no sediment, the risk is assumed to be negligible and the guideline user is directed to a special section in the guidelines (Cases of “negligible” reservoir sediment) to address this circumstance. Negligible sediment impact may be common for removal of low-head dams.

The uncertainty of the reservoir sediment volume is typically greatest at the beginning of the analysis. Additional data collection may be necessary to reduce this uncertainty to an acceptable level before completing the final iteration of the dam removal analysis guidelines for sediment steps.

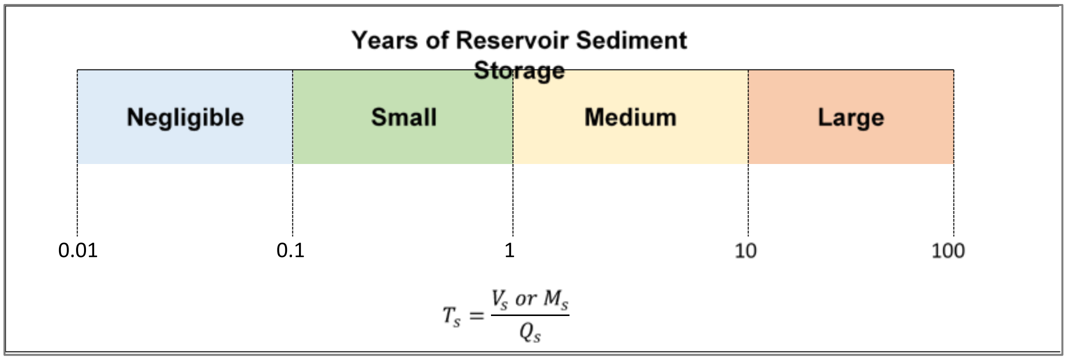



**Figure 16.—Relative probability of sediment impact based on ratio of reservoir sediment volume or mass (Vs) to average annual sediment load (Qs).**

Sediment-related effects tend to diminish with distance downstream because of tributary inflows of water and sediment along with deposition along the channel. Coarse sediment-related effects also tend to diminish with increasing distance downstream because coarse sediment waves are attenuated and they lose mass through deposition with distance downstream. For example, infrastructure 1 km below the dam could be at a higher risk from greater sediment deposition than a project 10 km downstream of the dam. In addition, sediment impacts may diminish with time after dam removal because rates of reservoir sediment erosion diminish with time. However, coarse sediment initially released and deposited in the channel is likely to be subsequently reworked during future high flows. This lag in transport can delay the peak impact at downstream locations, particularly for dam removals with large sediment releases (multiple years of average annual load). The probability of sediment impact may, in some cases, be reduced when computing the risk of consequences for concerns far downstream from the dam.

## Example calculations

For the removal of Chiloquin Dam on the Sprague River near the town of Chiloquin, OR, two independent methods were used to estimate the reservoir sediment volume (Randle and Daraio, 2003):

1. A longitudinal profile and cross section method.
2. A sediment thickness and area method.

A predam topographic map was not available for the reservoir area. Prior to dam removal, a bathymetric survey of the reservoir was performed and a longitudinal profile was plotted along the reservoir bottom (Figure 17). The slope of the predam channel bottom was estimated by assuming a straight line between the downstream channel and the upstream portion of the reservoir. The estimated predam profile is likely lower than the actual profile so that reservoir sediment volume is over estimated rather than underestimated. Cross sections of the reservoir bottom were plotted and a predam channel was estimated to coincide with the longitudinal profile of the predam channel. Enough reservoir cross sections are needed to describe geometric variations in the reservoir. An example cross section is presented in Figure 18.

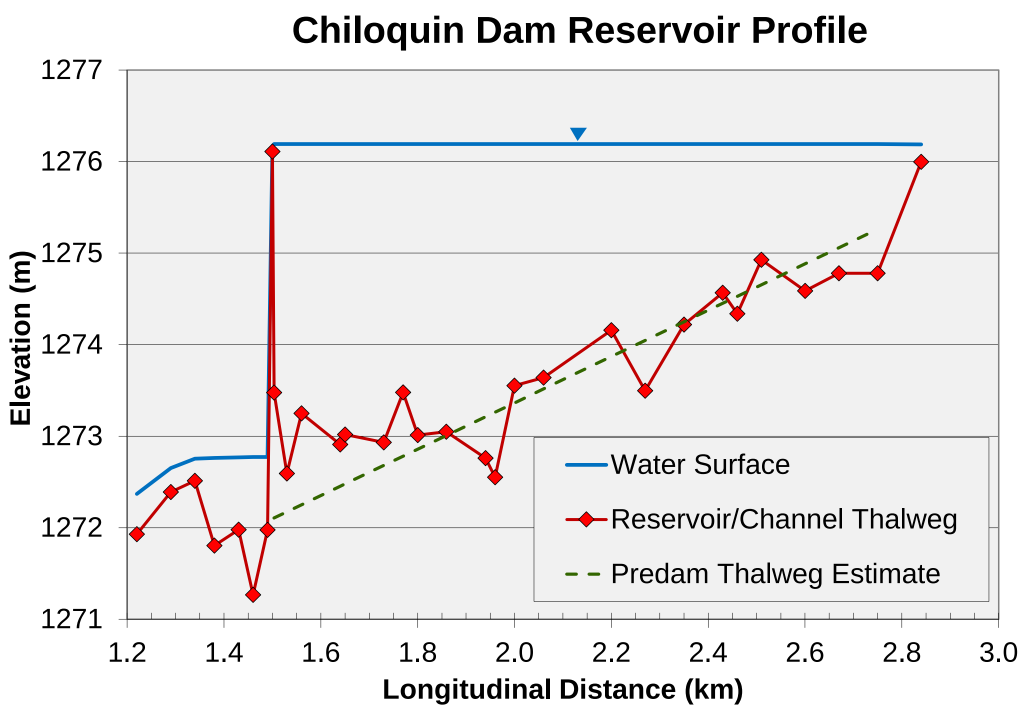



**Figure 17.—Longitudinal profiles of the reservoir behind Chiloquin Dam.**

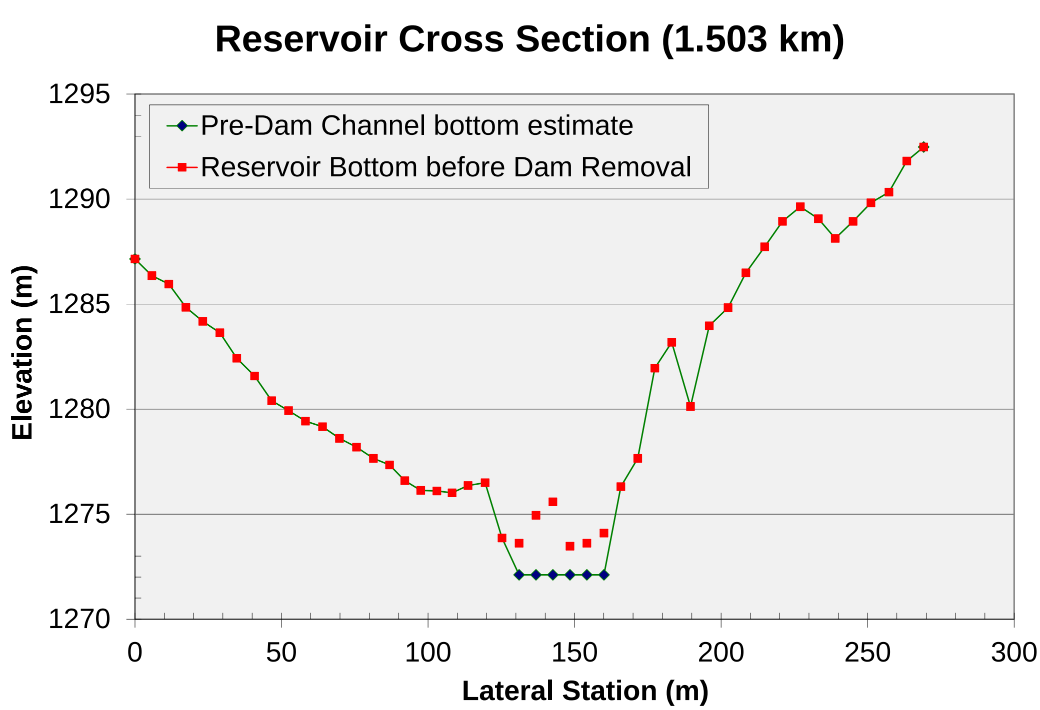



**Figure 18.—Example reservoir cross section plot.**

An estimate of the reservoir sediment volume ($V_s$) was computed by summing the product of cross-sectional area of the sediment and the incremental reservoir length. The estimated reservoir sediment volume using this method was 35,000 $m^3$ (45,000 $yd^3$).

$$V_s = \sum A_i \, (\Delta x_i)$$

Where $V_s$ is the reservoir sediment volume
$A_i$ is the cross-sectional area of the reservoir sediment at cross section $i$
$\Delta x_i$ is the longitudinal distance half-way upstream and downstream to the next cross sections.

Reservoir sediment thickness was also estimated by divers using thickness probes. Based on these measurements, the average sediment thickness was computed for the downstream and upstream areas of the reservoir (Figure 19). The average sediment thickness was then multiplied by the respective planimetric area. The estimated reservoir sediment volume using this method was 27,000 $m^3$ (36,000 $yd^3$).

The two methods both produced reservoir sediment volumes that are tens of thousands of cubic meters and both methods were applied in a way to conservatively overestimate the reservoir sediment volume.

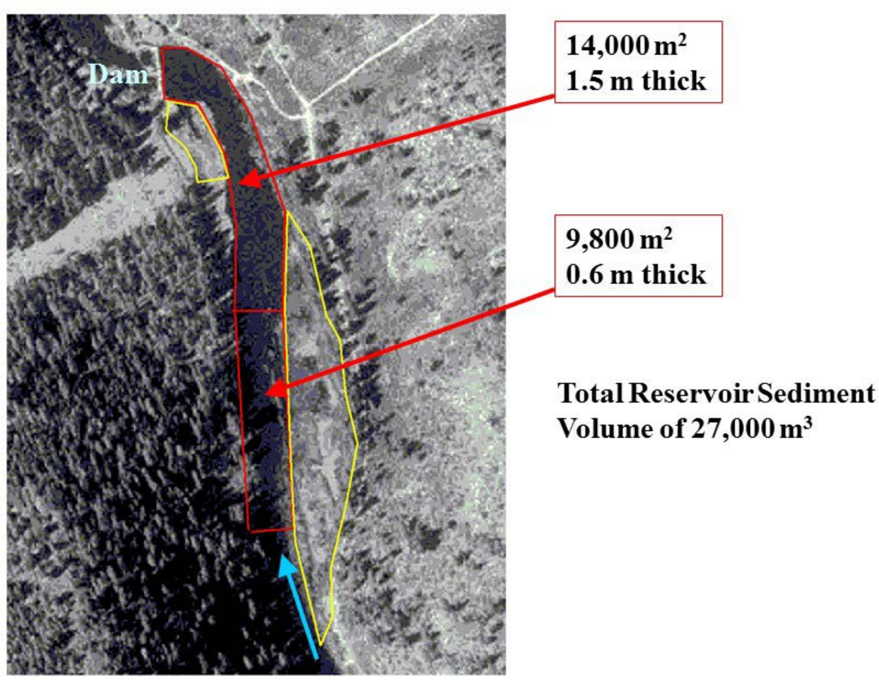



**Figure 19.—Aerial photograph of the reservoir behind Chiloquin Dam.**

# STEP 5: REFINE POTENTIAL SEDIMENT-RELATED CONSEQUENCES AND ESTIMATE RISK

For a dam removal project, risk is defined as the chance of harmful effects to human resources (e.g. water quality, land, and infrastructure) or to ecological systems (e.g. aquatic or terrestrial species) resulting from exposure to an environmental stressor, in this case the release of reservoir sediment. For dam removal, risk is computed as the product of the probability of a sediment impact and the consequence of that impact. The probability of a sediment impact is based on the relative reservoir sediment volume from Step 4. Consequences are assessed qualitatively, as described in Steps 5a and 5b, and then applied in a matrix with the probability of impact to estimate the qualitative risk in Step 5c.

## Step 5a: identify consequences

A list of potential sediment-related consequences should be generated for the project by building upon sediment concerns identified in Step 1b while also considering sediment benefits identified in Step 1c. The level of consequences may have to be estimated qualitatively. The degree of consequence from releasing reservoir sediment can be determined by considering the dominant particle grain size and duration of impact.

For each consequence, the following questions should be answered:

- Where is the potential sediment impact concern located relative to the dam?
- Is there available fine or coarse reservoir sediment to cause an impact?
- When are the sediment impact concerns expected to occur (during dam removal, seasonal, all year)?
- Are the consequences expected to occur over the short term (during and immediately after dam removal) or long term (persisting for years to decades)?

The sediment grain size stored in the reservoir will play a role in the expected consequences and it may be useful to differentiate fine from coarse sediment consequences. Reservoir sediment deposits composed largely of fine sediment are most likely to result in elevated suspended sediment concentrations and turbidity levels along with floodplain deposition. However, if the fine sediment has cohesive properties, erosion may take longer until larger flood peaks occur. Releasing coarse sediment may lead to deposition along the channel and filling of river pools. Excessive coarse sediment deposition may result in stream bank erosion, channel alignment changes, and increased flood stage. Coarse sediment deposition could bury water intakes and impair water treatment operations. Sand-sized sediment can also be transported as suspended load, particularly during peak flows, and add to the turbidity from clay and silt-sized particles and floodplain deposition.

The consequences of a sediment-related effect depend on the magnitude and duration of the impact and if there is recovery after the impact is over.
The short and long-term sediment effects from dam removal can be very different. For example, the concentrations of sediment eroded and released from the reservoir will be initially high and then decrease to very small levels over the long term.

It is important to limit the potential consequences to what may actually occur based on the available reservoir volume and the proportions of fine and coarse sediment. For example, Savage Rapids Reservoir near Grants Pass, Oregon had 98% coarse sediment stored in the reservoir with only 2% fine sediment (Bountry et al. 2013). 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 screening-level concentrations and the fine sediment volume was too small to cause any significant water quality impacts. During the actual dam removal, only small spikes in turbidity occurred that were limited in duration (hours to days) and no greater in magnitude than during a typical storm event (Bountry et al. 2013; Tullos et al. 2016).

Consequences can also depend on regulations and the perception of stakeholders about the resources of concern. Public education and outreach regarding 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.

Although the release of reservoir sediment may have temporary consequences for water quality and channel substrate, dam removal may provide long-term benefits (e.g., restoration of fish and boat passage, elimination of dam safety problems) that offset the short-term consequences. At small dams up to 30 feet high, the majority of the reservoir sediment that is going to erode usually does so within 2 to 3 years (MacBroom and Schiff, 2013).

## Step 5b: rank consequences

List and qualitatively group the potential consequences of impacts to resources into low, moderate, and high categories so that, when combined with the probability of impact, the risk can be estimated. Ranking of consequences may be subjective and determined through a discussion with stakeholders to determine level of concern for potential consequences should they occur.

For a given dam removal project, there may be a wide range of potential consequences ranging from low to high. For determining the level of data collection, analysis, and modeling, it is recommended to take the highest consequence associated with coarse or fine sediment.

Examples of low consequences are where there is no infrastructure, recreation use, or property that could be impacted by the release of reservoir sediment, such as in an undeveloped canyon reach of river that is not easily accessible or open to public use. In addition, sediment-related impacts would not threaten the continued existence of threatened or endangered species. Other types 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 consequences might include cases where sediment-related impacts cause temporary (days to weeks) problems for downstream water intakes or the aquatic ecosystem. Medium consequences could also be temporary halts to recreation use or public access within impacted areas. Medium consequences could also be applied to address uncertainty among stakeholders where the consequence is not low or high.

Examples of large consequences would include streambed aggradation that leads to flooding or erosion of property or infrastructure. Another large consequence would be increased sediment concentrations making it difficult or impossible for water users to obtain water for beneficial uses. Another example of a large consequence could be increases to sediment concentrations that would threaten the continued existence of threatened or endangered species.

## Step 5c: compute risk of sediment impact

Once the consequences have been estimated, the risk of sediment impacts can be estimated using the matrix provided in Table 6. The level of sediment analysis and modeling is then guided by the level of risk. Regulatory documents may use the term “exposure” of a sediment stressor rather than probability (U.S. EPA, 1992). The exposure of a sediment stressor depends on the physical and chemical sediment properties.

The probability of the sediment impact is typically based on the total amount of sediment stored in the reservoir. However, there may be cases where there is value in looking at probabilities of fine and coarse sediment separately or only one size category if it is the dominant sediment size.

**Step 5: refine potential sediment-related consequences and estimate risk**

Table 6.—Matrix to estimate the risk of sediment impacts from the probability of occurrence and the consequence should the impact occur.

| Probability of fine or coarse sediment impact | Consequence of Sediment Impact | | |
|---|---|---|---|
| | **Small** | **Medium** | **Large** |
| **Small** | Low Risk | Low Risk | Moderate Risk |
| **Medium** | Low Risk | Moderate Risk | High Risk |
| **Large** | Moderate Risk | High Risk | High Risk |

# STEP 6: DEVELOP DAM REMOVAL AND SEDIMENT MANAGEMENT ALTERNATIVES

Once the level of risk from sediment impacts is determined in Step 5, the guideline user must develop a dam removal and sediment management plan in Step 6. Because the dam removal plan influences the rate and potentially the magnitude of sediment erosion, the dam removal and sediment management plans should be developed together. This information can then be used to guide the analysis of sediment impacts in Step 7. Where Federal actions or decisions are involved (including the granting of permits), a range of reasonable sediment management alternatives must be considered to meet the project purpose and need.

Low or moderate risk cases - For reservoirs with a negligible, small, or moderate risk of sediment impact without presence of contaminants (see Step 5 and Table 6), initially assume rapid and complete dam removal with reservoir sediment eroded by available stream flows. This initial assumption should be changed, or mitigation should be added to the sediment management plan, if subsequent analyses reveal impacts that would be unacceptable to stakeholders. The initial assumption of rapid and complete dam removal is meant to consider the river erosion alternative before considering other sediment management options that are potentially more expensive.

High risk cases - For reservoirs having a high risk of downstream sediment impact (see Step 5 and Table 6), rapid dam removal and release of all stored sediment may, at least temporarily, overwhelm the channel and aquatic environment. Rapid and complete dam removal may be considered, but such a choice is unnecessary where unacceptable impacts to resources are obvious.

## Step 6a: Develop the dam removal plan

The dam removal alternative identifies whether all or only part of the dam will be removed, and whether the dam will be breached rapidly or in stages. There are many alternative methods to removing a dam depending on the type of material (concrete, earth, rock, etc.). These methods include mechanical excavation or demolition, blasting, or cutting (USSD, 2015). Some dams are partially breached and drained ahead of full dam removal. The selection of a dam removal strategy may incorporate how the timing of flow and sediment releases to the downstream channel would affect resources. For example, dam removal may be selected during in-water work periods, during a low-flow period that avoids critical aquatic species use, or timed to occur just before a storm event. The Guidelines for Dam Decommissioning Projects (USSD, 2015) is a good reference for dam removal alternatives and methods.

The construction or installation of coffer dams for dam removal may be necessary, but do not automatically assume they are needed because they can significantly increase project costs. When contracting for dam removal, focus the specifications on the desired outcomes during and after dam removal and not the methods to be employed by the contractor. This can result in substantial cost savings compared with contracts that specify methods. The construction of coffer dams may introduce additional sediment and potentially increase the probability of sediment impact for negligible and small cases. Failure of a coffer dam can add to sediment impacts.

The following paragraphs describe a range of factors that should be considered when developing the dam removal plan.

## Full or partial dam removal

The type of material used to construct a dam (concrete, masonry, rock fill, or earth) is important for determining how much of the dam to remove, the volume of material for disposal, and the removal process itself (USSD, 2015 and ASCE, 1997). All of the dam may be removed or portions may be left behind for historical preservation or to retain sediment. Complete dam removal means the complete removal of the dam and all associated facilities. However, a partial dam removal could be a less expensive alternative that preserves a portion of the historical structure. For example, removing only the portions of the dam that block fish passage could be less expensive than completely removing all structures. Spillways, power plants, penstocks, and dikes could be left behind for historical preservation or utilized in the future operation of the project. For example, Sunol and Niles dams on Alameda Creek in California were partially removed to reduce costs while still meeting the project objectives of restoring anadromous steelhead passage and removing a public safety hazard (Marcin Whitman, electronic communication, August 2017). Any remaining structures would have to be left in a safe condition and may require periodic maintenance. A portion of the dam could also be left behind to retain reservoir sediment or to reduce flood peaks. This could mean removing only the portion of the dam blocking the river channel and retaining portions of the dam along the predam floodplain or reservoir margins.

Where a dam spans a valley width that is significantly wider than the river channel, a portion of the dam could be removed from the old river channel and the remaining dam left in place to help retain a significant portion of the reservoir sediments. A portion of Savage Rapids Dam on the Rogue River in Oregon was left behind to help protect a downstream pumping plant from damage during floods and for historical preservation (Figure 20). The former spillway and new walkway at Glines Canyon Dam on the Elwha River in Washington was left in place to save cost, allow public viewing access of the project, and for historic preservation.

**Figure 20.—A portion of Savage Rapids Dam (near Grants Pass, OR) was removed to allow fish passage while the remaining portion helps to protect a downstream pumping plant.**

A partial dam removal could also mean that only 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 may reduce or eliminate any dam safety concerns by eliminating or reducing the size of the reservoir, but fish passage facilities might still be required. The lowest portion of the dam could be retained to act as a grade control to prevent any downstream channel degradation that may have occurred from progressing upstream after dam removal. This was successfully done at the Zemko Dam in 2007 in Connecticut (MacBroom and Schiff, 2014) and Stage Coach Dam on San Luis Obispo Creek in California (Marcin Whitman written communication, March 9, 2017). The lowest portion of the dam could also be retained to act as a barrier to prevent the upstream migration of exotic aquatic species.

## Potential barriers to sediment erosion

Erosion resistant materials within the reservoir could create fish or boat passage problems after dam removal and prevent erosion of reservoir sediments. Erosion resistant materials may also slow the rate of bank erosion, thus slowing the recovery of a natural landscape in the former reservoir area, as well as prolonging the potential for sediment impacts downstream from the dam site. If erosion-resistant materials or structures are encountered, then mechanical removal may be necessary.

Remnant structures that span the restored channel can create undesired grade control after dam removal and slow or stall upstream progression of sediment erosion. For example, following the removal of a 6-m (19.7 ft) high dam on

Amethyst Brook in Massachusetts, the channel headcut upstream and encountered an old timber crib dam that had been buried in the reservoir sediment (Magilligan et al., 2015). Historical blasting of hillslopes, construction of cofferdams, tunneling, and removal of bedrock or soil can all result in permanent changes to the landscape. At some sites historical dam failures may also have affected the channel elevation. For example, Lake Aldwell formed upstream of Elwha Dam (Elwha River, Washington) failed upon first filling creating a 70 ft scour hole beneath the dam, hillslope failures from the rapid reservoir drawdown, and scour in the downstream river. The logistics of removing remnant structures with the dam in place may be much easier, and much less expensive, than waiting until after dam removal. This is especially true if dam operations are used to divert flow around the work area. For example, it may be possible to use dam outlets, penstocks, or spillways to divert river flows around short reaches of river where boulders, structures, or debris may exist. The removal of boulders, old structures, and debris after dam removal will be more difficult if they are partially or fully buried by sediment and construction debris from the dam removal. In addition, these features would have to be removed under active river-flow conditions. Substantial legacy dams associated with 19th century logging drives and sawmills were found in the Penobscot River in Maine at the Veazie and Great Works Dams removal sites. Early detection enabled engineered plans to breach them to allow for fish, sediment, and small boat passage (MacBroom and Schiff, 2013).

## Reservoir drawdown

For small capacity reservoirs, reservoir drawdown may occur within a few hours and have minimal impact on downstream river stage. For large reservoirs, the rate of reservoir drawdown needs to be slow enough to avoid a flood wave from the reservoir that would cause downstream flood damages. Also, the drawdown rate needs to be slow enough to avoid inducing any potential landslides along the reservoir margins or a slide failure of any earthen dams.

Dam removal projects often require an initial reservoir drawdown to expose portions of the infrastructure and reservoir sediment before construction activities can commence. For dam removals that include an initial drawdown, sediment erosion should be expected when the drawdown elevation intercepts or is near the elevation of the reservoir sediment deposits. The ability to drawdown the reservoir pool depends on how flows are released through, over, or around the dam. If the dam has low-level, high-capacity outlet works or a 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 proportion of sediment could 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 (USSD, 2015 and ASCE, 1997). A series of notches were cut into Glines Canyon Dam to release flow downstream during dam removal (Figure 21). A large tunnel was drilled and blasted through the bottom of Condit Dam to rapidly drain the reservoir and eroded sediments (Wilcox et al., 2014).


**Figure 21.—A series of notches were cut into Glines Canyon Dam (near Port Angeles, WA) with a hydraulic hammer to release river flows downstream during dam removal.**

Dam removal and reservoir drawdown plans must prepare for the possibility of floods occurring during dam removal. The occurrence of a flood may simply mean the temporary halt of dam removal and reservoir drawdown activities. However, a flood overtopping the dam could cause failure of the remaining structure and a downstream flood wave that could be many times larger than the reservoir inflow. If the remaining structure can withstand overtopping flows, then floods may help erode and redistribute sediments throughout the reservoir.

Some recreationalists may have a strong desire to be among the first to boat or swim the stream channel through the former dam site after initial reservoir drawdown. However, this can be quite dangerous, and even deadly, because the temporarily high turbidity will obscure the view of rapidly changing channel conditions and channel debris. Tragically, a boater was killed the day Savage Rapids Dam was breached because a motorized boat traveling through the former reservoir unexpectedly struck a shallow bottom and possibly debris that could not be seen (Bountry, 2013). For this reason, boaters and swimmers must be kept away from the former dam and reservoir site until reservoir and channel conditions are no longer rapidly evolving (i.e. changing daily) and high turbidity levels have dropped.

## Phased dam removal

The rate of removal and reservoir drawdown has a strong influence on the rate that sediments are eroded and transported downstream. The effects from releasing a large volume of reservoir sediment downstream can be reduced by slowing the rate of dam removal and 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 and composition of the reservoir sediments. However, that phasing of dam removal will also extend the period of high sediment concentration and turbidity in the river. It is possible that both a rapid and phased removal will need to be analyzed to compare the impacts.

The rate and timing of phased or incremental reservoir drawdown should meet the following general criteria:

- The reservoir discharge rate is slow enough that a downstream flood or reservoir slope instability does not occur.
- The release of coarse sediment is slow enough so that any riverbed aggradation does not cause flooding to people and property along the downstream river channel.
- The concentration of fine sediment released downstream is not too great, or its duration so long, so that it overwhelms downstream water users or causes unacceptable impacts to the aquatic environment.

For cases with a coarse sediment delta, the duration of constant reservoir elevation between drawdown increments (a few weeks to a few months) should correspond to the length of time necessary for the river channel to erode exposed sediment and redeposit it across the width of the receded reservoir.
If the hydrology is not adequate to mobilize the reservoir sediment, additional time may be required for channel headcut erosion to progress to the upstream end of the reservoir. The total time required for hold periods (weeks to months) will depend on stream flows, the length of the reservoir sediment deposit, erodibility of the sediment, and objectives of the hold periods.

If phased dam removal is necessary, develop a plan that will reduce the risk of sediment impacts by incrementally releasing a manageable amount of sediment that can be transported by the downstream channel. For example, a dam with a reservoir containing a coarse sediment volume equivalent to 40 years of average annual sediment supply, could be removed over a four-year period.

This rate of phased dam removal could be slowed if subsequent analyses reveal unacceptable impacts (e.g. increased flood stage or avulsion from channel aggradation or burial of critical infrastructure or habitat). The rate could be increased if impacts are much lower than thresholds where harm occurs although uncertainty and factors of safety should be considered.

The phased release of fine sediment needs to consider the downstream concentration and duration of suspended sediment and acceptable impacts to the aquatic environment and water users. High concentrations of suspended sediment over a short duration will impact fewer year classes or generations of aquatic species than lower sediment concentrations of sediment over a long duration of time. However, water users may not be able to divert and treat water with excessively high sediment concentrations.

## Step 6b. Develop sediment management alternatives

Once a decision is made to remove a dam, a decision is needed to determine what will be done with the former reservoir area. The selection of a reservoir sediment management strategy often depends on the vision for the post-removal reservoir landscape, along with tolerance for downstream sediment releases. Sediment management may also include the excavation of a pilot channel to initiate river erosion along a prescribed alignment through the reservoir or mechanically shaping the remaining reservoir sediments to remain in a more stable condition. In an age of heightened environmental sensitivity, green or natural river erosion approaches are finding a strong foothold in the restoration and rehabilitation of stream ecosystems.

Sediment management alternatives can be grouped into four general categories (ASCE, 1997):

1. **No action.** Leave the existing dam and 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.
2. **River erosion.** Allow rivers flows to erode the reservoir sediment.
3. **Mechanical removal.** Remove part or all of the reservoir sediment by hydraulic dredging, mechanical dredging, or conventional excavation for long-term storage at an appropriate disposal site (see USACE, 2015 for more information on dredging).
    a. Hydraulic dredging operations remove sediment by fluidizing and pumping the material to the processing location.
    b. Mechanical dredging operations capture the sediment in wet conditions, and then lift the captured material to the surface onto a barge or other platform for transport and processing.
    c. Excavation uses similar equipment as mechanical dredging, but operators isolate a segment of the sediment and water column in an enclosure, dewater the enclosure, and remove the exposed sediment using conventional land-based excavation equipment.

4. **Stabilization.** Engineer a river channel through or around the reservoir sediment and provide erosion protection to stabilize part or all the reservoir sediment over the long term.

A sediment management plan can also consist of a combination of these categories. For example, fine sediment 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.

## No action

A no action alternative is often required by the federal National Environmental Policy Act (NEPA) or state regulatory agencies to compare baseline conditions with proposed alternatives. If no action is selected, the dam, reservoir, and sediment would be left in place. For reservoirs that are full of sediment, future floods, sluicing, and dredging can cause temporary changes in sediment storage, but the inflowing sediments are generally transported through the reservoir pool. If the reservoir is not already full of sediment, future sedimentation will continue. The life of the reservoir may be extended by reducing the upstream sediment loads, bypassing sediment through or around the reservoir, or removing the existing sediment by sluicing or dredging. If the reservoir continues to trap sediment, the remaining reservoir capacity will eventually be filled with sediment, but this could take decades to occur, depending on the reservoir size and the upstream sediment loads. Reservoir sedimentation at the dam may also plug low-level dam outlets, requiring dredging or flushing and likely a change in reservoir operations. Eventually, reservoir sedimentation will cause velocities through the reservoir to increase and subsequently decrease the sediment trap efficiency.

## River erosion

Allow the river to erode sediment from the reservoir through natural processes, sometimes referred to as passive sediment management. This option may include a pilot channel to initiate erosion processes. Some dam removals have formed a cofferdam out of reservoir sediment that is allowed to breach and erode. Dams with gates or outlets may consider drawdown to initiate partial reservoir erosion.

The river erosion alternative potentially has the least cost, but results in the greatest amount of sediment released to the downstream channel and potentially the greatest amount of uncertainty. Sediment concentration depends directly on the rate of reservoir drawdown, which is often associated with the rate of dam removal. This alternative has been utilized on dams of a range of sizes, including Chiloquin Dam on the Sprague River in Oregon (Randle and Daraio, 2003), Gold Hill Dam (WaterWatch, 2017a), Savage Rapids Dam (Bountry et al. 2013), and

Gold Ray Dam on the Rogue River in Oregon (WaterWatch, 2017b), Marmot Dam on the Sandy River in Oregon (Major et al. 2008), Condit Dam on the White River in Washington (Wilcox et al. 2014), and Elwha and Glines Canyon Dams on the Elwha River in Washington (Randle et al. 2015). The dam removal plan associated with these projects included both rapid and phased reservoir drawdowns.

For most small reservoir sediment volumes, the dam is completely removed and a high percentage of the reservoir sediment is expected to erode. However, there may be cases where some of the dam is left in place and this may limit the amount of sediment erosion, especially if the dam is not removed all the way down to the predam river bed. Alternatively, if portions of the dam are left in place along the left or right abutments, then some reservoir sediment near the dam may not be eroded. 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 reduce the extent and rate of lateral erosion.

Initially, reservoir sediment erosion is a function of the base level adjustment at the dam site and largely independent of flow. Higher flows capable of mobilizing reservoir sediment may be required to initiate lateral erosion and/or progression of headcuts depending on the grain size, slope, and cohesive properties of the sediment.

## Mechanical removal

The mechanical removal alternative is typically the most expensive, but may be necessary when sediments are contaminated and must be removed from the system. Mechanical removal may be selected when impacts to downstream water quality and aquatic habitat are not acceptable and the cost of removing sediment is feasible.

An example is the 7.9 m high Hemlock Dam in Washington State with predominantly sand-size reservoir sediment (42,000 $m^3$) that was removed to minimize risk to downstream fish habitat (Figure 22; Randle and Greimann, 2004; Claeson and Coffin, 2015). After removal of the sand, a channel was cut in the historical path, the floodplain sculpted, 2,000 $m^3$ of gravel and cobble were added, and native vegetation planted to the former reservoir area to facilitate recovery (Claeson and Coffin, 2015).


**Figure 22.—Hemlock Dam site, Washington. A - looking upstream at dam. B - Looking upstream at reservoir sedimentation and lake prior to dam removal. C - Looking downstream at Trout Creek about 0.8 km downstream of dam.**

If mechanical removal is required, evaluating potential alternate beneficial uses of the reservoir sediment can be accomplished using guidance such as the federal beneficial use planning manual (U.S. EPA and USACE, 2007). For example, dredged reservoir sediment may be utilized to accomplish beach restoration in areas that have eroded. Dredged reservoir gravel may be used in reaches where gravel is needed for spawning habitat.

Methods of mechanical removal are briefly described in the USSD dam removal guidelines (2015). They include conventional, mechanical or hydraulic dredging along with mechanical sediment conveyance including transport by sediment slurry pipeline, truck, and conveyor belt. Use of conventional earth moving equipment to move or remove sediment is a common practice at small dams and is affordable if proper disposal sites are nearby. It usually requires installation of temporary haul roads if the sediment is too weak to support equipment.

## Sediment stabilization

The reservoir stabilization alternative can be a cost effective way of preventing sediment from entering the downstream channel, so long as the stabilization measures do not catastrophically fail at some point in the future. However, there are limited cases that document the success of stabilization over long time periods following dam removal (e.g. no future erosion). The challenge is to design a stable channel and floodplain within a dynamic environment adjusting to a base level lowering. If reservoir sediment can be relocated to terraces above the predam floodplain that are not predicted to erode, then they will have much less impact on future river processes and be much less subject to river erosion. Vegetation planting can be incorporated to help stabilize sediment. The extent to which vegetation can stabilize deposits will depend on several factors:

1. The location of the deposit relative to high-river flows. If the deposit will be exposed to high velocities, then vegetation may not permanently stabilize the sediment. If the deposit is located in an area that will be above the floodplain, then erosion can only occur through overland flow and geotechnical processes.
2. The thickness of the sediment deposit relative to the depth of the root zone of the species that will recolonize. For high sediment terraces that are much thicker than the root depth, it may be impossible to adequately stabilize them with vegetation. Streambank protection may be needed to stabilize high reservoir terrace banks.
3. The soil texture and nutrients of the deposit. If the deposit is composed of primarily coarse sediment, then it will be difficult to establish vegetation because the deposit will not retain the moisture or nutrients necessary for plant growth.
4. The depth to groundwater after dam removal. If the deposit is well above the future groundwater elevations, then it will be difficult to establish and maintain woody riparian species such as willow and cottonwoods.

For the San Clemente Dam removal, the Carmel River was rerouted in order to stabilize sediment on that side of the former reservoir. The stabilized sediment was not significantly eroded after several floods in 2017, at least one exceeding the 10-year flood peak (Amy East, written communication, 2017). Prior to the 2017 floods, knickpoint erosion migrated through the Carmel River upstream from stabilized reservoir sediment. This upstream channel erosion released sand and gravel downstream that filled pools and replenished formerly depleted spawning gravel along the downstream channel.

At some sites, infrastructure such as bridges may exist upstream of the dam site within the reservoir sediment deposit or upstream channel or tributaries that enter the reservoir. If the infrastructure has piers or embankments in or near the channel banks, the structure could be at risk from headcut or knickpoint erosion following dam removal. At the 2011 Briggsville Dam removal in Massachusetts, undersized abutment riprap was grouted in places and successfully withstood Hurricane Irene (written communication Jim MacBroom, March 3, 2017). Infrastructure can be relocated, setback, or altered to reduce the risk of failure. Alternatively, grade structures could be installed to stabilize the channel bed and limit incision of reservoir sediments. However, care should be taken to design the foundations of grade control structures deep enough so they are not undermined.

## Channel Formation in Former Reservoir

In some dam removal projects, sediment management plans may include excavating a pilot channel or creating a new channel and floodplain within the reservoir. These methods are employed at sites where stakeholders want more certainty about the future reservoir landscape. However, some sites with regraded and shaped channels have failed during storm events. Another common alternative is to allow the river to reshape the channel and floodplain within the former reservoir and to utilize adaptive management, when necessary, to shift river position or modify localized areas.

### *Excavation of pilot channels*

Some reservoirs are many times wider than the river channel and have relatively thick delta deposits (more than 10 feet) at the upstream end of the reservoir. In this case, it may be desirable to initiate erosion along the central portion of the delta surface through an excavated pilot channel (Figure 23). The pilot channel will encourage more uniform lateral erosion across the reservoir deposit. For thinner or cohesive deposits, the pilot channel alignment could be located to coincide with the predam channel alignment if that is known and important to restore. Care should be taken to avoid establishing a pilot channel at a location where channel incision could reach bedrock (or some other erosion resistant material) that is higher than the predam channel. If this occurs, the channel could become perched on bedrock and result in fish passage problems, greatly limit the lateral erosion of reservoir sediment terraces, and prevent or slow the channel from finding its original predam course along the valley bottom (Bromley et al. 2011). Mechanical removal and/or placement of sediment, large woody debris or other flow deflectors or obstructions may be required to help guide flow into the pilot channel.

**Figure 23.—A pilot channel excavated through the Lake Mills delta and alder forest growing on the delta was cleared in preparation for the removal of Glines Canyon Dam near Port Angeles, Washington (photograph courtesy of Bureau of Reclamation, December 2010).**

### *Creation of newchannel and floodplain*

In urban environments, there can be significant public support as well as scientific environmental justification to create the ultimate channel as part of the project. There are a variety of approaches that can be utilized. These fall under the following two, broad categories of restoration and reclamation.

Restoration: Remove or rework the accumulated sediment with the goal of re-creating the historic channel. This holistic approach does not focus on individual elements but would seek the reestablishment of the structure and function of the system to a predam condition.

Reclamation: Create a new channel within the existing reservoir sediment. The goal of this approach would be to restore the bio-physical capacity of the ecosystem while accepting that its structure might be different than the original morphology. A stable-channel-design approach is needed to help ensure the channel is viable over the long term.

As an example, Idylwilde Dam in Colorado on the Big Thompson River was removed by the city of Loveland and the U.S. Forest Service after being severely damaged by a flood in 2013. The 191,000 $m^3$ (250,000 $yds^3$) of reservoir sediment stored behind the dam was removed and used as fill material to repair several roads damaged by the flood. The remaining sediment was reshaped to recreate a stream channel "near where it likely historically had been in relationship to the valley" (Cloudman, 2014).

Either restoration or reclamation can be applied depending on the desires of decision makers and stakeholders, the physical constraints of the system, the conditions under which a dam is removed, and funding. Successful and sustainable stream work requires a thorough, contextual understanding of dynamic physical, chemical, and biological processes; risks and limitations; and range of applications for appropriate tools. It also involves weighing the wide array of management and intervention options that can be used to attain the desired and achievable condition. The overall stream restoration planning process should result in clear and obtainable goals, which should be implemented through appropriate designs.

Fortunately, there are a rich system of existing guides used to treat or restore streams which cover the full range of treatments, from natural to management to structural. Several federal agencies have compiled guidance into collections that are acceptable to the practitioner (USDA Natural Resources Conservation Service, 1998; Copeland et al. 2001, USDA Natural Resources Conservation Service, 2007). Many of the tools available in these stream restoration approaches are applicable and have been used to address the pool area of a dam removal. In addition, the hydrologic, hydraulic and sediment related data collected and analysis conducted as part of the dam removal work is directly applicable to either a reclamation or a restoration work in the pool area. The evaluation and recommendation of specific approaches for specific conditions are beyond the scope of this document.

## Multiple dam removals

When multiple dams within a river watershed are being removed, the dam removal and sediment management plans must incorporate how the water and sediment released from the upper dams will influence sedimentation and erosion in the downstream dams. Dam removal, and the subsequent erosion and release of reservoir sediment, could be sequenced so that sediment from upstream reservoirs does not redeposit in downstream reservoirs. If eroded reservoir sediment did redeposit in a downstream reservoir, then there would be a superposition of impacts as the volumes of reservoir sediment combined. The exact sequence depends on the relative reservoir sizes, but generally would begin with the downstream most dam and progress upstream, or occur simultaneously. Alternatively, the downstream dam could be removed last so that the downstream reservoir contained all or a significant portion of the upstream sediment. This strategy could be used to shorten the duration of sediment impacts below the downstream most dam. However, the downstream most dam, may not capture all the fine sediment released from the upstream dams. If sediment is trapped behind the downstream dam, the magnitude of the sediment release will be amplified. In the case of the Elwha River Restoration Project, the removal of Elwha Dam and Glines Canyon Dam began concurrently, but the removal of Elwha Dam was completed first and prior to the arrival of the coarse sediment wave released past Glines Canyon Dam. On the Upper Klamath River in Oregon, the simultaneous removal of four dams is being planned: John C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate Dams (USSD, 2015). The dams are being removed simultaneously primarily to limit the duration of high suspended sediment concentrations.

# STEP 7: CONDUCT SEDIMENT ANALYSIS BASED ON RISK

The most common questions about sediment with regard to dam removal include:

- What will happen to the reservoir sediment and what will the effects be on the aquatic environment, human use, infrastructure, and property?
- What will the new reservoir landscape look like after dam removal?

The answers to these questions, and their importance to stakeholders, largely depend on the level of sediment risk. For the negligible risk category (cases with little or no sediment), only simple calculations and comparisons are recommended to verify that the reservoir sediment volume is very small relative to the potential sediment storage areas of the downstream channel (see Cases of “negligible” reservoir sediment).

First, the required level of effort (based on risk) needs to be determined. Then the sediment effects related to dam removal can be predicted along with the associated uncertainty. Development of a conceptual model, computations of total stream power, and mass balance are recommended for the low, moderate, and high sediment risk categories (Figure 24). Geomorphic analysis, sediment wave modelling, and sediment transport capacity calculations are recommended for the moderate and high risk categories. Numerical sediment transport modeling, laboratory modeling, and field experiments are recommended for the high risk category.

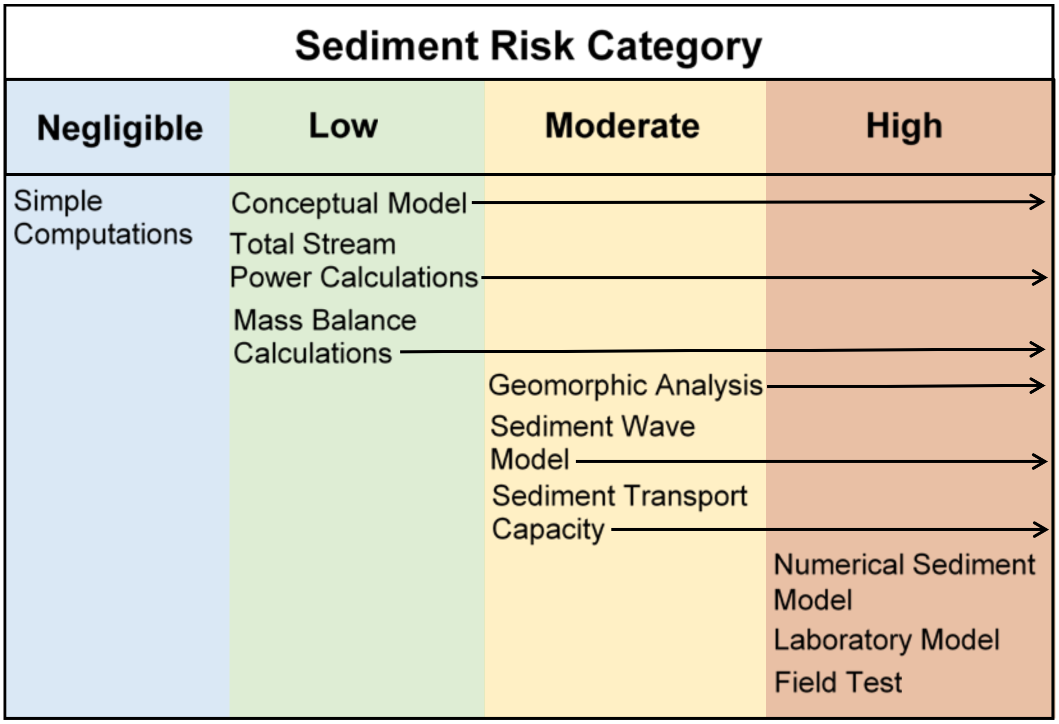



**Figure 24.—Sediment analysis and modeling options for each sediment risk category.**

The recommended level of quantitative analyses and modeling increases progressively with risk and also varies with sediment grain size and the physical setting. The sediment analyses and modeling strategies are described separately in subsections of Step 7.

A sediment wave model can be used to simulate the downstream movement and diffusion of the reservoir sediment (upon dam removal) as an elongated wave through the downstream channel (Greimann et al., 2006 and Greimann, 2011). Sediment wave models are recommended for moderate and high risk cases. Aggradation problems for low risk cases are not common, but a sediment wave model could be used to validate this assumption. The application of a sediment wave model estimates how the coarse reservoir sediment deposition thickness downstream from the dam site will vary over both distance and time. Calculations of sediment transport capacity are recommended for the moderate sediment risk category to estimate the rate that reservoir sediment can be moved downstream. Numerical modeling, laboratory modeling, or field experiments are recommended for high sediment risk categories to forecast the rates and amounts of sediment erosion from the reservoir and the corresponding downstream rates and amounts of sediment transport and deposition. Laboratory models, field experiments, and numerical models can be used to help understand and simulate reservoir sediment erosion and the downstream transport and deposition. Experiments work best when hypotheses or predictions are made in advance to guide the measurements and interpret the results.

In addition to risk, sediment analyses and modeling strategies can be linked to three general impact categories:

1. Stream channel aggradation (sediment deposition)
2. Changes to water quality from increased sediment loads
3. Changes to ground water levels and permeability

The applicability of the sediment analyses and modeling to the impact categories is presented in Table 7.

Table 7.—Applicability of sediment analyses and modeling to impact categories.

| | Sediment Impact Categories | | |
|---|---|---|---|
| **Sediment Analysis & Modeling** | **Aggradation** | **Water Quality** | **Ground Water** |
| Conceptual Model | √ | √ | √ |
| Empirical Reservoir Sediment Erosion Estimates | √ | √ | |
| Total Stream Power Calculations | √ | | |
| Mass Balance Calculations | √ | | |
| Sediment Wave Model | √ | | |
| Sediment Transport Capacity Calculations | √ | | |
| Geomorphic Analysis | √ | √ | √ |
| Numerical Modeling, Laboratory Modeling, and Field Experiments | √ | √ | √ |

# Develop a conceptual model

The conceptual model is mostly a qualitative description with supporting graphics of what will happen to the reservoir sediment, including the effects on downstream channel geomorphic process and forms, and what will happen to the reservoir landscape and upstream channel after dam removal. This description should include qualitative estimates regarding the proportion of reservoir sediment expected to erode, a description of the downstream transport mechanisms, and a description of sediment depositional areas over the short and long term.

The conceptual model is developed from field inspection and measurements, literature review, and professional experience. The conceptual model will describe the important physical processes expected to occur as a result of dam removal and guide the quantitative analyses and modeling tasks. The details of the conceptual model, and the level of effort to develop it, will increase with the level of sediment risk. The conceptual model should be a dynamic document updated whenever new information becomes available.

## Reservoir sediment erosion

An overview of reservoir sedimentation is presented in the Appendix A which may help inform development of a conceptual model. The conceptual model that addresses reservoir sediment erosion and downstream effects must address the important physical processes and the sediment-related concerns of stakeholders. A general conceptual model for erosion of reservoir sediment was developed by Doyle et al. (2002 and 2003a) and later modified by Cannatelli and Curran (2012). These general conceptual models were further modified for these dam removal analysis guidelines for sediment (Figure 25). However, the sequences and processes can be a bit different for an individual dam removal, so a site specific conceptual model should be developed for each project.

The general conceptual model begins with water and sediment in the reservoir (Figure 25a). Initial reservoir drawdown exposes a network of channels flowing over the exposed sediments (Figure 25b). Continued reservoir drawdown results in channel degradation (incision) with the fastest rates occurring in the channel that conveys the most flow. Channel degradation advances upstream through knickpoint or headcut migration, depending on the sediment grain size and stream power. There may be initially several erosional channels that form, but it is likely that the high flow channel will eventual capture all the flow as it erodes faster.

Channel incision could be limited by erosion resistant materials at the dam site, either naturally occurring (bedrock, boulders or cobbles) or remnants of the dam (e.g. boulders, timber piles, concrete, sheetpile, caisson[3]) (Gartner et al. 2015). For reservoirs with very thin layers of sediment, the underlying predam geomorphology may control locations, rate, and extent of incision. If the reservoir sediment has discontinuous patches of sediment such as in predam pools and slackwater areas, sediment erosion processes in one patch may occur independently from other patches.

Strongly cohesive sediment and bedrock can slow the rate of upstream headcut migration to a very slow rate, especially during periods of low flow. For example, during the phased removal of Brewster Creek Dam, Illinois, the headcut erosion through this low gradient channel took over 7 years to progress through cohesive sediment deposits and reach the upstream end of the former reservoir (Straub, 2007). Following removal of Dinner Creek Dam and Maple Gulch Dam in Oregon, the headcuts at each site stalled when encountering a former bedrock valley wall that confined the predam channels (Stewart, 2006). At Dinner Creek Dam the second flood post-removal allowed the channel to erode through an alder

[3] A watertight retaining structure that allows construction work to be carried out under dry conditions.

forest and migrate off the bedrock. However, at Maple Gulch Dam the discharge was intermittent and the channel remained perched above the original river bed at the conclusion of the study.

Because reservoir deltas typically extend upstream from the reservoir pool, headcut erosion will erode these upstream reservoir deposits (Figure 25c). However, erosion is generally not expected to occur upstream through predam sediments. Union City Dam was an exception because the river incised below the predam river bed elevation (Wildman and MacBroom, 2005). An exposed sanitary sewer pipe with rock riprap caused local downstream scour in the post-dam removal channel. When the pipe failed, a headcut progressed upstream from the scour location, which began about 0.5 m (1.6 ft) below the original river bed. Because the bed was lower than the predam bed at Union City Dam, the incision extended slightly farther upstream of the reservoir sedimentation effects.

In general, channel degradation and widening continues with reservoir drawdown until the predam surface is reached. The extent and rate of channel widening depends on the cohesive properties of the sediment at the river level, the location of the incised channel relative to geologic controls (bedrock, etc.), the rate of reservoir drawdown, and hydrology (Figure 25d).

Reservoir sediment erosion can be described in two phases (Pearson et al. 2011; Major et al. 2012, Randle et al. 2015; Tullos et al. 2016, Major et al. 2017, Collins et al. 2017). Erosional processes are initially dominated by the rate and amount of reservoir lowering (first phase) rather than hydrology. The hydrology after dam removal is primarily responsible in achieving the final equilibrium extent of lateral reservoir sediment erosion (second phase). During the second phase, additional erosion occurs when floods are large enough to go over bank and access impounded sediments more distant from the newly-formed channel (Collins et al. 2017) or when significant bank erosion occurs. The reservoir-valley width influences the two-phase erosion responses.

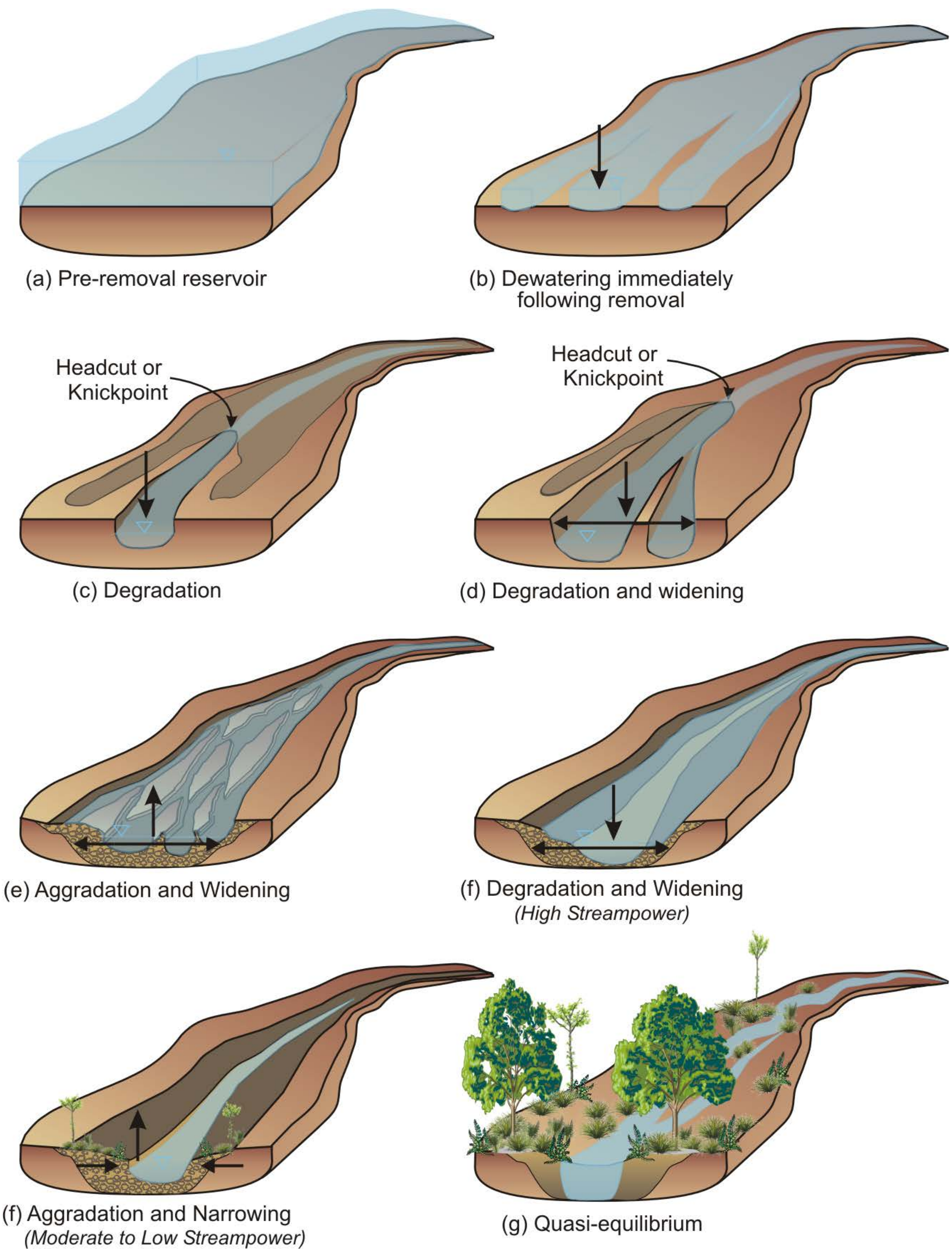



**Figure 25.—Conceptual model of sediment erosion from the reservoir modified from Doyle et al. (2003a) and Cannatelli and Curran (2012).**

The initial channel erosion width through the reservoir sediment is a function of sediment cohesion, amount of reservoir drawdown, and the stream-flow discharge. Erosion widths in non-cohesive sediment will tend to be wider than in cohesive sediments. Bromley (2011) found that, during steady flow, larger reservoir drawdown increments produced more erosion than smaller drawdown increments for the same total reservoir drawdown. However, erosion channels will tend to widen over time through lateral bend migration and braiding, which is accelerated during periods of high stream flow. If the rate of reservoir drawdown is slow, there will be more time for lateral erosion at higher elevations of the reservoir. Conversely, if the rates of reservoir drawdown are fast, then channel degradation or incision will also be fast and there will be less time for channel widening at higher elevations of the reservoir. Mass wasting of reservoir sediment terraces can occur during rapid rates of reservoir drawdown due to slope instability.

In general, the rates of reservoir sediment erosion are expected to decay exponentially over time because the most easily eroded sediment will have already been eroded and higher magnitude, lower frequency stream flows will be needed for additional erosion.

Erosion rates will be relatively fast through coarse reservoir sediments that are devoid of woody vegetation because there is typically little or no cohesion. Conversely, erosion rates can be relatively slow through fine, consolidated cohesive reservoir sediments unless rapid reservoir drawdown creates extensive mass wasting (Figure 25d). Cohesive sediments likely will erode locally along the outside of channel bends. If fine cohesive sediments are unconsolidated (low bulk density), then they can have very low resistance to erosion and be more erodible than coarse sediments. Rates of erosion and downstream transport may be considerably slower in ephemeral streams where erosion is limited to the occurrence of episodic rainfall runoff. If the reservoir is drawn down in phases, multiple increments of the incision and widening may occur.

Coarse sediment eroding from the upstream portion of the reservoir will prograde downstream and some will likely deposit along the lower portion of the reservoir if that space has not already filled with sediment. The rates of downstream sediment transport and deposition depend on rates of upstream erosion and the downstream transport capacity. Channel degradation and widening are most likely to occur where sediment transport capacity, or stream power, are high. Channel widening may also occur due to erosion of the terraced banks (Figure 25f). Sediment bar deposition is expected along channel margins when sediment transport capacity, or stream power, are low. Deposition results in a narrower active channel (Figure 25f). Eventually, vegetation may grow on the exposed reservoir topography and remaining reservoir sediment terraces. Woody species may provide some stability to these terraces depending on density and root depth relative to terrace height (Figure 25g). The final channel planform through the former reservoir will depend on the upstream inputs of water, wood, and sediment, reservoir valley slope, and any geologic or human-built constraints. The channel morphology may include braided and meandering channels as the river adjusts to the lower base level (Randle et al., 2015).

Similar erosion processes are expected to occur in tributary channels that enter the reservoir. Reservoir sediments eroded from tributary channels will tend to form alluvial fans at the confluence with the main channel and locally influence the main channel’s lateral position. While the erosion processes are similar, the rate at which tributaries incise and widen may be slower than the rate of erosion in the main channel. When tributary erosion lags behind, the tributary may occupy a steeper, shorter path to connect with the main channel than predam conditions, and become temporarily perched on a higher terrace.

The reservoir landscape that develops after dam removal will depend on the thickness, size gradation, and cohesive properties of sediment. Narrow reservoirs (less than three times the active channel width) and reservoirs with predominantly non-cohesive or coarse sediment are expected to erode the greatest proportion of sediment as a result of dam removal (MacBroom and Shiff, 2013). A significant volume of sediment may be left behind in reservoirs that are much wider than the river channel, especially when the sediments have cohesive properties or are deposited on terraces within the former reservoir. Cohesive properties of the sediment may exist when at least 20% is composed of clay, when woody material or litterfall (plant material, such as leaves from trees) is abundant in the sediments, or a combination of both. The greater the amount of sediment cohesion, the slower the rate of lateral reservoir sediment erosion and the greater the sediment volume that will be left behind within the former reservoir. If the cohesive sediments have a very low bulk density (high water content) and have not consolidated, then they will have low shear resistance and can be easily eroded.

The presence of woody material and litterfall in reservoir sediment deposits can affect the rate and extent of reservoir sediment erosion while providing an increased supply of wood and litterfall to the downstream channel. During reservoir 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, beaver dams, or debris may exist that could limit the extent of headcut migration or lateral erosion and may 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 wood to the downstream channel may increase as a result of dam removal. Large wood released may help restore fluvial processes and form log jams, provide surfaces for vegetation to grow on, and improve aquatic habitat. Small woody material, and any accompanying litterfall, may also pose challenges to operate and maintain fish screens at water diversions and treatment facilities.

## Downstream sediment transport and deposition

The risk of downstream sediment impacts depends on the amount and rate of reservoir sediment erosion, the transport capacity and geomorphic sensitivity of the downstream channel, and hydrology.
The hydraulic capacity to transport fine sediment (silt and clay), or wash load, is typically very large so the majority of the fine sediment is expected to keep moving downstream until deposited in a downstream reservoir, lake, estuary, or coastal area. Some fine sediment may deposit in low velocity areas of floodplains, channel eddies, and in the interstitial spaces of coarse sediment along the channel bottom. Measurable fine sediment deposition in the channel may occur if significant amounts of stream flow are lost to the ground water. Fine sediment may be eroded away during future floods following dam removal, but fine sediment deposition can temporarily affect aquatic invertebrates, slow-moving organisms such as mussels, the permeability of coarse sediments, ground water flow, and wells. Tributaries contributing additional flow downstream of the dam may help dilute effects of wash load released during dam removal.

Coarse sediment eroded from a reservoir may be transported downstream as bed load or suspended load, depending on the local stream velocity, shear stress, and turbulence. The primary controls on hydraulics are the channel slope, discharge, bed roughness, and confinement. Downstream transport rates for coarse sediment will be limited by the hydraulic capacity of stream flows and at least some deposition can be expected in low-velocity areas of the stream channel. For coarse sediment loads, the stream channel may adjust over time to increase its sediment transport capacity by achieving a straighter and steeper slope with less roughness. Immediately downstream of the dam excess storage capacity for coarse sediment is often available due to local scour resulting from trapping in the upstream reservoir.

Coarse sediments tend to travel downstream in long, low amplitude waves with the greatest deposition occurring just downstream of the dam removal site. At Savage Rapids Dam, coarse sediment buried the first riffle and filled the first few deep pools downstream (Bountry et al. 2013). Reservoir sediment released from a dam on the North Fork Poudre River, Colorado, deposited primarily in pools along a 12 km (7.5 mi) reach. During the subsequent spring snowmelt, sediment was progressively scoured from the upstream and then the downstream pools (Wohl and Cenderelli, 2000). At Marmot Dam, sediment deposited in a wedge just downstream of the dam site and restored the predam grade (Major et al. 2012). In high transport capacity environments, like the bedrock canyon downstream of Condit Dam, sediment may rapidly transport through the reach with little deposition until reaching a lower gradient section of river (Wilcox et al. 2014).

Kibler et al. (2011) provides a conceptual model of channel evolution for the downstream river response to a release of coarse sediment from a dam removal. Initially following the release of coarse reservoir sediment, sediment deposition tends to fill in the pre-removal channel thalweg and results in low complexity morphology and habitat. During this phase, the channel substrate is dominated by coarse grain sizes from the reservoir. As reworking occurs, the river sorts the released sediment forming a more heterogeneous channel with a defined thalweg, bars, pools, and riffles. For reservoirs with large coarse sediment releases, significant bar development can result in channel widening, channel braiding, and floodplain deposition (Major et al. 2017). For the Elwha River Restoration Project, coarse sediment waves released from Lake Mills and Glines Canyon Dam moved downstream and dispersed (Magirl, 2015). These sediment waves increased downstream channel braiding, sinuosity, and bank erosion (East et al. 2015).

## List of questions for the conceptual model development

Questions that the conceptual model should try to address are listed below along with some example answers. Actual answers should be customized for each project based on local site characteristics gathered in prior steps.

- Has the reservoir operations had a significant effect on hydrology (stream flows) that needs to be incorporated in the sediment analysis?
    - *Reservoir operations have no significant effect on hydrology*
    - *Reservoir operations do have a significant effect on hydrology*
    - Note: If the active reservoir pool volume is small compared with the mean average annual stream flow volume (< 1%), then dam removal would not be expected to have much effect on the downstream hydrology. If the reservoir stores water during high flows and releases stored water during low flows, then the effects on downstream hydrology should be considered. As of 2016, very few, if any, dams have been removed where the primary purpose was water supply or flood control, so the effects of dam removal on hydrology have been small. In some cold region cases, dam removal could increase the severity and frequency of ice dams (see White and Moore, 2002).
- Will the dam be removed during a period of low, average, or high stream flows and are these flows capable of mobilizing available reservoir sediment?
    - *Dam removal during low flow with low sediment transport rates*
    - *Dam removal during average flow with moderate sediment transport rates*
    - *Dam removal during high flow with high sediment transport rates*
    - Note: Non-cohesive or coarse reservoir sediment may be mobilized during the average annual flow and larger flows. Whereas, multiple floods may be needed to erode cohesive and consolidated reservoir sediment.

- How much sediment will be eroded from the reservoir and over what time frame?
    - *erosion of 50%, 60%, 70%, 80%, 90%, or 100% of the total volume*
    - *erosion period of days, weeks, months, or years*
- What proportion of eroded reservoir sediments are expected to be transported along the stream bed (bed load or bed-material load) versus suspended in the water column (suspended load or wash load)?
    - *Bed load transport may account for 10% to 30% of the total sediment load while 70% to 90% may be transported as suspended load*
- What will the reservoir landscape eventually look like?
    - *predam topography without reservoir sediment*
    - *sediment terraces along the margins of the reservoir valley*
- What species of vegetation will grow on the exposed reservoir landscape and how long will that take?
    - *native vegetation on the exposed landscape*
    - *invasive vegetation on the exposed landscape*
- What will happen to coarse sediment that is eroded from the reservoir?
    - *transport downstream to a reservoir, lake, or estuary*
    - *deposition along the channel banks in eddies or as bars*
    - *deposition along the channel bottom, especially in river pools*
    - *deposition of finer sediments on top of a coarser streambed with possible effects to the aquatic environment, ground water flow, and well yields*
    - *deposition at water diversion and pumping plant intakes resulting in the reduced water diversions and increased diversion of sediment*
    - *floodplain deposition during flows greater than the active channel capacity*
    - *aggradation of riffles or other hydraulic controls resulting in more frequent inundation of the floodplain*
    - *significant deposition that results in streambank erosion, channel widening, and effects on property and infrastructure*
    - Note: Estimate how long coarse sediment deposits along the downstream channel are expected to persist. If the reservoir had been trapping coarse sediment for decades, then some of the depositional bars after dam removal may persist over the long term because the upstream sediment supply has been restored.

- What will happen to fine sediment eroded from the reservoir?
  - *increase in turbidity and suspended sediment concentration during the period of reservoir drawdown, and channel incision and widening within the exposed reservoir*
  - *downstream deposition of fine sediment along floodplains, in reservoirs and in estuaries*
  - *the increase in turbidity may affect aquatic species, which may help native species that evolved under high sediment conditions*
  - *the increase in turbidity may affect downstream water users because of increased diversion of sediment, which may require additional water treatment and sediment removal*
- What will happen to woody and other organic material eroded from the reservoir?
  - *woody material will deposit along the downstream channel in slow velocity areas and add to other wood jams already in the channel;*
  - *woody and organic material will accumulate on trash racks and screens of downstream water intakes*
- What effect will upstream sediment and wood loads have on the downstream channel after dam removal?
  - *the reservoir had already filled to its sediment storage capacity so the upstream sediment and wood loads were already being transported downstream, however, these loads will increase as the reservoir sediment erodes with dam removal*
  - *upstream sediment and wood loads are still being trapped in the reservoir, so downstream sediment and wood loads will increase because of dam removal and restoration of the loads upstream from the reservoir*
- How will the supply of water and sediment from downstream tributaries affect the transport of sediment?
  - *downstream tributaries will supply relatively little water or sediment;*
  - *downstream tributaries will supply large volumes of water, some sediment, and significantly increase the sediment transport capacity*
  - *downstream tributaries will supply some water and significant sediment loads that will add to the loads from the upstream reservoir sediment*

## Empirical reservoir sediment erosion estimates

Not all of the sediment may be eroded from a reservoir following dam removal, especially within the first year and especially for wide reservoirs. Sawaske and Freyberg (2012) evaluated 12 predominantly low-head dam removals (6 to 45 feet high) and found that the sediment volume eroded from the reservoir during the first year ranged from 8 to 65 percent with an average of 28 percent. They also found that the erosion volume was less where the sediment deposits were predominantly fine and consolidated or cohesive. Major et al. (2017) evaluated 16 dam removal cases, including some of those assessed by Sawaske and Freyberg (2012) along with some more recent large dam removals. For reservoirs with coarse sediment, Major et al. (2017) found that the sediment volume eroded from the reservoir ranged from 1 to 77 percent, with an average of 43 percent, within the first year of dam removal (Table 8). For reservoirs with more than 30 percent fine sediment, Major et al. (2017) found that the sediment volume eroded from the reservoir ranged from 8 to 72 percent, with an average of 25 percent, within the first year. The percentage of total reservoir sediment erosion continued to increase over a period of 2 to 4 years after dam removal, but the rates of erosion generally decreased with time.

Table 8.—Portion of sediment volume eroded from the reservoir after dam removal for case studies reported by Major et al. (2017).

| Dam and State | Sediment Type | Short Term (< 1 year) | | Long Term (> 1 year) | |
|---|---|---|---|---|---|
| | | Time after dam removal (years) | Sediment Erosion Volume (%) | Time after dam removal (years) | Sediment Erosion Volume (%) |
| Condit, WA | > 30% Fine | 0.7 | 72 | | |
| Glines Canyon, WA | > 30% Fine | 1 | 37 | 5 | 72 |
| Elwha, WA | > 30% Fine | 1 | 20 | 5 | 50 |
| Rockdale, WI | > 30% Fine | 0.8 | 17 | | |
| Ivex, OH | > 30% Fine | 0.2 | 13 | | |
| La Valle,WI | > 30% Fine | 1 | 8 | | |
| Brewster, IL | > 30% Fine | 1 | 8 | 3.7 | 13 |
| Milltown, MT | Coarse | 0.4 | 77 | | |
| Simkins, MD | Coarse | 1 | 73 | 3.6 | 94 |
| Merrimack Village, NH | Coarse | 1 | 63 | 1.5 | 79 |
| Marmot, OR | Coarse | 1 | 53 | 1.8 | 58 |
| Savage Rapids, OR | Coarse | 0.4 | 50 | | |
| Lost Man, CA | Coarse | 0.6 | 30 | | |
| Brownville, OR | Coarse | 1 | 30 | 1.9 | 38 |
| Secor, OH | Coarse | 0.4 | 10 | | |
| Stronach, MI | Coarse | 1 | 1 | 2.8 | 3 |

The portion of sediment that erodes from a reservoir is generally believed to be less for wide reservoirs than for narrow reservoirs (Wildman and MacBroom, 2010 and Randle et al. 2015). Sawaske and Freyberg (2012) found this to be true when the ratio of the average width of the reservoir sedimentation to channel width was greater than 2.5. This is because the eroding channel, and developing floodplain, may not need to be as wide as the reservoir valley width and some reservoir sediment terraces may be perched on natural terraces that the river is not as likely to erode. However, erosion widths can be quite wide through coarse reservoir sediments that lack the cohesion provided by clay or the roots of woody vegetation (Randle et al. 2015). This was the case for erosion of the upper layer of the delta in Lake Mills behind Glines Canyon Dam (Figure 26). During the Condit Dam removal, rapid and large amounts of reservoir lowering led to mass wasting and an increased volume of reservoir sediment erosion (Major et al. 2017).


**Figure 26.—Looking upstream at extensive lateral erosion of Lake Mills delta (upper coarse layer) near Port Angeles, WA less than 1 year after phased dam removal began.**

The initial alignment of erosion channels through reservoir sediment can affect the total amount of erosion. This is because the eroding channels have a tendency to incise along their initial alignment and then widen (Randle et al. 2015). In the case of multiple channels, the channel conveying the most flow will tend to incise at the fastest rate and capture flow from the other channels. Erosion rates can be expected to accelerate as flow is captured from other channels. If the erosion channel alignment is located along the reservoir margin, there is less room for the channel to widen and a lower likelihood of planform sinuosity developing. Channel incision may be limited by bedrock, or a highly erosion resistant surface, along the valley margin. If the initial channel alignment through the reservoir does not coincide with the predam channel alignment, the river could end up cutting into a predam terrace. If it is important that the channel re-occupy the predam channel, a pilot channel can be utilized to reduce uncertainty of the post-removal channel alignment. It may not always be necessary that the channel return to the same channel or it could be difficult to identify the alignment of the predam channel.

Erosion through the Lake Aldwell delta (behind Elwha Dam) initially occurred along the valley wall and within a formerly forested area of the predam valley

(Figure 27). The large cedar tree stumps in former Lake Aldwell slowed the rate of incision and lateral migration across the valley toward the predam alignment. Particularly in wide reservoirs (more than 2 to 3 times the channel width), excavation of a pilot channel may help ensure that the initial alignment of the channel eroding through the reservoir sediment coincides with the predam channel alignment.

**Figure 27.—The Elwha River initially incised through the Lake Aldwell delta over a cleared forested area that did not coincide with the predam channel alignment.**

The proportions of sediment eroded from reservoirs vary widely among the reported case studies. Collins et al. (2017) observed a two-phase erosion response (vertical and then lateral erosion) even in small reservoirs, and the second phase can be protracted. Even during the first phase, when flows are of secondary importance, it commonly takes a few months after reservoir drawdown to achieve about 50% erosion of the sediment mass.

The data reported by Major et al. (2017) are summarized for the first year of dam removal in Table 9. For half of these case studies, the sediment-erosion volume percentages were available for periods ranging from 1.5 to 3.7 years after dam removal (Table 8). Where possible, the trend lines of the data reported by Major et al. (2017) were extrapolated to estimate the portion of reservoir sediment that was expected to erode over the long term (Table 9).

Table 9.—Summary of sediment volume eroded from the reservoir over the short term (< 1 year) and long term (> 1 year) based on data reported by Major et al. (2017).

| Reservoir Sediment Type | Portion of Reservoir Sediment Volume Erosion | |
|---|---|---|
| | Short-term Estimate (%) | Long-term Estimate (%) |
| Coarse | 1 to 77, Average = 43, Median = 50 | 4 to 100, Average = 67, Median = 78 |
| > 30% Fine | 8 to 72, Average = 25, Median = 17 | 10 to 90, Average = 46, Median = 39 |

The data presented in Table 9 may be used to help guide estimates of the sediment volume that may erode from a reservoir. In general, reservoir sediment will continue to erode following dam removal until a new equilibrium is reached, but the rates of erosion during the second phase typically decrease over time. The average sediment erosion volumes are significantly less for reservoir sediments that are composed of more than 30 percent silt and clay.

If the relative reservoir width (ratio of reservoir sediment width to river channel width) is greater than 2.5, then the proportion of sediment eroded from the reservoir would typically be less than for narrower reservoirs. The relative reservoir width should be computed using the active channel width of the stream in a wide alluvial reach that has essentially the same discharge as that flowing through the reservoir reach.

In cases where reservoir sediment has deposited on hillslopes and old river terraces that are higher than the predam floodplain surfaces, river erosion may not be able to access these perched reservoir deposits unless the erosion of these deposits occurs before the channel has incised down to the predam surface. 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 recomputed and Step 6 should be revisited.

## Assessing reservoir sediment stability

If the reservoir sediment erosion processes described in the conceptual model (Figure 25) have occurred, then the remaining sediment should be relatively stable. Additional guidance on assessing the stability of sediment remaining in the reservoir is provided below:

- For most reservoirs, assume that the predam topographic surface, if exposed, will be relatively stable over the long term. However, an erosion channel may incise through a predam terrace.

- If the thickness of the reservoir sediment deposit is thin (less than a typical active channel depth), then the deposit's topography is likely to be consistent with the predam valley landscape. After dam removal, thin layers of sediment remaining on high surfaces above the newly formed channel and floodplain are likely to be relatively stable, particularly if new vegetation establishes.

- As the thickness of the reservoir sediment deposit increases beyond a typical active channel depth, its topography will become increasingly dissimilar than the predam valley landscape and sediment terraces will become increasingly susceptible to local erosion and instability.

- If an incising river channel encounters erosion resistant material (e.g. old dam or structure, bedrock, large rocks, clay), then either a large portion of the reservoir sediment may be left behind or a prolonged period of reservoir sediment erosion may occur. Under this circumstance, vertical incision may cease, at least temporarily, and lateral erosion may dominate.

- In many cases, the remaining reservoir sediment can become stabilized by vegetation. Factors that influence vegetation include sediment texture, nutrients, slope, sun exposure, protection from wind erosion, proximity to water, and passive or active seeding and planting.
    - If the root depth of vegetation can survive long enough to become deeper than the sediment thickness then the vegetation is likely to stabilize the reservoir sediment. However, local erosion from channel meander bends may still occur.
    - If the reservoir sediment thickness is greater than the root depth of vegetation, then vegetation may only help to control surface erosion from rainfall runoff, but not limit bank erosion. However, floodplain vegetation along the toe of a sediment terrace may help limit erosion.

## Total stream power calculations

A total stream power analysis will help identify downstream channel reaches where sediment released from the reservoir is likely to be transported or deposited. The greater the total stream power, the greater the sediment transport capacity and the less potential for reservoir sediment deposition. Total stream power (*P*) can be computed as the product of discharge (*Q*), longitudinal channel slope (*S*), and the unit weight of water ($\gamma$) (Yang, 1996):

$$P = \Upsilon\, Q\, S \tag{9}$$

The average annual discharge (or a discharge of some consistent flow frequency) can be assumed for the channel below the dam and all downstream tributaries. Stream gage records will be the best source of data for mean-annual discharge. Stream-discharge estimates may have to be extrapolated from other gaged locations based on drainage area. For most streams, the discharge tends to increase with distance downstream after tributaries are encountered. However, stream flow can be taken from the channel at surface water diversions and pumped from wells. Some reaches can also lose or gain stream flow to and from the ground water.

For most streams, the longitudinal river slope decreases with distance downstream. However, some rivers encounter steep reaches through bedrock canyons or reaches near the mouth resulting from local geologic controls. For example, the Methow and Entiat Rivers in eastern Washington State have steeper reaches in the downstream-most section of the watershed until reaching the backwater caused by the Columbia River.

## Mass balance calculations

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.

There are several ways to put the reservoir sediment volume into perspective. Calculate the average thickness of reservoir sediment if the entire volume were to deposit evenly over a length of the downstream channel that had relatively low total stream power. For this computation, assume that the sediments deposited evenly across the average bankfull channel width. If the computed sediment deposition thickness is less than 10 percent of the average channel depth at bankfull discharge, then compute the ratio of the reservoir sediment volume to the volume of a typical sand or gravel bar along the downstream channel (Eq. 1). If the potential sediment deposition volume is less than that of a few sand or gravel bars, then the effects on the physical channel likely would be small and no other calculations or modeling are necessary. However, if the computed deposition thickness is significant, then more evaluation is necessary.

Separate analyses for coarse and fine sediment will be useful. Repeat the above calculation for only the coarse sediment. If the computed deposition thickness of coarse sediment is less than 10 percent of the average bankfull depth, then compute the average length of deposition assuming a thickness:

- For gravel and cobble-bed streams, assume a deposit thickness equal to one or two times the coarsest particle size ($d_{90}$) of the existing downstream bed material.
- For sand-bed streams, assume the deposit thickness is equal to one or two times the typical dune height of the existing downstream channel or assume the deposit thickness is equal to 10 percent of the average channel depth at the bankfull discharge.

The computed deposit length can then be divided by the average active channel width to help provide some context. For example, the computed result may indicate that the coarse reservoir sediment may deposit evenly over a longitudinal distance equivalent to so many channel widths with an average thickness equal to the largest cobbles of the existing streambed.

For fine reservoir sediment, initially assume that it will erode as quickly as the reservoir is drawn down and will be transported downstream. Then compute the average sediment concentration as the ratio of the fine reservoir sediment mass and the volume of water discharged during the reservoir drawdown period. The fine sediment mass can be computed by multiplying the fine sediment volume by the unit weight. The unit weight can be measured from reservoir sediment cores or estimated (e.g. 0.56 to 1.12 $Mg/m^3$ or 35 to 70 $lbs/ft^3$, Table 3 and Table 4) based on the portions of clay and silt and years of compaction.

The peak sediment concentration will be greater than the average concentration, but the computed average concentration will be overestimated using the assumption that all the fine reservoir sediments erode during the reservoir drawdown period. If the calculated average sediment concentration would be expected to cause significant impacts to the aquatic environment or downstream water users, then the rate that fine sediment will erode from the reservoir should be evaluated in more detail using numerical modeling, physical modeling, or field experiments. Highly cohesive sediment may take a few years to erode from a reservoir, especially during drought periods. The period of erosion may have to be estimated.

Based on the total stream power calculations and knowledge of downstream reaches, predict the most likely locations for fine sediment deposition (e.g. downstream slow velocity reach, reservoir, lake, estuary, or ocean).

## Sediment wave model

The sediment wave model is fairly simple to use and provides estimates of coarse sediment thickness that tend to decrease with time and distance downstream from the dam. This type of model is limited to main channel deposition and does not account for more complex processes such as channel migration or floodplain deposition. 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 and it assumes there is a uniform slope downstream of the dam.

An analytical sediment wave model can be found in Greimann et al. (2006) or in the ASCE Monograph on Sediment Dynamics upon Dam Removal, Chapter 9: Movement of Sediment Accumulations (Greimann, 2011). This sediment wave model was verified with laboratory data and then used to estimate coarse sediment (sand and gravel) deposition for the removal of Hemlock Dam on Trout Creek in southwest Washington State. Prior to dam removal, reservoir sediment thickness values ranged from 0.70 to 2.7 m (2.3 to 8.8 ft) with an average thickness of 1.8 m (5.9 ft) over a longitudinal distance of 290 m (940 ft). Longitudinal profiles of sediment deposition thickness are plotted for the initial conditions in the reservoir and along the downstream channel at various times after dam removal ranging from 0.5 to 32 days (Figure 28). The model predicts that the maximum sediment deposition would occur immediately downstream from the removed dam (0.64 m or 2.1 ft after 0.5 day). At 0.5 mile downstream from the dam site, the model predicts a maximum deposition thickness of 0.2 m (0.5 ft), which occurs after 32 days.

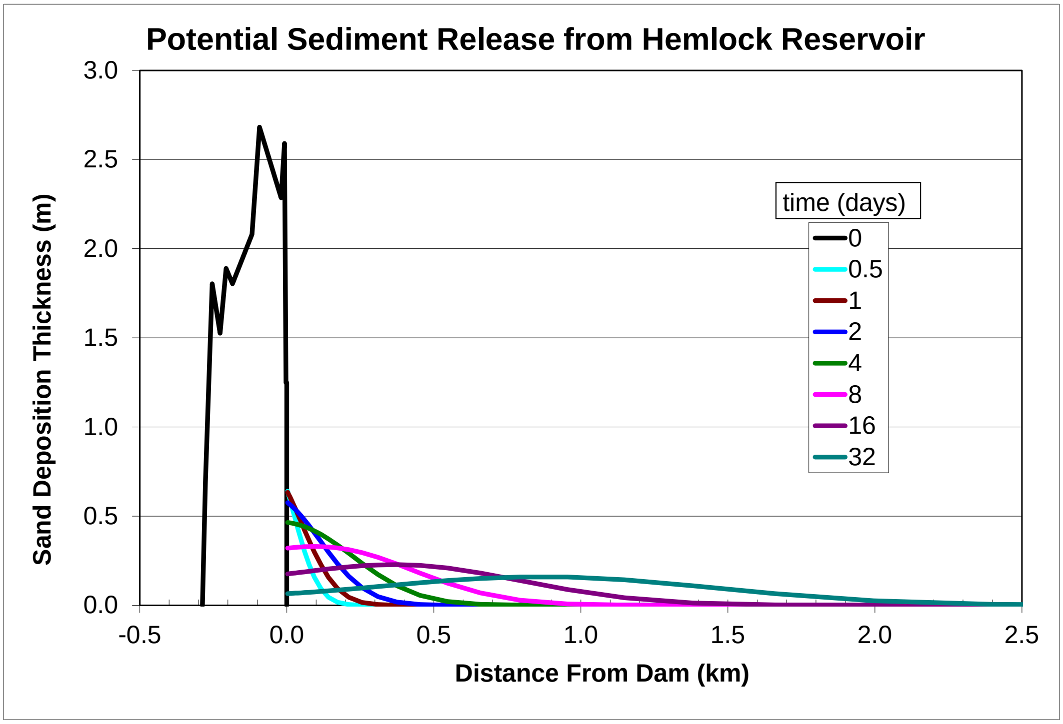



**Figure 28.—Example sediment wave model results for the removal of Hemlock Dam on Trout Creek in southwest Washington State.**

## Sediment transport capacity calculations

Sediment transport capacity is the hydraulic capacity of a stream channel to transport sediment (see step 4a). The upstream sediment supply may be greater or less than the hydraulic transport capacity. The actual sediment load will be the lesser of the upstream sediment supply or the hydraulic capacity. Deposition can be expected when the supply is greater than the hydraulic capacity, while erosion can be expected when the capacity is greater than the supply.

Sediment transport capacity can be computed to estimate the ability of the stream channel to transport sand and gravel-sized sediment eroded from the reservoir. A variety of predictive equations may be used to compute sediment transport capacity at various downstream locations of interest for a range of stream discharges. Sediment transport capacity should be calculated for downstream reaches of concern that have the lowest transport capacity based on the total stream power calculations. The required input data for the sediment transport equations are described in Step 4a, Method 4: sediment-discharge rating curve.

## Geomorphic analysis

For moderate and high risk dam removals, a geomorphic analysis is recommended. The geomorphic analysis should describe the channel's reference (pre-modification) condition as far as possible and explain how this has been progressively modified over the years by human activity. An example of how to do this is provided in the fluvial audit paper by Sear, Newson and Thorne (1995). This output provides the basis for a narrative explanation of the channel system's sensitivity and thus how it may respond to the proposed dam removal. Initially, the geomorphic analysis should utilize historical aerial photographs, geologic maps, soil maps, topographic maps, historical ground photographs and accounts, and field reconnaissance. Additional analysis may require collection and interpretation of sediment and soil samples. The geomorphic analysis will describe the physical setting of the dam, reservoir, and river channel, a description of geologic controls, significant water and sediment sources, and characterization of the river and reservoir sediment. The geomorphic analysis also will identify historical channel trends and allow for estimates of future channel evolution following dam removal. Where possible, a quantitative geomorphic analysis should be applied. This could include the analysis of sediment transport rates for mixed grain sizes and a sediment budget as a first step in the analysis.

Example components of the geomorphic analysis for the downstream channel and floodplain include:

- Estimate the proportions of the existing bed-material particle sizes along the downstream channel (e.g. percentages of cobble, gravel, sand, silt, and clay).
- Identify significant downstream tributaries and their relative contribution of water and sediment (incorporate total stream power computations).
- Characterize distinct reaches of the downstream channel. The reaches should be distinguished by longitudinal slope, channel or valley width, channel planform, geology, land use, etc.
- Describe the potential depositional environments for sediment (e.g. pools, bars, side channels, floodplains, downstream lake, reservoir, or estuary).

For dam removals with a significant reservoir drawdown and steep reservoir shoreline, the potential for landslides during reservoir drawdown should be investigated by an experienced geologist.

There are numerous references for geomorphic analysis of stream channels. The American Society of Civil Engineers (ASCE) Sedimentation Engineering Manual (Garcia, 2008) provides two chapters:

- Fundamentals of Fluvial Geomorphology (Biedenharn et al. 2008)
- Engineering Geomorphology (Schumm and Harvey, 2008)

The ASCE Sediment Dynamics upon Dam Removal also provides a chapter on the geomorphic effects of dam removal (Skalak et al. 2011).

## Laboratory modeling

Laboratory or physical models can provide useful qualitative predictions of complex processes such as knickpoint erosion, armoring, channel widening, braiding, meandering (with bank cohesion), downstream transport, and deposition. There can be sediment scaling issues with laboratory models that can make quantitative predictions difficult. For example, the specific gravity, particle fall velocity, cohesion, and the grain sizes of clay, silt, sand, and gravel cannot be scaled in the same way. Therefore, the exact physical properties of coarse and fine sediment, including cohesion, are not easily replicated in the laboratory. For example, the apparent cohesion due to matric suction within the sand can be an important force in the laboratory, but not in the field. Bromley et al. (2011) constructed a physical model to simulate the sediment erosion in Lake Mills behind Glines Canyon Dam in Washington (Figure 29). This physical model was used to evaluate the proportion of reservoir delta erosion in response to the rate of dam removal and the initial alignment of the erosion channel.


**Figure 29.—Gordon Grant (left) inspects the physical model constructed by Chris Bromley (right) at the Saint Anthony Falls Laboratory, MN of Lake Mills behind Glines Canyon Dam to investigate reservoir sediment erosion processes.**

## Field experiments

Field experiments can be quite useful and there are no scaling issues. A field experiment requires the ability to lower the reservoir pool, or open a sluice gate, and a monitoring program to test hypotheses or predictions. The reservoir drawdown or sluice gate opening needs to be enough to create a measurable response, but not so much that environmental effects create significant problems for resources of concern. Support from stakeholders and permitting agencies is also helpful and may be necessary.

A reservoir drawdown experiment was conducted at Lake Mills in April 1994 (Figure 30) to investigate reservoir delta erosion processes on the Elwha River in advance of dam removal (Childers et al. 2000).


**Figure 30.—Time lapse photograph of the lower Lake Mills delta during the reservoir drawdown experiment on April 19, 1994.**

## Numerical modeling

Numerical models can simulate channel degradation of the exposed reservoir sediments during dam removal and transport and deposition over time and with distance downstream. Numerical models do not have scaling issues, they do not create environmental impacts, and they can simulate a wide range of scenarios. Numerical models are good at estimating the relative effects of different dam removal and sediment management alternatives, different hydrologic scenarios, and sensitivity analysis. However, numerical models have difficulty representing the rapid headcut associated with dam removal and cannot simulate all the complex geomorphic processes found in nature. Some of the most difficult processes to simulate are bank erosion, meander-bend formation, lateral-channel migration, sediment stratification, bed material mixing, pool-riffle formation, and erosion processes with log jams and scattered wood.

The domain of a numerical model may include the entire reservoir area, the delta extending upstream from the reservoir pool, and the channel downstream from the reservoir. The model should include the entire downstream length of channel where there are impact concerns. An appropriate downstream model boundary may include a lake, estuary, major tributary, entrance to a bedrock canyon, or a grade control structure. The numerical model can be used to simulate and track both the bed-material load and the wash load.

Accurately estimating the volume of sediment that is expected to erode from a wide reservoir is difficult because the processes of channel widening and lateral migration are quite complex. Numerical models can predict the vertical erosion of a channel through the reservoir sediment, but numerical models are not generally available to predict the lateral channel erosion, which is a problem when the reservoirs are much wider than the river channel. Most numerical models maintain their initial channel alignment with no ability to simulate meander bend formation or lateral channel migration. Bank erosion and channel widening can be simulated by incorporating empirical methods such as angle of repose, erosion width versus discharge relationship, etc.

Numerical models to simulate sediment transport, erosion, and deposition are often one dimensional, which means that hydraulic and sediment transport variables represent average conditions for each stream cross section and time step. One-dimensional models are powerful tools because they are able to simulate many tens of river miles, over decades of time, and for many alternatives and scenarios including dam removal (Greimann, 2013). One-dimensional models have a uniform water surface elevation across the channel cross-section, so do not accurately simulate lateral variation of hydraulics such as in multi-threaded channels. One-dimensional models cannot simulate eddies and most do not attempt to predict the velocity distribution across the channel and, therefore, cannot simulate the distribution of sediment erosion and deposition across the channel for a given time step. The entire wetted cross section is assumed to have either erosion or deposition over a given time step. The models adjust each cross section over time in the vertical direction and some models have the ability to adjust the cross section width.

There are some two dimensional hydraulic and sediment transport models that assume depth-averaged conditions for each cell of the model mesh. These models do simulate variations in hydraulics and sediment transport both along and across the stream channel and floodplains. Eddies can be simulated as well as erosion in some parts of the channel and deposition in other parts of the channel or floodplain. Because two-dimensional models are more computationally intensive than one-dimensional models they are typically applied to less than 20 km (10 miles) of river and simulate days to months of time rather than years. The number of alternatives or scenarios simulated may have to be limited, although advance in computer processing methods or using coarser mesh spacing can allow longer reaches to be simulated.

Some three-dimensional sediment transport models exist, but mostly for research. These models are even more computationally intensive than two-dimensional models and are often applied to less than a mile of river and simulate less than a week of time. The historical trends of increased computational hydraulics capability and computer speed mean that the use of two and three dimensional sediment transport models may be more common in the future.

Many numerical sediment transport models are available. The list of models is too numerous and evolving too rapidly to present in the dam removal analysis guidelines for sediment. Given the complexity of numerical sediment transport models, the choice of the person applying the model may be more important than the choice of the model. The choice of the model depends on the questions to be answered and the processes to be simulated. The ASCE Sedimentation Engineering manual (Garcia, 2008) provides some important chapters on sediment modeling:

- Chapter 14: “Computational Modeling of Sedimentation Processes” (Thomas and Chang, 2008).
- Chapter 15: “Two- and Three-Dimensional Numerical Simulation of Mobile-Bed Hydrodynamic and Sedimentation” (Spasojevic and Holly, 2008).
- Chapter 23: “Development and Application of Numerical Models of Sediment Transport Associated with Dam Removal” (Cui and Wilcox, 2008).

The ASCE monograph: Sediment Dynamics upon Dam Removal (Papanicolaou and Barkdoll, 2011) also provides chapters specific to modeling sediment:

- Chapter 8: “Modeling and Measuring Bed Adjustments for River Restoration and Dam Removal: A Step toward Habitat Modeling” (Granata et al. 2011).
- Chapter 9: “Movement of Sediment Accumulations” (Greimann, 2011).
- Chapter 10: “Guidelines for Numerical Modeling of Dam Removals” (Randle and Bountry, 2011).
- Chapter 11: “Sedimentation Studies for Dam Removal Using HEC-6T” (Thomas, 2011).

Some tips are summarized below for numerical sediment modeling of dam removal:

- For most reservoirs, the predam channel and valley topography are more resistant to erosion than the overlying reservoir sediments. The presence of the reservoir pool and sediments over decades of time may compact the predam alluvial materials. Therefore, specify that the numerical model may only simulate the erosion of reservoir sediments and not the predam topography. This can be accomplished by assuming a non-erodible surface beneath the reservoir sediments. For cases where a new river channel alignment may form over a predam floodplain or terrace surface, the channel may incise the predam surface, but the incision would not be significantly deeper than the predam river channel.

- For one-dimensional model simulations of reservoir sediment erosion, cross sections must be spaced closely enough to account for the steep channel slopes created by knickpoint or headcut erosion. If measured reservoir cross sections are too widely spaced (more than one half of a typical river channel width apart), then interpolate cross sections between the measured cross sections. If a two-dimensional model is used, the model mesh size is typically fine enough to simulate the steeper slopes caused by knickpoint or headcut erosion.

- The rate of reservoir sediment erosion can be simulated using a sediment transport model that computes how the transport capacity changes over time in response to changing stream flows and changing sediment conditions over time. There are many sediment transport equations available for sand and gravel (Garcia, 2008), but relatively few for fine sediment. Cui et al. (2017) applied a set of three sediment transport capacity formulas by Chang (1963) to compute the concentration of fine sediment erosion for the proposed removal of Matilija Dam near Ventura, CA.

$$C = \left\{ \begin{array}{ll} 50\left(\dfrac{V^3}{gH\nu_s}\right)^{1.55} & , \dfrac{V^3}{gH\nu_s} \leq 10 \\ 135\left[ln\left(\dfrac{V^3}{gH\nu_s}\right)\right]^{3.1} & , 10 < \dfrac{V^3}{gH\nu_s} \leq 100 \\ 620\left(\dfrac{V^3}{gH\nu_s}\right)^{0.7} & , 100 < \dfrac{V^3}{gH\nu_s} \end{array} \right\} \quad (10)$$

  Where $C$ is the suspended sediment concentration in mg/L. $V$ is the average flow velocity, $g$ is the acceleration due to gravity, $H$ is the average water depth, and $\nu_s$ is the settling velocity of the median sediment size. The sediment transport capacity is a function of the dimensionless ratio $V^3/(g\,H\,\nu_s)$ and the applicable formula depends on this ratio.

- Sand and gravel eroded from the reservoir may deposit along the downstream channel, but deposited sediment will not generally mix with the existing bed. Numerical models will typically assume that depositing sediment mixes with the underlying streambed. However, simulated mixing of stream bed sediment with eroded reservoir sediment can result in a mixed grain size that is too coarse for subsequent transport. For example, simulated mixing of medium sand (0.5 mm diameter) with cobbles (130 mm diameter) will result in a mixed grain size that is much coarser than the deposited sand and that under predicts the true transport capacity and over predicts downstream sediment deposition. Simulations should not allow models to mix depositing reservoir sediment with coarser bed-material. This can be accomplished by specifying the initial bed material for the downstream channel as a thin layer (0.1 foot or 2 cm) with the same grain size as the reservoir sediment. Do not specify the grain size in the model as the predam removal coarse or armored stream bed. The model may simulate deposition on top of the initially thin sediment layer (representing the streambed surface), but specify that the model is not allowed to simulate erosion beyond this thin layer. In reality, the streambed material below the dam may experience some erosion or mobilization, but for the downstream channel, simulation of sediment deposition and subsequent transport is of primary importance. Simulating the erosion of the existing streambed is usually not important.

- If a dam removal can result in a rapid reservoir drawdown and release of a small flood, then a level-pool routing model should be used to predict the rate of reservoir drawdown and the resulting discharge hydrograph. The data requirements for a level-pool routing model include a table of reservoir surface area versus elevation, the geometric properties of the dam opening, and the reservoir inflow discharge hydrograph. The reservoir inflow assumption may be a constant or steady value for dam removal during low-flow conditions or a flood hydrograph for dam removal during high-flow conditions. Controlled increments of dam removal were used to drain Lake Aldwell behind Elwha Dam during periods of low flow (Figure 31).


**Figure 31.—Photograph of Lake Aldwell spilling through an excavated breach in Elwha Dam near Port Angeles, WA on October 17, 2011.**

# Special considerations

In addition to the analysis and prediction of reservoir sediment erosion and downstream transport, special considerations may be warranted for climate change and the case of multiple dam removals in the same watershed.

## Climate change

The 2014 National Climate Assessment provides predictions of climate change effects on hydrology are regionally based and long-term (U.S. Global Change Research Program, 2014). Most dams that have been removed have been hydrologically small, run-of- river dams that did not significantly affect (more than 10% change) downstream hydrology. Although future hydrology may change with a changing climate, the hydrology will not change as a result of dam removal for run-of-river projects. For these cases, there is no need to consider climate change in the dam removal analysis. In addition, for large reservoirs that are not yet full of sediment, climate change could affect the rate of reservoir sedimentation (Pinson et al., 2016). If dam removal takes many years to implement, sediment management and mitigation plans may need to be updated.

Altered hydrology due to climate change could affect flood frequency and the future sediment yield from the watershed. Sediment typically erodes from a reservoir within a few years following dam removal and this short term process would not be influenced by future climate change. Therefore, there is no need to consider future climate when evaluating the short term effects of dam removal. However, if the reservoir sediment management plan calls for storing all or part of the sediment within the reservoir over the long term, then altered hydrology due to climate change, and altered flood frequency, should be considered when designing bank stabilization for the remaining reservoir sediments.

## Multiple dam removals

The approach to take for analyzing multiple dam removals depends on the sequencing of dam removal. If the downstream-most dam is removed first, then the sediment effects can be evaluated independently from those of the upstream dams. When the next upstream dam is removed, predicted changes to the downstream channel topography from the first dam removal can be used as the initial conditions for evaluation of the next upstream dam removal.

If the upstream-most dam is removed first, then the effects should be evaluated with the downstream dams in place. Sediment released past the upstream dam that is removed can be expected to deposit in the reservoir pool behind the next dam downstream if storage capacity still remains. When the next downstream dam removal is evaluated, any increases in discharge or sediment supply, caused by the upstream dam removal, will have to be considered as an updated boundary condition for the downstream dam removal. In addition, any predicted topographic changes to the downstream reservoir or stream channel should be used as the initial conditions for evaluation of the next downstream dam removal.

If multiple dams are removed concurrently, then a more complex analysis will be needed to evaluate the superposition of sediment waves eroded from each reservoir. The released sediment wave from a reservoir can be several kilometers (miles) long with the greatest intensity in the middle portion (Greimann et al. 2006). The fastest portion of the sediment wave released from an upstream reservoir may catch up with the slowest portion of the downstream sediment wave, depending on the distance between the reservoirs. If the downstream sediment wave slows or stalls due to deposition, then the upstream sediment wave will add to the deposition. An experienced sediment analysis team is required to evaluate the effects of multiple dam removals.

# STEP 8: ASSESS UNCERTAINTY OF PREDICTIONS

To quantify the impact of dam removal, predictions must be made using a model. The model can be conceptual, empirical, numerical, or laboratory. All predictions have a certain level of uncertainty associated with them. Estimates of sediment transport and deposition need to have enough certainty to estimate where deposition is most likely to occur and if the deposition will be significant for a given dam removal scenario. Significant deposition could lead to lateral migration, stream bank erosion, channel widening, and increased flood stage. The source of the uncertainty of the prediction can be classified as:

1. Observational uncertainty: This is uncertainty in the data used to make the prediction of impacts. One example is the reservoir volume, another is streamflow.
2. Parameter uncertainty: Uncertainty in the parameters used in the model to make predictions.
3. Model structure uncertainty: uncertainty in the model formulation. This refers to model limitations.

In this step the guideline user estimates the confidence of each data category to assess if the data are adequate for decision making or if additional data collection or analyses are needed. The data categories where uncertainty may be most significant are discussed in the following sections. After assessing uncertainty levels, determine if more data collection or analysis are needed to increase the certainty of predictions.

## Observational Uncertainties

### Reservoir sediment volume uncertainty

The reservoir sediment volume needs to be known with enough certainty to determine the relative reservoir sediment size (e.g. small, medium, or large). This determination is based on the years of sediment load trapped within the reservoir ($T_s$) and an estimate of the uncertainty. The uncertainty in the years of sediment load trapped within the reservoir depends on uncertainty of the reservoir sediment volume or mass and the uncertainty of the average annual sediment load, which depends on the method used.

For many small dams, the predam reservoir topography was never measured, so the sediment volume has to be estimated from sediment thickness measurements or assumed predam topography. The uncertainty of the sediment thickness measurements generally increases with the sediment thickness and must be estimated. If a legacy channel still exists through the reservoir sediments, then the sediment is likely not thick and there would be greater confidence in the sediment volume estimate.

Data from thickness probes should be considered to represent the minimum sediment thickness. Vibracoring and drilling can penetrate deeper into the sediment than thickness probes. Attempts should be made to construct the predam reservoir topography from the present reservoir topography and estimates of sediment thickness. If the estimated predam reservoir topography seem reasonable, then the relative reservoir sediment thickness may also be reasonable. Estimation of the predam, longitudinal profile through the reservoir, based on the upstream and downstream channel profiles, is useful for comparison with the constructed predam reservoir topography. If the constructed predam topography appears to be reasonable and is consistent with the estimated profile through the reservoir, then there is some confidence with the sediment volume estimate.

For reservoirs where the predam topography was measured, the uncertainty of the reservoir sediment volume primarily depends on how well the datums are known for the predam and present surveys and on the detail of the predam survey. Widely spaced contours of a predam map will lead to more uncertainty than more tightly spaced contours.

If the sediment volume uncertainty is significant, then it is suggested that a range of sediment volumes is input in to the numerical model to compute the uncertainty in the impact prediction associated with the reservoir volume.

## Sediment grain size distribution uncertainty

The sediment grain size distribution should be known with enough certainty to estimate the proportions of fine and coarse reservoir sediment, estimate the median grain size of the coarse sediment, and the availability of armor size sediments. In addition, knowing the proportion of clay in the fine sediment will be needed to help characterize cohesive properties. The uncertainty of the grain size distribution decreases with the collection of more sediment samples, both across the surface of the reservoir deposit and at different depths. Collect enough sediment samples so the estimated uncertainty is low enough to accurately estimate the proportions of fine and coarse sediment, the median gain size, and the presence of armor sizes. If uncertainty exists in the sediment gradation, a range of sediment gradations can be used within a numerical model to compute the uncertainty associated with the sediment grain size distribution.

### Contaminant uncertainty

The absence or presence of contaminants needs to be known with enough certainty to determine if reservoir sediment needs to be removed or stabilized in place, and to predict their effects if released downstream. The uncertainty related to the presence of contaminants decreases with the collection of more sediment samples (spatially throughout the reservoir area and with depth) and with the number of potential contaminants being tested for from each sample. The uncertainty related to the effects of contaminants can sometimes be addressed by incorporating additional studies that analyze potential threats to biological communities and human health. Regional or local sediment quality guidelines may provide more information on how to incorporate special studies (Wenning and Ingersoll, 2002). If contaminants are suspected in the reservoir sediments, collect enough sediment samples to accurately determine if they are present and, if so, their concentration.

### Stream flow hydrograph uncertainty

The evaluation of the sediment effects associated with dam removal must consider a range of stream flows to understand sensitivity and reduce uncertainty. The hydrology of streams with long-term gage records will be much better understood than streams without gage records. Stream gage records near the dam will provide more certainty than gages farther away.

The uncertainty related to stream flows increases with flow variability. Streams with flash floods, including those prone to rain on snow events, will have more hydrologic uncertainty than streams dominated by ground water or snowmelt. Stream flow regulated by upstream dams may have more discharge certainty than unregulated rivers.

Use a range of reasonably possible hydrologic time series when predicting sediment-related effects to understand the sensitivity of stream flow. Use the estimated frequency of peak stream flows in each hydrology to characterize and rank the hydrologic time series.

## Parameter Uncertainty

Typically, there are several parameters that need to be defined in a sediment transport model. The most common are the hydraulic roughness values, the reference shear stress (or a similar parameter in the sediment transport formula), and the active layer thickness in the model. It is recommended that the hydraulic roughness values be first calibrated to observed water surface elevations, then a range of possible roughness values be used in the computation of sediment transport impacts. Similarly, the reference shear stress could be calibrated to observed bed load transport rates, then a range of possible calibration values could be used in the simulation of sediment transport.

## Model Structure Uncertainties

Each type of model, whether it be conceptual, empirical, numerical, or laboratory has certain limitations associated with its formulation or structure. The limitations have been described in the previous sections and these limitations result in prediction uncertainties. The model structure uncertainty is usually relatively harder to estimate than the observational or parameter uncertainty. It is, essentially, the “unknown unknowns” of our prediction. Perhaps the most straightforward method to estimate the model structure uncertainty in a prediction is to apply multiple models such as applying numerical modeling, physical modeling, and field experiments. In addition, multiple numerical models or at least sediment transport formulas within a numerical model can be applied to estimate a range of potential results.

# STEP 9: DETERMINE IF SEDIMENT IMPACTS ARE TOLERABLE AND MODIFY SEDIMENT MANAGEMENT PLAN

Once the sediment effects of dam removal have been estimated, the next step is to determine if these impacts are tolerable. Compile the predicted sediment effects and associated uncertainty from Steps 7 and 8. Then assess the impacts to resources of concern such as aquatic organisms and habitat, property, water quality, infrastructure, and water use. If sediment impacts and uncertainty are tolerable, then proceed to Step 10 and develop the monitoring and adaptive management plans. If the uncertainty of impact is considered too high, then consider additional data collection and analysis that would reduce that uncertainty or develop management plans that could adapt to uncertain conditions. Consideration should also be given in this step to how the benefits of dam removal and released sediment compare against impacts, both in the short-term and long-term temporal scales.

If predicted sediment impacts are not tolerable, then consider revising the dam removal and sediment management plans (Step 6) and adding sediment mitigation options (see below) to reduce impacts to tolerable levels, or leave all or a portion of the dam in place. After revised dam removal and sediment management alternatives are formulated, additional sediment analysis (Step 7) and uncertainty assessment (Step 8) may be needed. The dam removal and sediment management plans, along with other mitigation actions, should be fully described before conducting additional analyses (Step 7) and assessing uncertainty (Step 8). The plans should allow for some flexibility because not all variables like hydrology can be controlled. For example, the dam removal contractor may encounter unexpected construction difficulties or reservoir sediment erosion and downstream transport may behave unexpectedly.

If impacts are too high, there are various options to consider:

- Incremental or phased dam removal to slow erosion and downstream release of reservoir sediment.
- Changing the timing of dam removal to shift the impacts period to a different season.
- Reducing the amount of reservoir sediment that is allowed to erode by use of one or more of the following methods:
  - Sediment removal prior to dam removal
  - Sediment stabilization within the reservoir prior to dam removal
  - Leave a portion of the dam in place

It is important to realize that these methods can reduce the amount of sediment released downstream, but they can have other negative side effects such as increasing the duration of high suspended sediment concentrations, decreasing the habitat quality within the reservoir after dam removal, or aesthetic concerns.

## Example water quality mitigation

Water quality impacts could be of concern for downstream water users and for the aquatic environment. New water treatment plants could be constructed to handle high sediment loads as a result of dam removal and pre-treat water for existing users. These treatment plants could be temporary. Alternatively, existing treatment plants could be upgraded to handle additional sediment loads during dam removal. Other water sources could also be found on a permanent or temporary basis.

High concentrations of sand, gravel, fine wood (twigs and branches), and organic matter released from the reservoir could easily clog downstream fish screens at surface water diversions. Where possible, consider the use of wells and infiltration galleries to divert or extract water during the high sediment loads associated with dam removal. The water withdrawal rate of wells and infiltration galleries can be significantly less than surface diversion, but they will exclude sand, gravel, and all sizes of wood from the diverted water. High concentrations of clay and silt released from the reservoir could reduce the hydraulic conductivity of the river alluvium, depending on the fraction of surface-water flow that enters the ground water. For some rivers, the fraction of surface water entering the ground water may be quite small with only a minor reduction in hydraulic conductivity. However, reductions in hydraulic conductivity could be large for ephemeral streams.

When there are concerns about the water quality impacts on the aquatic environment, consider the timing and duration of the impacts related to dam removal. High sediment concentrations as a result of dam removal are temporary. The magnitude and duration of impacts can be adjusted by controlling the rate of dam removal. A faster rate of dam removal can reduce the duration of impacts and effect fewer generations of species, but increase the magnitude of impacts while they occur. A slower rate of dam removal can reduce the magnitude of impact, but increase the duration. If the impacts still would be lethal, then a shorter duration of impacts may be more desirable.

If there are sensitive species (e.g., threatened or endangered) present downstream from the dam that are unlikely to tolerate sediment impacts, in terms of survival, reproduction, or habitat requirements, then adjust the timing of dam removal or modify the sediment management plan to avoid impacting sensitive life stages. If possible, considering removing the dam and allowing reservoir sediment erosion at a time when the species are not susceptible to the impacts. If the dam must be removed when species are present, consider whether excavation or stabilization of the reservoir sediment is necessary or if the sensitive species in question can be temporarily relocated to minimize impacts.

## Example flooding mitigation

For reservoirs with large volumes of coarse sediment, aggradation of the downstream channel may occur that could increase flood stage. For these cases, consider slowing the rate of dam removal to avoid excessive aggradation. Also, consider constructing new levees and dikes, raising existing levees, and providing stream bank stabilization to mitigate sediment aggradation effects.

# STEP 10: DEVELOP A MONITORING AND ADAPTIVE MANAGEMENT PLAN

More than 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. These calls for increased monitoring were 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. 2003b, Hart et al. 2002, H. John Heinz III Center for Science, 2003). Robust project monitoring was recognized as necessary to improve the practice of dam removal.

While many still note the relative paucity of quantitative monitoring, especially for low-head dam removals (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 (Collins et al. 2017; Wilcox et al. 2014; Warrick et al. 2015; Burroughs et al. 2009; Cheng and Granata, 2007; Doyle et al. 2002 and 2003a; Kibler et al. 2011; Major et al. 2008, 2010, 2012, and 2017; and Pearson et al. 2011). We have learned that the geomorphic responses of the upstream and downstream channels vary considerably owing to sediment grain size distribution, reach gradients, valley morphology, regional physiography, surficial geology (e.g. glaciated versus non-glaciated), and climate zone. Thus, it is necessary to monitor several sites to adequately represent the range of fluvial habitat variability across the nation so that practitioners can have useful analogs for planning and prediction. Post-removal debriefing or “lessons learned” documents would be helpful to better inform the dam removal science and engineering community. Documentation of project objectives, decision processes and actual decisions, and any data collected or post removal evaluation would be most helpful.

Monitoring may also be warranted to support adaptive management at any given site. The fundamental motivations for using adaptive management is to reduce project risks and improve project results. 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, the reasons for this should be explored and existing actions should be modified or new actions implemented to achieve those objectives. For the Elwha River Restoration Project near Port Angeles, Washington, monitoring tasks were designed to be conducted in a “real-time” operational mode for rapid decision making during the dam-removal process.

## 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 of 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. Permit compliance and ecological effectiveness 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.

Permit compliance sediment monitoring is usually concerned with documenting suspended sediment concentrations during dam removal construction activities. 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 dam removal construction period at sites that are 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 done just after completion of dam removal construction to 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 requires monitoring over larger spatial scales, including control sites or control reaches, and the over durations considerably longer than compliance and implementation monitoring. For example, monitoring of a small dam removal on the Patapsco River in Maryland, included locations 6 river kilometers (4 river miles) downstream and over a two-year period to observe whether conditions exceed pre-determined erosion or aggradation thresholds (NOAA, 2010).

Effectiveness monitoring is usually focused on parameters that will document whether the project was successful at achieving specific objectives, for example, improved habitat conditions for 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) to be undertaken and better equips practitioners to improve future dam removal construction methods and prediction tools. Thus, effectiveness monitoring advances the scientific basis for the practice of dam removal.

In phased dam removal approaches, monitoring can be applied to help adaptively manage specific implementation actions such as approving the next increments of dam removal or anticipating the sediment-related effects of subsequent dam removal increments. Adaptive management works well when the sediment-related effects of phased dam removal are predicted and near real-time monitoring is conducted to test those predictions. Near real-time monitoring is needed for decision making as the project is being implemented. If monitoring results confirm the predictions or if there are no unanticipated problems, then phased dam removal and sediment management continues as planned. However, if monitoring results detect unanticipated problems, then the task is to determine why these problems are occurring, implement additional measures, and develop corrective actions before proceeding with the next planned increments of dam removal and sediment management. Additional measures could mean increased frequency and spatial coverage of monitoring or additional types of monitoring to better understand what is happening.

## 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.

From a practical perspective, monitoring designs are also driven by available project monitoring budgets which can be constrained. Indeed, the relative lack of dam removal monitoring, 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 (Bellmore et al. 2017). 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. Monitoring could help reduce costs by allowing a less conservative and less costly design.

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 understand if changes to the river system have been brought about by the removal. A simple before and after monitoring design will accomplish this by sampling the parameters of interest before the removal and again after the impact (East et al. 2015, Draut et al. 2011). 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 an upstream 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.

## Monitoring 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 water users and recreationist. 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
- Stage recorders to detect changes in water surface elevation that may result from bed aggradation or incision
- Time-lapse photography stations including web cameras
- Geomorphic mapping using repeat orthophotography (braiding index, sinuosity, etc.)

- Bed material grain size distribution measurements
- Stratigraphic observations and measurements of sediment deposits
- Suspended sediment and bed load measurements
- Turbidity measurements

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. Pebble counts (Wolman, 1954) are a widely utilized method for documenting bed-material particle size in gravel and cobble bed streams because they are easy to implement, however, they are limited in quantifying the fraction of fine material in the bed. New methods use photogrammetry to digitally measure and process bed-material particle size (Warrick et al. 2009). Harrelson et al. (1994) also provide detailed methods for stream channel surveys. Methodologies for some of the other parameters listed are reviewed in Kondolf and Piegay (2003). In addition to traditional survey and sampling methods, integration of LiDAR and digital camera technology offers opportunities to expand sampling coverage and provide more detailed data. Structure for motion was applied on the Elwha River dam removal project to provide frequent (bi-weekly to monthly) repeat orthophotography and digital elevation models of the reservoir areas and downstream river reaches (Randle et al. 2015, East et al. 2015). Many continuous water quality monitoring measures, like turbidities measured with certain probe models, “peg out” and cannot be used effectively in extremely high sediment concentrations that can occur as a result of dam removal. The guideline user might want to seek out monitoring devices that are specifically designed to handle such high concentrations.

For dam removal cases needing to monitor contaminant effects, Cantwell et al. (2014) and Katz et al. (2016) showed effective use of sediment traps and passive samplers upstream and downstream of the dam site. These techniques were used on the Pawtuxet River (Rhode Island) in 2011 to document dissolved organic contaminants and metal concentrations during dam removal. Cantwell et al. (2014) noted the passive samplers in particular had high sensitivity, could monitor contaminant bioavailability, and assess potential changes in contaminant toxicity. For large releases and phased dam removal, suspended sediment and selected trace element monitoring at Milltown Dam removal provided temporal data to quantify impacts from reservoir sediments eroded and transported downstream versus background loads (Sando and Lambing, 2011).

Sediment loads can be directly measured at discrete points in time before, during, and after dam removal using traditional methods for suspended sediment concentration and bed load (Edwards and Glysson, 1999; Nolan, et al. 2005; and Gray, et al. 2008). Surrogate technologies can also be used to continuously measure suspended sediment concentrations (Rasmussen, et al. 2009, U.S. Geological Survey, 2014; and Landers, et al. 2016).

# Example Case Studies

Case studies are summarized in this section to help illustrate examples of low risk, moderate risk, high risk, contaminants, and multiple dam removals.

## Negligible Reservoir Sediment case study: Gold Hill Dam removal, Oregon

Gold Hill Dam was located on the Rogue River, 195 km (121 mi) upstream from the mouth and upstream from Gold Hill, Oregon (Reclamation, 2001). The dam had a hydraulic height of 2.4 m (8 ft) and a crest length of 300 m (1,000 ft) aligned in the shape of an "L" (Figure 32). The dam diverted water for municipal use by the City of Gold Hill and was operated as a run-of-the river facility. "The dam was the second greatest barrier to fish passage in the Rogue River Basin. Salmon migrating downstream passed into the dam's diversion canal and were trapped or injured. Adult salmon were slowed by the dam on their way back to their spawning grounds." (Water Watch, 2017a).

**Figure 32.—Gold Hill Dam on the Rogue River prior to dam removal in 1999 (left), during dam removal in 2008 (center), and after dam removal in 2008 (right).**

A new municipal water intake was constructed in 2005, which made the dam obsolete. Gold Hill Dam was the removed during July and August 2008. Both full and partial dam removal were considered. Hydraulic model simulations indicated that full dam removal (rather than partial dam removal) would guarantee successful fish passage and only increase project costs by 4 percent relative to partial dam removal.

The reservoir impounded behind the dam had little to no trap efficiency. Divers found only 350 m$^3$ (460 yd$^3$) of fine sediment, which was considered a negligible volume ($T_s$ = 0.005 yr) relative to average annual sediment load of the Rogue River estimated at 80,000 m$^3$/yr (100,000 yd$^3$/yr). More sediment was used to construct the cofferdam (used to dewater the site for dam removal) than the volume of reservoir sediment. As a check on the negligible ranking, the volume of a typical gravel bar was estimated using equation 1 (Volume = Bar Width$^2$ x Bar

Depth). The gravel bar volume was greater than the reservoir sediment volume and validates the negligible sediment risk ranking:

$$11{,}000m^3 bar\ volume = (69m\ bar\ width)^2(2.4m\ bar\ detph) > 350m^3\ reservoir\ sediment\ volume$$

No contaminants were found in the reservoir sediment. The reach downstream of Gold Hill Dam contained several large pools 10 to 15 m deep (30 to 50 ft) that had excess storage capacity relative to the reservoir sediment volume. Therefore, the risk of sediment impacts was negligible because there was so little sediment relative to the downstream river transport capacity and storage. During dam removal the river was allowed to erode and transport the 350 $m^3$ of reservoir sediment downstream and no significant sediment impacts were detected.

## Low risk case study: Chiloquin Dam removal, Oregon

Chiloquin Dam was located on the Sprague River, 1.4 km (0.9 mi) upstream from the confluence with the Williamson River and upstream from Chiloquin, Oregon. The dam had a hydraulic height of 3.4 m (11 ft) and a crest length of 45 m (150 ft) (Figure 33). The dam was constructed in 1914 to divert water for irrigation into the Modoc Point Irrigation District Main Canal and was operated as a run-of-the river facility. The dam was believed to block fish passage of 95 percent of the endangered Lost River and shortnosed suckers from Upper Klamath Lake to upstream spawning habitat (Juillerat, 2008). Dam removal was expected to provide endangered fish access to 130 km (80 mi) of habitat. “The two suckers are a traditional food for Klamath Indians, who annually hold ceremonies to welcome the spawning run of the fish (Juillerat, 2008).”

**Figure 33.—Chiloquin Dam on the Sprague River just prior to dam removal in 2008 (left), during dam removal in 2008 (center), and after dam removal in 2008 (right).**

A new pumping plant with state-of-the-art fish screens was constructed in 2007, which made the dam obsolete. Chiloquin Dam was removed during August 2008.

The ratio of reservoir capacity to mean annual inflow was 0.00014, which corresponds to an expected reservoir sediment trap efficiency near zero. Two methods were used to produce estimates of the reservoir sediment volume that represented potential upper limits of stored sediment (Randle and Daraio, 2003):

1. The product of average-measured-sediment thickness and planimetric area for two reservoir areas.
2. The cumulative products of sediment cross-sectional area and longitudinal channel length between cross sections.

The estimates of reservoir sediment volumes were 28,000 $m^3$ or 44,000 tonnes (36,000 $yd^3$ or 49,000 tons) and 34,000 $m^3$ or 55,000 tonnes (45,000 $yd^3$ or 61,000 tons). The relative reservoir sediment volume was considered small ($T_s$ = 0.2 to 0.3 yr) using an estimated average annual sediment load of the Sprague River of 200,000 to 300,000 tonnes/yr (200,000 to 300,000 tons/yr). Sediment samples were collected and tested for possible contaminants, but none were found. The potential consequences were considered medium and included sediment deposition on spawning riffles and sediment deposition along Williamson River near Klamath Lake. The risk of sediment impacts was considered low because of the small reservoir sediment volume and the medium consequences of sediment impacts should they occur.

Following the removal of Chiloquin Dam in August 2008, sediment eroded from the reservoir impoundment without high river flows (Bauer and Collins, 2009). About 1,600 cut logs were then found sunk along the bottom of the former reservoir. The eroded sediment temporarily deposited in the deepest pools of the Sprague River downstream from the dam. Riffle areas were largely unaffected by sediment deposition. No changes in river bed elevation or bed material size were detectable downstream from the Williamson River confluence. A year after dam removal, the sunken logs in the reservoir had not significantly moved.

## Moderate risk case study: Savage Rapids Dam removal, Oregon

Savage Rapids Dam was a 12-m (40-ft) tall concrete structure located on the Rogue River upstream from Grants Pass, Oregon and 174 km (108 mi) upstream from the river mouth. The ratio of reservoir capacity to mean annual inflow was 0.0001, which corresponds to an expected reservoir sediment trap efficiency of near zero. The reservoir sediment was composed of 95% sand and gravel with negligible contaminants and less than 10% fine sediment. The reservoir sediment volume was equivalent to two years of the river's annual sediment load (Bountry et al. 2013). In this case study, the "probability" of coarse sediment impact is medium while the probability of fine sediment impact is negligible. A water intake for irrigation, located just downstream (80m or 270 ft) of the dam, had a medium consequence if buried with sediment because it could temporarily reduce the irrigation water supply. The expected coarse sediment **"consequence"** for the intake near the dam was medium, and the **"risk"** results in a moderate rating for the local intake. Data collection and analysis occurred to improve understanding of how much sediment might bury the intake and for how long. The intake was operated seasonally between April and October. The answers helped the project team suggest removal of the dam in the fall to allow a full winter high flow season to flush reservoir sediment farther downstream.

The first winter flow season following dam removal did flush reservoir sediments into downstream pools, but enough deposition occurred at the intake that excavation was required for the first season of operation. In the years following additional excavation was not required. A second water intake that provided municipal water was located 3.1 km downstream. The municipal water intake was experienced increased suspended sands during initial flushing of the reservoir sediment which was deemed a medium consequence because it would be only a temporary increase in operational costs over a short duration of hours to days with little risk of having to stop operations. This resulted in a low risk for the municipal water intake. Turbidity impacts to fish were expected to be of low consequence because the increase in suspended sediment would be temporary and the dam removal was intended to restore fish passage which was a greater benefit than the short-term impact. Actual turbidity following dam removal was increased above background for the first few days to the same order of magnitude as a typical storm and quickly recovered to background levels (Figure 34) (Bountry et al. 2013; Tullos et al. 2016). As this example illustrates, the assigned risk may vary depending on the sediment grain size, how far a critical site is from the dam, how much sediment is released, and how long elevated sediment levels are expected to last.

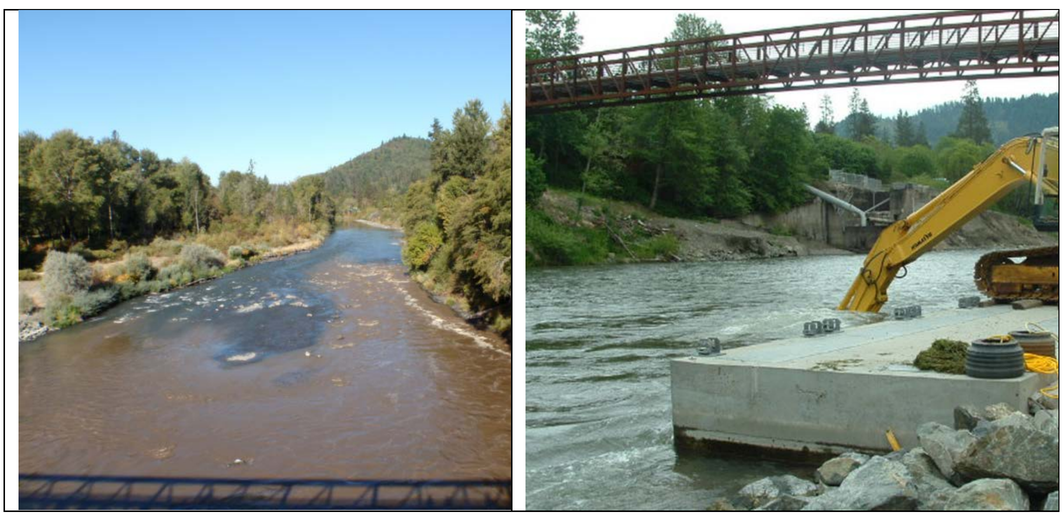


**Figure 34.—Downstream view of short-term turbidity plume released from breaching of Savage Rapids Dam in Oregon (left photo) and view of sediment excavation at water intake just downstream of dam (right photo). Photo taken by Jennifer Bountry, Bureau of Reclamation.**

## Moderate risk case study: Shuford Dam removal, North Carolina

Shuford Dam was constructed on the Henry Fork River near Brookford, North Carolina during the late 1800s to power an adjacent textile mill, but the dam no longer served a purpose (Singer McCombs, 2016). "The dam removal eliminates the public safety risk of an unmaintained dam, improves the local community's ability to recreate safely on the Henry Fork River, and restores the river back to its natural free flowing state." "The ecological goals of the dam removal are to reconnect fish populations above and below the dam and improve the instream habitat by letting the river flow freely… Historically, freshwater mussels were found in the Henry Fork, but have been extirpated for about 100 years because of the impacts of dams and pollution. The North Carolina Wildlife Resources Commission is interested in restoring freshwater mussels to this stream now that the dam removal will create suitable habitat once again."

The reservoir impoundment contained a medium relative sediment volume (Singer McCombs, 2016). A due diligence sediment analysis was performed, which indicated some potential sources of contamination from the upstream watershed. Sediment samples were collected, but laboratory analysis did not find contaminants of concern. The U.S. Army Corps of Engineers 404 permit required that some of the reservoir sediment be excavated with heavy machinery while the remainder of the sediment was allowed to erode and transport downstream like in a natural storm event. Numerical hydraulic and sediment modeling was necessary to meet this requirement. Resource management concerns included the stability of an upstream bridge after the reservoir sediments were eroded and how to appropriately manage the medium volume of sediment in the former impoundment. The risk is characterized as moderate based on stakeholder and regulator concerns.

The 11 m (35-ft) high dam was removed in two phases between July and November 2016 (Erin Singer McCombs, American Rivers, written communication, March 7, 2017). The first phase removed about 1 m (3 ft) from the top of the dam and notched it in the center. The dam was left in this manner for two months to let reservoir sediment erode and transport downstream. After two months, the rest of the dam was removed. The project was completed in November 2016. Limited monitoring is being conducted for fish and physical geomorphic changes.

## High risk case study: Elwha and Glines Canyon Dam removals, Washington

The Glines Canyon Dam (64 m or 210 ft) and Elwha Dam (32 m or 105 ft) on the Elwha River were removed during the period 2011 to 2014 to restore fish passage, honor federal trust responsibilities to the Lower Elwha Klallam Tribe, and connect the downstream river to the pristine upstream watershed within Olympic National Park in Washington State (Warrick et al. 2015). Glines Canyon Dam tops the list in Table 1 for having the largest dam height and reservoir storage capacity of a dam removal project. Lake Mills behind this dam also had the largest reservoir sediment volume. The ratio of reservoir capacity to mean annual inflow was 0.045, which corresponds to an expected reservoir sediment trap efficiency of 70 percent. The combined reservoir sediment volume of 21 million $m^3$ (27 million $yd^3$) was large and equal to several decades worth of upstream sediment supply ($T_s$ = 90 yr) (Randle et al. 2015). This volume was too large for dredging, so river erosion was the only economically viable option to remove sediment during phased dam removal. Sediment-related consequences were considered large and included increased sediment concentrations to the aquatic environment and downstream water users and increases in flood stage from riverbed aggradation. Sediment risks were considered high and nearly two decades of complex planning and mitigation negotiations occurred prior to dam removal. Sediment risks were mitigated by the construction of water treatment plants, flood control levees, and a sediment monitoring and adaptive management program to guide the timing and increments of dam removal.

Concurrent dam removal began in September 2011. The removal of Elwha Dam was completed within one year (by April 2012) while the removal of the upstream Glines Canyon Dam was completed in three years (Figure 35,Figure 36, Figure 37, and Figure 38) (August 2014). As of September 2016, 72 percent of the sediment has been eroded from Lake Mills and 50 percent has eroded from Lake Aldwell. Sediment concentrations were high during dam removal with peak concentrations reaching 10,000 mg/l. Nearly every downstream river pool was temporarily filled with sediment. New gravel bars formed along the channel that had been absent while the dams were in place, inducing bank erosion and increased river sinuosity in unconfined alluvial reaches. Flood stage for the 2- to 10-yr floods increased by about 0.6 m (2 ft). Despite the deposition in the downstream channel, about 90 percent of the sediment eroded from the reservoirs was transported to the coastal estuary and enlarged the coastal delta 460 m (1,500 ft) into the sea.

**Figure 35.—Elwha Dam on the Elwha River prior to just to dam removal in 2011 (left), during dam removal in 2012 (center), and after dam removal in 2012 (right).**

**Figure 36.—Lake Aldwell Delta upstream from Elwha Dam prior to just to dam removal in 2011 (left), during dam removal in 2012 (center), and after dam removal in 2015 (right).**

**Figure 37.—Glines Canyon Dam on the Elwha River prior to just to dam removal in 2011 (left), during dam removal in 2012 (center), and after dam removal in 2015 (right).**

**Figure 38.—Lake Mills delta upstream from Glines Canyon Dam prior to just to dam removal in 2011 (left), during dam removal in 2012 (center), and after dam removal in 2015 (right).**

## Contaminants case study: Lower Dam removal, Massachusetts

Lower Dam was on Ox Pasture Brook near Rowley, Massachusetts. The dam was 3 m (10 ft) high and located within state conservation land with no nearby infrastructure, which meant there was limited consequences from sediment exposure or mobilization (Alex Hackman, Massachusetts Division of Ecological Restoration, written communication, 2017). The dam was removed to achieve ecological restoration through fish passage and restored tidal flows at the head-of-tide on this small coastal stream (Figure 39).

Sediment sampling during 2007 and 2008 included five samples in the impoundment, two downstream, and one upstream; laboratory analyses included heavy metals, PCBs, VOCs, PAHs, and pesticides (Alex Hackman, Massachusetts

Division of Ecological Restoration, written communication, 2017). By products of DDT, including DDD and DDE, were detected in the reservoir sediment at concentrations several times above the marine ecological screening values. The same legacy pesticides were detected upstream and downstream, but at slightly lower concentrations. The volume of reservoir sediment was estimated to be 11,000 m$^3$ (15,000 yd$^3$) and primarily consisted of fine sediment and organic matter (Alex Hackman, Massachusetts Division of Ecological Restoration, written communication, 2017). The average annual sediment load was unknown. About 1,000 to 2,000 m$^3$ (1,000 to 2,000 yd$^3$) of this material was predicted to erode. An in-stream sediment management approach was proposed, permitted, and implemented because of the presence of the contaminants throughout the watershed and in the reservoir sediment and the cost and damage to wetlands from potential dredging. About 2,000 m$^3$ (2,000 yd$^3$) of sediment was excavated for channel reformation. The remainder of the sediment was stabilized in place as restored floodplain wetlands.

Dam removal was completed in 2009. This was the first permitted project in Massachusetts involving in-stream sediment management and pollutant concentrations above ecological screening values and background levels. The project involved only a small volume of sediment erosion and downstream transport, 800 m$^3$ (1,000 yd$^3$) (Alex Hackman, Massachusetts Division of Ecological Restoration, written communication, 2017). Downstream monitoring was required as a permit condition. Monitoring results indicated a slight increase in downstream contaminant concentrations within the channel and marsh surface, followed by a return to background concentrations within 16 months after dam removal. Project partners included the Massachusetts Division of Ecological Restoration, Massachusetts Division of Fisheries and Wildlife, NOAA, American Rivers, Northeast Massachusetts Mosquito Control and Wetlands Management District, and Stantec Consulting Services.


**Figure 39.—Rapid Revegetation the Impoundment Following the Removal of Lower Dam (Photos by Alex Hackman, MA Division of Ecological Restoration).**

## Multiple dam removal case study: Battle Creek Hydroelectric Project, California

The Battle Creek Hydroelectric Project is located in California along the North Fork and South Fork drainages of Battle Creek, which is a tributary to the Sacramento River. A variety of restoration alternatives were considered on Battle Creek to improve fish habitat and fish passage, including removal of up to five dams (Figure 40). The dams being considered for removal were selected because the profit margins associated with hydroelectric generation were marginal (Jones and Stokes, 2005). The 2005 planning study provides a good example of considering multiple dam removals in conjunction with a variety of hydroelectric reoperations and fish passage improvement strategies to determine how to best meet project objectives. For this project, reservoir sediment at the dams considered for removal consists of sand, gravel, cobble, boulders and wood. The sediment stored at each site is less than an average annual load, but cumulatively may be 1 to 2 years of average annual coarse sediment load. One reservoir contained limited sediment and no risk management actions were implemented. The remaining sites called for pilot channels to be constructed for a short distance upstream of the dam site to facilitate sediment flushing during high water events and to ensure that fish passage was adequate (Jones and Stokes, 2005).

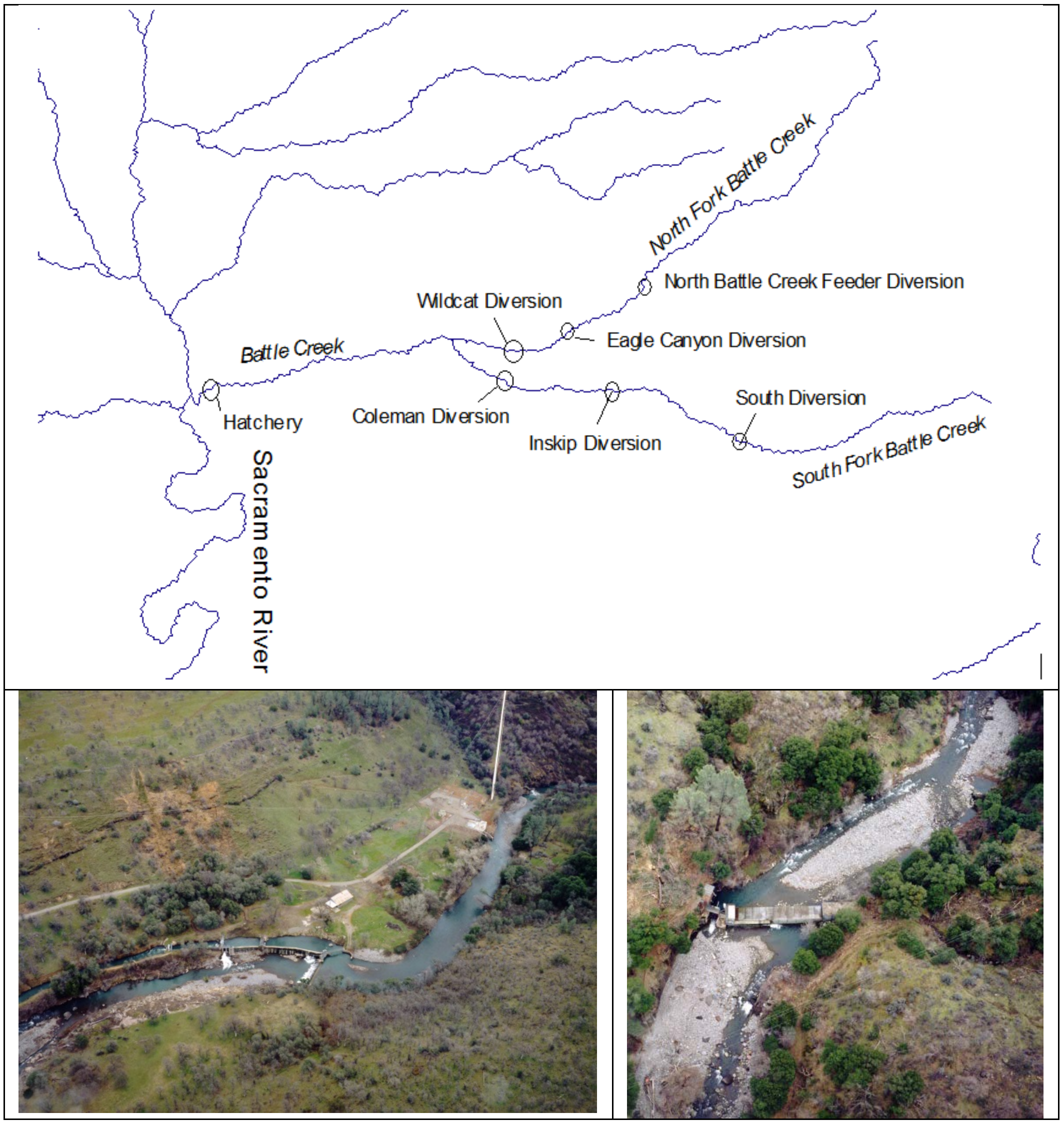



**Figure 40.—Locations of dams removed within Battle Creek Salmon and Steelhead Restoration Project (upper image), view of Coleman Diversion Dam (lower left), and view of South Diversion Dam (lower right) (Jones and Stokes, 2005). Note that Inskip Diversion and the hatchery were not removed.**

# CONCLUSIONS

While dams still provide a vital function to society, some need to be removed for various reasons such as changes to the benefit-cost ratio, dam safety concerns, sedimentation impacts to operations or water storage, legal and financial liability, ecosystem restoration (including fish passage improvement), site restoration, and public safety or recreation use. These dam removal analysis guidelines for sediment provide engineers and scientists ten steps for determining and implementing the appropriate level of sediment data collection, analysis, and mitigation for dam removal projects. The process is tiered based on estimated level of risk from releasing reservoir sediment downstream. Users are encouraged to apply the guidelines in an iterative process, first with readily available information, and again as more data and analysis results become available.

Because the consequences of releasing contaminated reservoir sediment can be large, each project team must evaluate if contaminants are present using a multi-step approach. A screening step is recommended to first determine if there is "reason to believe" contaminants could be stored within the reservoir sediment and there is greater than 10% fines. If there is no concern and less than 10% fines, the user can continue with the remaining guideline analysis steps. If a potential concern of contaminant presence is identified, sampling and chemical and biological analysis may be accomplished to inform whether reservoir sediment can be safely released into the downstream river considering both human consumption and effects on aquatic species of concern. Comparison with local, state and federal sediment quality criteria and background water quality are incorporated into the contaminant analysis steps. If the contaminants cannot be safely released, mitigation must be implemented that often consists of dredging and disposal of contaminated sediment or capping in place with adequate protection from future seepage or erosion. If contaminants can be safely released into the downstream river channel, the guideline user can proceed with determination of risk of sediment-related impacts.

Risk of sediment-related impacts (low, moderate, and high) is determined from the product of the probability of sediment impact (small, medium, or large) and the consequence(s) of those impacts (small, medium, or large) should they occur. The probability of sediment impact is determined from the relative reservoir sediment volume (small, medium, or large), which corresponds to the number of years of average annual sediment load stored in the reservoir, $T_s$. An accurate estimate of the reservoir sediment volume and grain size (fine versus coarse proportions) is key to determining the probability of sediment impact, along with either measured or estimated average annual sediment load. Projects with a small probability of sediment impact have 0.1 to 1 year of average annual sediment load trapped within the reservoir, a medium probability case has 1 to 10 years of average annual sediment load, and a large probability case has greater than 10 years (decades) of average annual sediment load trapped with the reservoir. For dam removal cases with little or no measured reservoir sediment volume (less than 10% average annual load stored in reservoir), simplified procedures are utilized to verify if these cases have negligible risk of sediment release and can bypass intensive data collection and modeling. The consequences of sediment impacts, should they occur, are based on qualitative value judgements from the stakeholders and the project team. Depending on the composition of reservoir sediment, consequences may be separately considered for release of fine sediment versus coarse sediment. Benefits of sediment release and improved connectivity to the upper watershed above the dam(s) are also considered concurrent with determination of consequences, particularly over the long-term, to help weigh potential impacts with restoration opportunities.

After determination of risk, a dam removal and sediment management plan is selected. During the first iteration, rapid dam removal and complete river erosion of reservoir sediment is recommended to evaluate magnitudes and duration of sediment impacts. In some cases with large risk or where construction logistics are already known, alternatives such as phased dam removal may be included early in the analysis phase. The level of analysis recommended increases with increasing risk. Conceptual models are recommended to help capture important and potentially unique sediment processes for each site and communicate with other team members, decision makers, and stakeholders how these processes correlate with sediment risk. As risk increases, more quantitative analysis is recommended to help reduce uncertainty and inform dam removal and sediment management planning. Before finalizing dam removal and sediment management plans, the guideline user assesses uncertainty in key steps to determine if the uncertainty is acceptable for decision making or can be reduced through more robust data collection or analysis. During dam removal, uncertainty can be mitigated by the monitoring of expected outcomes and adaptively managing the project to achieve the desired goals. For cases that require mitigation of sediment impacts, a range of dam removal and reservoir sediment management options including adaptive management may be implemented to help reduce impacts to acceptable or tolerable levels.

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# APPENDIX A

# RESERVOIR SEDIMENTATION PROCESS

This section focuses on the spatial variation of reservoir sediment deposits and the temporal reservoir sedimentation history to help inform expectations of river responses following reservoir drawdown and dam removal. All reservoirs formed by dams on natural rivers are subject to some degree of sediment inflow and deposition. Reservoirs tend to be very efficient sediment traps because of the very low flow velocities (Morris and Fan, 1997; Reclamation, 2006). The coarsest sediment particles tend to deposit first, at the upstream end of the reservoir, while finer particles tend to deposit farther downstream. If the reservoir retention time is short, the finest particles may pass through the reservoir, especially during periods of high flows. Sand, gravel, and cobble tend to deposit as a delta at the upstream end of the reservoir while silt and clay tend to deposit along the reservoir bottom (Figure A-1). In addition, wood of all sized (twigs to large logs) can accumulate throughout the reservoir sediment deposit. When fine sediments reach the dam without being released downstream, a muddy lake condition is formed and the deposits tend to be level (Morris and Fan, 1997).

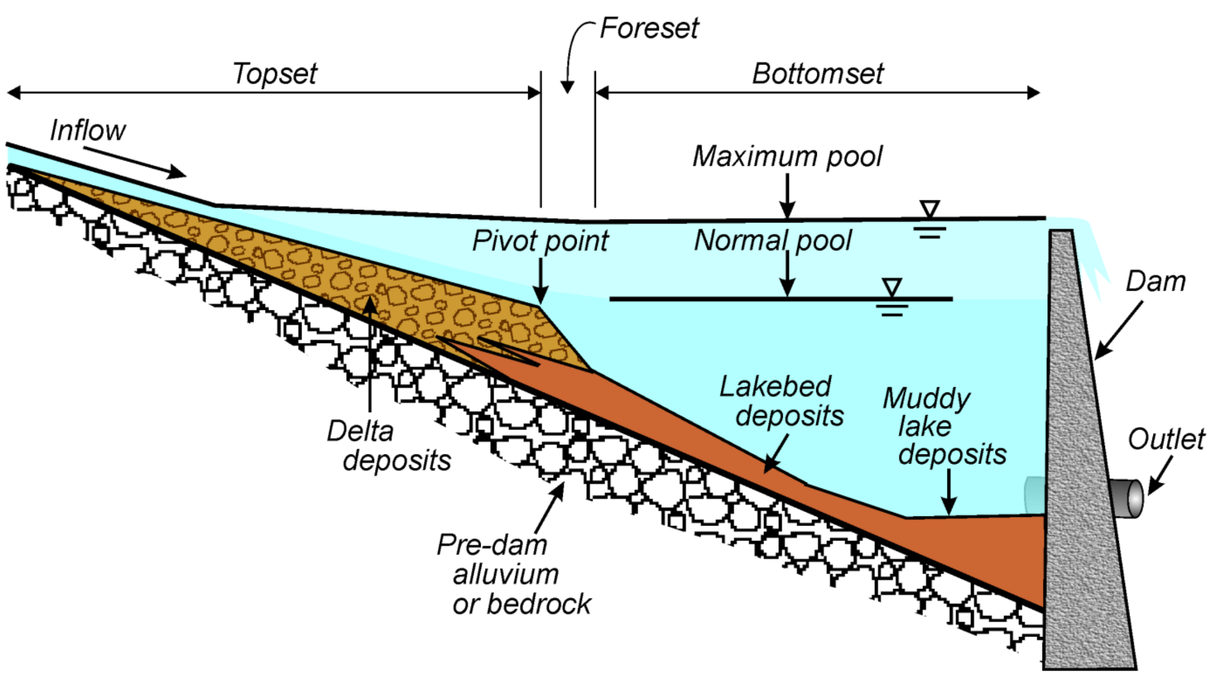


**Figure A-1.—Reservoir sediment profile with delta and lakebed sediment deposits (after Morris and Fan, 1997).**

Reservoirs with deltas or sediment deposits that are near the crest of the dam may aggrade above the normal operating pool, especially during peak flood events. When sediment aggrades above the normal operating pool, vegetation establishment and large wood recruitment often occur. Even when a reservoir is full of sediment, a dominant active channel will be present. Vegetation can create additional resistance to erosion, and influence the location of the active channel passing through the reservoir. On Marble Bluff Dam in Nevada, vegetation formed on the reservoir sediment deposit creating an island just upstream of the dam (Figure A-2).


**Figure A-2.—Vegetation has grown on extensive reservoir sedimentation behind Mable Bluff Dam, which is located on the Truckee River approximately 3 miles upstream from Pyramid Lake and 50 miles downstream of Reno, Nevada. The inset ground photograph is looking upstream at vegetated island that has formed on reservoir sediment deposit just upstream from the dam. The low-flow channel path is to the right of the island in this photograph, and a side channel has formed on the left side of the island. Aerial photograph is from Google Earth. The ground photograph was taken by Jennifer Bountry, Reclamation, November 18, 2016.**

Conceptually, reservoir sediment deposits can be divided into three main longitudinal zones: topset deposit, foreset deposit, and bottomset deposit (Julien, 1995; Morris and Fan, 1997; Bridge, 2003). The topset is the delta deposit created by rapidly settling coarse sediment. The foreset deposits represents the face of the delta advancing into the reservoir. Foreset deposits are differentiated from topset deposits by relatively finer grain sediment and a much steeper slope, usually at the angle of repose for the grain sizes composing the delta. The downstream limit of bed material transport in the reservoir corresponds to where the topset deposit ends and the foreset deposit begins. The pivot point at the downstream end of the topset deposit will progress downstream with continued reservoir sedimentation. Bottomset deposits, often referred to as lakebed sediment, are the fine sediments deposited beyond the delta by turbidity currents or non-stratified flow. Lakebed sediment often deposits across the entire inundated landscape beneath the reservoir surface, including the reservoir hillslopes and coves. The reservoir deposits may also include organic and woody material of varying sizes.

The longitudinal slope of the delta topset has been found to vary between 20 to 100 % of the predam channel slope, with an average slope of about 50% of the predam channel slope (Strand and Pemberton, 1982). The actual delta slope depends on the sediment grain size, reservoir level fluctuations, and flow velocity or shear stress. The average of foreset slopes observed in Reclamation reservoir resurveys is 6.5 times the topset slope; however, some reservoirs exhibit a foreset slope considerably greater than this; for example, Lake Mead's foreset slope is 100 times the topset due to the coarse sediment gradation (Strand and Pemberton, 1982; Reclamation, 2006).

Delta deposits commonly contain both coarse and fine sediments, where the bottomset beds are composed primarily of fine sediments (Morris and Fan, 1997). However, coarse sediments can be found within layers of the bottomset beds due to tributary sediment inflows, erosion of the exposed delta during reservoir drawdown, reservoir slope failures, and extreme floods.

The longitudinal deposition patterns will vary with the reservoir pool geometry, sediment inflow rate and grain size, and the amount and frequency of reservoir fluctuations. Morris and Fan (1997) presented four basic types of reservoir sediment deposition patterns (Figure A-3). The patterns depend on the sediment inflow characteristics and reservoir fluctuations. Multiple deposition patterns can exist simultaneously in different areas of the same reservoir. Small reservoirs with low sediment trap efficiency may only have thin deposits of sediment in various patches with relatively lower transport capacity (such as off-channel areas, pools and eddies) throughout the reservoir bottom (Gartner et al., 2015).

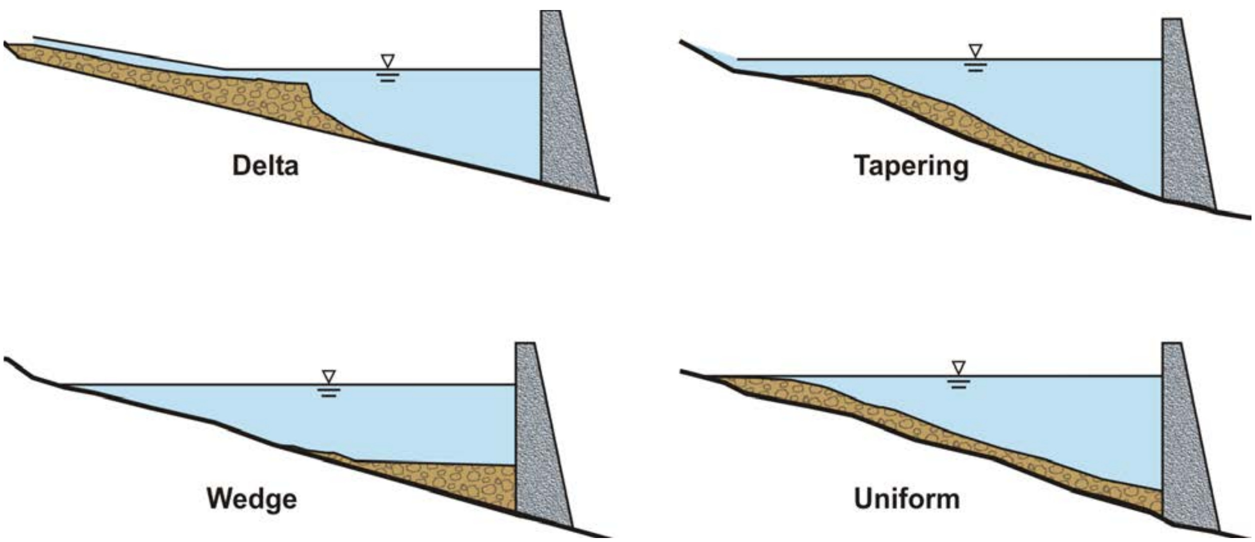


**Figure A-3.—Four basic patterns of reservoir sediment deposition: delta, tapering, wedge, and uniform (Morris and Fan, 1997).**

The four basic longitudinal patterns of reservoir sedimentation presented in Figure A-3 are described below:

- Delta deposits are at the upstream end of the reservoir and contain the coarsest fraction of the sediment load (Figure A-4). The delta may consist entirely of coarse sediment when the retention of water is short. However, the delta may also include a significant fraction of fine sediment when the retention time is long.

- Wedge-shaped deposits are thickest at the dam and become thinner in the upstream direction. Wedge-shaped deposits are caused typically by the transport of fine sediment to the dam by turbidity currents. Wedge-shaped deposits are also found in small reservoirs with a large inflow of fine sediment, and in large reservoirs operated at low water level during flood events, which causes sediment to be transported near the dam. Coarse sediment can create a wedge-shaped deposit over the entire length of the reservoir.
- Tapering deposits are progressively thinner in the downstream direction. This is a common pattern in long reservoirs normally held at a high pool level, and reflects the progressive deposition of fine sediments in the downstream direction.
- Uniform deposits are unusual, but do occur in narrow reservoirs with frequent water level fluctuation and a small fine sediment load.


**Figure A-4.—Looking upstream at Lake Mills delta on the Elwha River in Washington State during removal of Glines Canyon Dam. Photograph courtesy of National Park Service taken from time-lapse camera on February 12, 2012.**

## Upstream delta extent

Deltas typically do not form in reservoirs with little or no coarse sediment inflows. Coarse sediment entering a reservoir typically deposits at the upstream of end of the normal pool and forms a delta. As a delta builds in thickness over time, deposition will continue on the delta surface and above the normal reservoir water surface elevation along one or more of the upstream channels flowing into the reservoir. For the sediments deposited above the normal reservoir pool, vegetation will likely grow, further encouraging flow into more narrow and distinct channel paths. As the roughness increases on the delta surface with the accumulation of wood and vegetation, the backwater depth of the upstream channels will also increase. Through this process, the delta will expand farther upstream into narrower riverine corridors beyond the original reservoir pool formed by the dam. While these upstream areas may look like river corridors, they eventually incise upon dam removal (Randle et al., 2015).

## Sedimentation rates

All reservoirs formed by dams on natural water courses trap some sediment over time. Reservoirs with small sediment storage capacities typically fill with sediment within the first few years of operation, especially on large rivers. The sediment trap efficiency approaches zero for fine sediment first and eventually for coarse sediment. Once the sediment storage capacity has been filled, sediments may continue to deposit upstream of the reservoir pool, but will also be transported through the reservoir to the downstream channel. The reservoir sediment storage will be dynamic and vary over time as floods erode and deposit sediment, but the long-term average sediment load supplied from upstream will be transported through the reservoir. The process where a reservoir has filled with sediment was documented for Merrimack Village Dam (Pearson et al., 2011). Pearson and Pizzuto (2015) provide a five-step conceptual model for the evolution of the longitudinal sediment profile through the reservoir. Eventually, a ramp of sediment forms near the dam and bed material load is transported over the dam for the first time. Finally, the reservoir will reach a morphology where bed material load can be transported through the reservoir without net accumulation over the long term. Some scour of the reservoir sediment during floods would be likely after periods when the sediment storage is at a maximum while deposition is likely after periods when sediment storage is at a minimum.

If there is still room for the reservoir to trap sediment, the sedimentation rates vary over time with hydrology. The volume of reservoir sedimentation can increase substantially during floods. Inflowing reservoir sediment loads vary with discharge, the type of precipitation (rainfall or snowmelt), vegetation, wildfire, and land use.

## Legacy sediment and legacy dams

Some reservoirs in the eastern and mid-western United States accumulated sediment that eroded as a result of historical land clearance for agriculture and mining by European settlers during the early 1600s to mid-1800s, depending on region. Reservoirs upstream of milldams quickly filled, and then new, larger dams were built that buried or inundated the older dams (James, 2013;

Walter and Merritts, 2008; Knox, 2006; Jacobson and Coleman, 1986). Sedimentation has also infilled riparian wetlands and raised floodplains converting them to terraces rarely inundated. These sediments are sometimes referred to as legacy sediment, and can result in complex sedimentation patterns when identifying sedimentation behind a more modern dam.

It is common for dams to have been built downstream of an older, smaller dam, submerging it in the new enlarged pond. This interrupts sediment distribution and flow upon dam removal (Figure A-5). Legacy dams can add additional challenges to dam removal.

**Figure A-5.— Looking across at example of legacy dam. Photography courtesy of Jim MacBroom.**

## Trap efficiency

The proportion of inflowing sediment deposited in the reservoir relative to the total incoming sediment load is known as the sediment trap efficiency. The trap efficiency depends primarily upon the fall velocity of the various sediment particles, flow rate, and velocity through the reservoir (Strand and Pemberton, 1982). The particle fall velocity is a function of sediment particle size, shape, and density and the water viscosity. The flocculation or combining of fine sediment particles can increase the settling velocity. The reservoir sediment trap efficiency tends to decrease over time as sediment fills the reservoir. However, the trap efficiency also decreases temporarily during floods as flow velocity increases through the reservoir.

A small reservoir pool behind a diversion dam is expected to reach its sediment storage capacity for coarse sediment within a few years whereas the trap efficiency for fine sediment may be near zero soon after completion. A negligible or small reservoir sediment volume is expected for these small reservoir pools. Larger reservoir pools trap coarse sediment for decades and the trap efficiency for fine sediment can be significant. Therefore, simple estimates of reservoir sediment trap efficiency can be quite useful for initially estimating the relative sediment volume and the level of field data collection that is needed. The reservoir shape also influences trap efficiency with wide aspect ratios (reservoir width divided by channel bankfull width) increasing trap efficiency.

The ratio of the reservoir storage capacity to the average annual streamflow volume – referred to as the retention time - is a useful index to initially estimate the sediment trap efficiency. The reservoir sediment trap efficiency increases as the retention time increases. Churchill (1948) and Brune (1953) developed empirical relationships for reservoir sediment trap efficiency which were compared with empirical case studies from other locations in Strand and Pemberton (1982) (Figure A-6).

The Churchill (1948) trap efficiency curve is recommended by Strand and Pemberton (1982) for settling basins, small reservoirs, flood retarding structures, semi-dry reservoirs, and reservoirs that are frequently sluiced. Churchill (1948) correlated the percentage of the incoming sediment load passing through a reservoir with the ratio of the reservoir retention time (s) to the mean water velocity (m/s or ft/s) (sedimentation index). The sedimentation index can be made dimensionless by multiplying it by the acceleration due to gravity ($m/s^2$ or $ft/s^2$).

The Brune (1953) trap efficiency curve is recommend by Strand and Pemberton (1982) for estimating the long-term reservoir trap efficiency for large storage based on the correlation between the relative reservoir size (ratio of reservoir capacity to average annual inflow) and the trap efficiency. Using this relationship, reservoirs with the capacity to store 10 percent of the average annual inflow would be expected to trap between 72 and 98 percent of the inflowing sediment. Reservoirs with the capacity to store 1 percent of the average annual inflow would be expected to trap between 45 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 fine-sediment trap efficiency would be near zero.

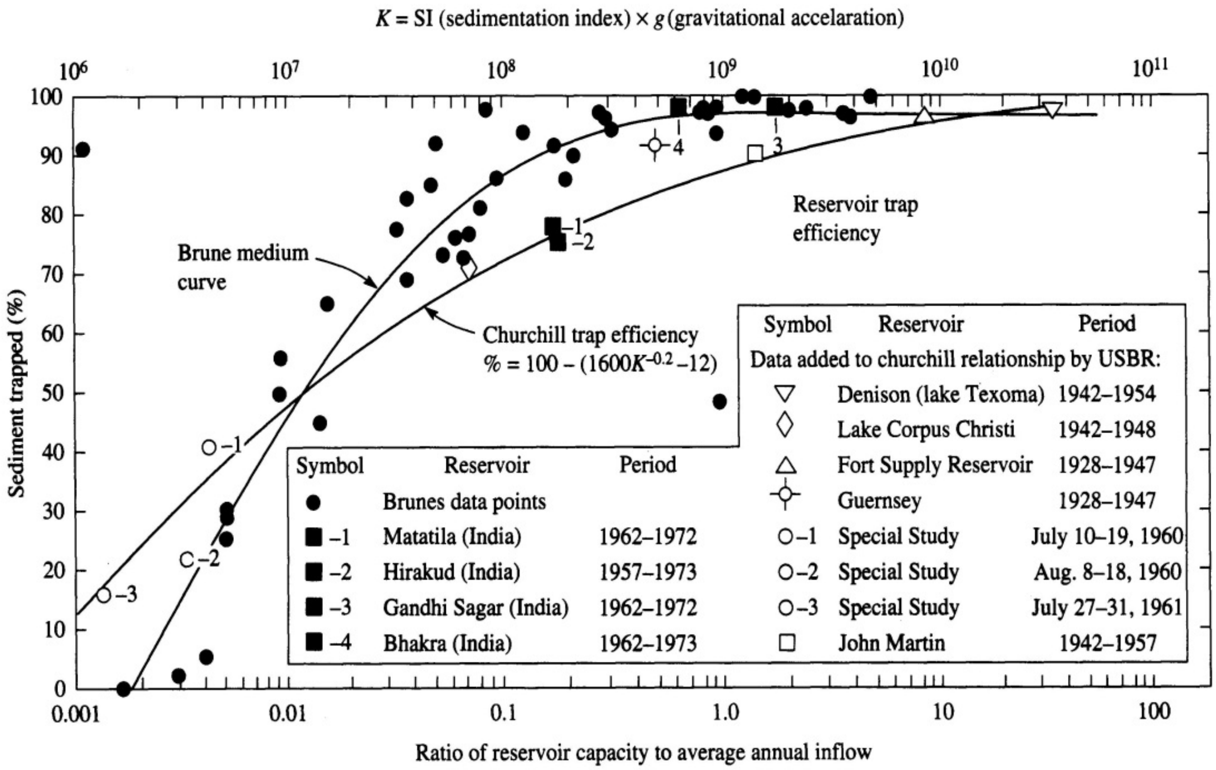


**Figure A-6.—Empirical reservoir sediment trap efficiency curves based on Churchill (1948) and Brune (1953) and additional case studies (Strand and Pemberton, 1982).**

Reservoirs will normally trap all of the inflowing coarse sediment until the reservoir is nearly full and reaches its sediment storage capacity (Figure A-7). After sediment has filled the reservoir, future floods will transport inflowing sediments through the reservoir, deposit some of these sediments, and erode some of sediment that had previously deposited within the reservoir. The delta upstream from the reservoir can continue to aggrade even after the reservoir has filled with sediment. The pool behind a small diversion dam is typically filled with sediment within the first few floods. In cases where the delta has reached the dam, the delta surface may partially erode resulting in a net loss in reservoir sediment storage during floods, and then refill during subsequent low flows.

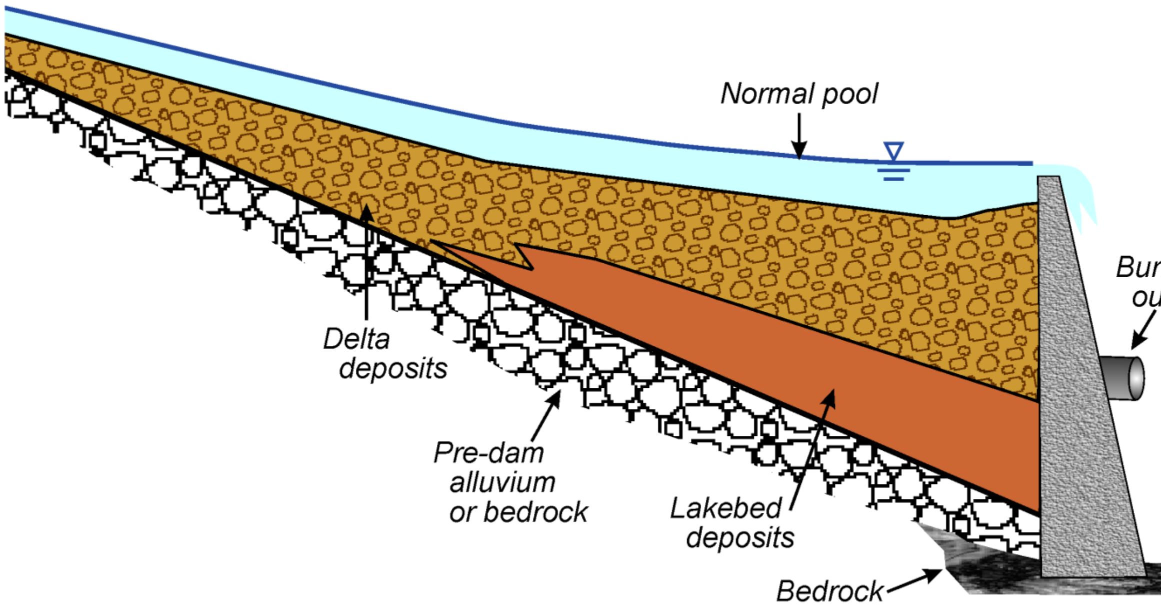


**Figure A-7.—Reservoir sediment profile after the reservoir has filled with sediment.**

# Reservoir operation effects on sedimentation

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 sediment trap efficiency 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 river operation), flood flows pass through the reservoir and sediment trap efficiency is reduced. When reservoirs are frequently drawn down, a portion of the reservoir sediments (typically the delta) will be eroded and redeposited deeper in the reservoir pool. In some cases, the sediments will be flushed out of the reservoir. Fine sediments that are exposed above the drawn down reservoir pool will compact as they dry out (Strand and Pemberton, 1982). For example, fine sediment would be compacted during droughts that result in reservoir drawdown.

The design life approach for dams was typically used in the United States (and many other parts of the world). Under the design life approach, the dam and reservoir were designed to trap a certain volume of sediment over certain period of time. The elevation of the lowest dam outlet is set to be above the reservoir sediment over the sediment design life. Once the reservoir sediment has reached the lowest outlet, some undefined action will have to be taken for continued reservoir operations or projects benefits may be reduced or lost. Life-cycle design is a new alternative for dams where the reservoir sediment is managed for sustainable use. For example, Three Gorges Dam in China was constructed with large sediment sluice gates that can be used to drawdown the reservoir during floods, increase flow velocity through the reservoir, and pass inflowing sediments downstream.